A TORQUE RECORDING DEVICE

By
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A Dissertation
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CERTIFICATE

Certified that the dissertation entitled "A Torque Recording Device", which is being submitted by Shri Narayan Prasad in partial fulfilment for the award of the degree of Master of Engineering in Advanced Electrical Machines of University of Roorkee is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

This is further to certify that he has worked for a period of 7½ months from 1st January to 15th August, 1965 for preparing this dissertation for Master of Engineering degree at the University.

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CONTENTS

SYNOPSIS

The importance of accurate torque measurement is well known. Several devices are available for this purpose. Most of them suffer from the slip-ring troubles.

Magnetic-coupled torquemeter, originally developed by B. F. Langer is free from slip-rings and can be used for high speeds.

This dissertation mainly deals with the development of a Magnetic-coupled torquemeter. The device has been designed and used for the recording of steady and transient torques.

This is preceded by a brief review of dynamometers and torquemeters developed from time to time.

CHAPTER I

INTRODUCTION

The need to measure the torque, or the torsion moment accurately in a shaft, either in a static condition or during rotation, has exercised the ingenuity of engineers for many years. Numerous devices have been suggested and produced from time to time for the purpose.

The torque acting on any of the machine elements can be either static, in which a couple is applied to the element without rotating it; or dynamic, in which the torsion moment is applied to the element that is rotating. The measurement of the torque of a rotating machine presents considerable difficulty, particularly when it is required to record the instantaneous values under rapidly varying conditions.

Upto about 1910, the devices used for torque measurement were purely mechanical[1]. Capacitance strain gauges[2,3] were developed by Carter and Shannon and found a useful application for the accurate measurement of torque. With the advent of resistance strain-gauge torquemeter[5], the industry got a convenient tool for the torque measurement. These meter were not very suitable under the extreme conditions of temperature, humidity and speed of the m/c. Magnetic-coupled torquemeter[12] was developed by Langer. Modification has been suggested herein and a torquemeter has been designed, fabricated and tested in the laboratory to prove the efficacy of this modification.

In most engineering works, it is the average value of torque during a cycle which is of interest to us, yet from the stand point of design of shaft and other stressed members, their life and strength, it is desirable to have a torque-time plot which is invaluable to an engineer. The developed torquemeter serves the above requirement.

CHAPTER II

TORQUE MEASUREMENT BY DYNAMOMETERS

Torque measurement is often associated with determination of mechanical power. In this connection, torque measuring devices are commonly referred to as dynamometers. When so applied, both torque and angular speed must be determined. Another important reason for measuring torque is to obtain load information necessary for stress or deflection analysis.

There are three basic types of dynamometers, absorption, driving, and transmission type. Absorption dynamometers dissipate mechanical energy as torque is measured, hence are particularly useful for measuring power or torque developed by power sources such as engines or electric motors. Driv ~~During~~ dynamometers, as their name indicates, both measure torque or power and also supply energy to operate the devices under test. They are, therefore, useful in determining performance characteristics of such things as pumps and compressors. Transmission dynamometers may be thought of as passive devices placed at an appropriate location within a machine or between machines, simply for the purpose of sensing the torque at that location. They neither add to nor subtract from the transmitted energy or power, and are sometimes referred to as torque meters.

2.1. Mechanical and Hydraulic dynamometers[16]

The most simplest type of absorption dynamometer is the familiar prony brake, which is strictly a mechanical device depending on dry friction for converting the mechanical energy into heat.

Another form of dynamometer operating on similar principles is the water brake, which uses fluid friction rather than dry friction for dissipating the input energy.

The dynamometer casing is mounted on turnnion bearings, so that it is free to rotate about the shaft except for the restraint provided by the torque lever arm. The capacity is a function of two factors, speed and water level.

The hydraulic dynamometer has the advantages of high power-absorption capacity in small space and at low cost. It is inherently unstable and requires constant manipulation of the control values to maintain constant torque during a run. It is well adapted to testing engines and automotive-propulsion loads.

2.2. Electric dynamometers[16,17].

Almost any form of rotating electric machine can be used as a driving dynamometer, or as an absorption dynamometer, or as both.

Eddy Current dynamometers

Eddy current dynamometers are of the absorption type. They are incapable of driving a test machine such as a pump or compressor, hence they are only useful for measuring the power from a source such as an I.C. engine or electric motor.

The eddy current dynamometer comprises in essence a metallic disc, driven by the shaft, rotating in a magnetic field. The magnetic field is produced by electromagnets. The rotation of the conducting disc in the magnetic field induces circulating eddy currents in the disc. Mechanical energy supplied by the shaft is thus converted to electric energy in the disc, which in turn is dissipated by ohmic resistance and converted to heat. The field structure is mounted on trunnion bearings so that it is free to rotate about the shaft. The torque reaction of the field structure is equal and opposite to the torque input to the shaft, less the friction torque of the trunnion bearings.

The torque absorption of the eddy current dynamometer is proportional to the square of the magnetic flux and directly proportional to the speed. The torque at high speeds is limited by the mechanical strength and the heat carrying capacity of the coolant.

In general the field of operation of eddy-current dynamometer is much wider, and the control by varying the field current is quite convenient.

2.3. Driving Dynamometers

Absorption dynamometers are useful only in testing engines. Tests of pumps or compressors require that the machine be driven by a source of mechanical power. A driving dynamometer is useful in such a case, because it provides the mechanical power required and the measurement of the power. Mostly the driving dynamometers are the electric motors. These can also be used as generators and then are particularly useful for testing engines which require an external source of power for starting. The dynamometer is worked as a motor to start the engine and then switched over to generator operation for measuring the output of the engine.

Electric Cradled Dynamometer[26,27].

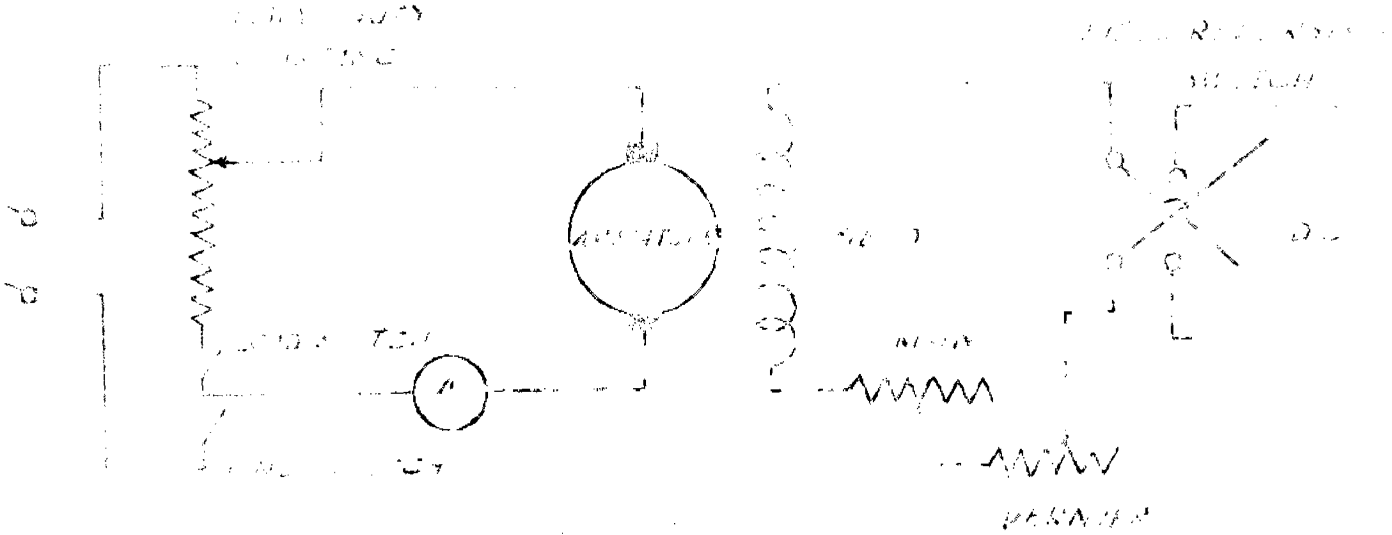
The electric dynamometer is a d.c. machine with the field structure cradled in trunnion bearings, so that it is free to rotate about the shaft except for the restraint provided by the torque-weighing arm and the connecting wires. Cradling in trunnion bearings permits the determination of reaction torque. It is useful tool for the measurement of the shaft power. The only disadvantage of this device is its high cost.

The circuit diagram for an electric dynamometer is as shown in Fig.D-1. It can be worked both as generator and motor.

When the dynamometer is used to test a gasoline engine, the ignition circuit can be led through a relay in the field circuit, so that the loss of field current will shut off the ignition and avoid overspeeds. Similar arrangements should be made for other types of engines operated without governors.

Sometimes when the d.c. supply is not available, the alternative arrangement is used for driving the dynamometer. Instead of controlling the voltage with the help of armature resistance, the field resistance is varied and so the control is achieved by small field rheostat. The circuit is as shown in Fig. D-2.

The generator field is energised from a separate exciter through a control so that the voltage can be reduced to very low values. Generator output is fed directly to the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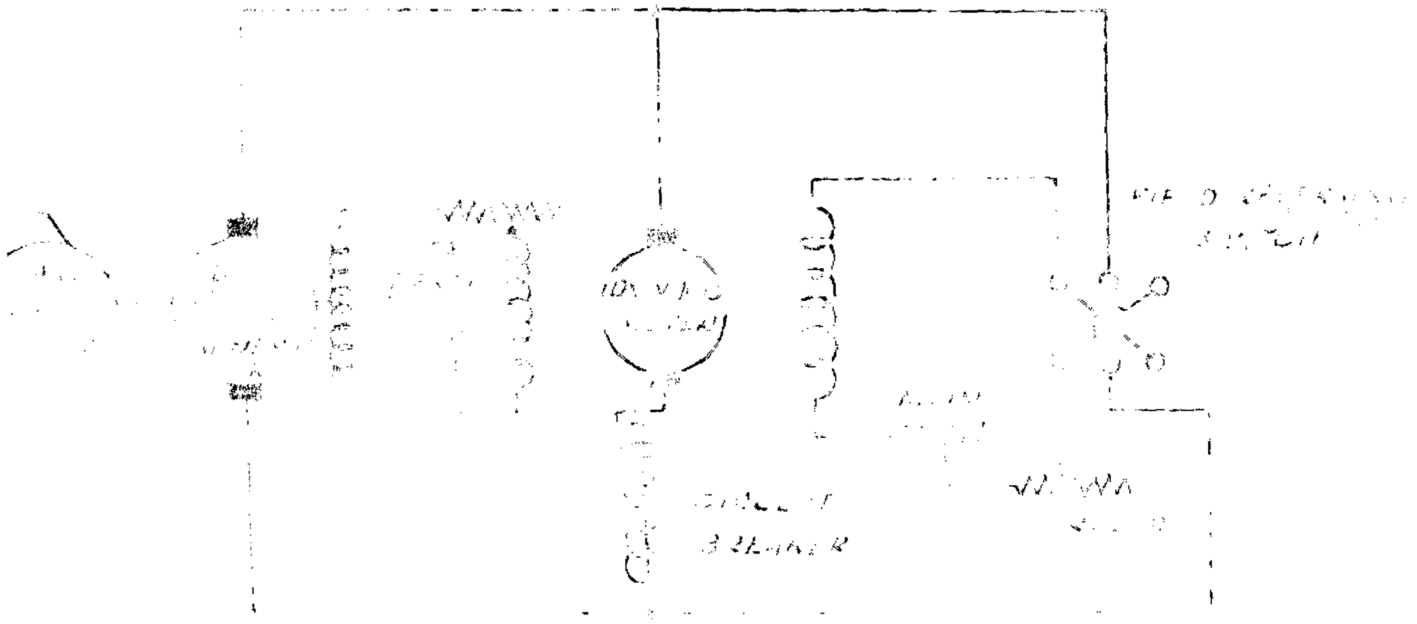
DYNAMO
FIELD REVERSING SWITCH
CIRCUIT BREAKER

dynamomotor. With full field on the generator the dynamomotor gets the maximum voltage and runs at top speed. As the generator field is weakened, the dynamomotor voltage and speed are reduced. If power is absorbed by the dynamomotor, the flow can reverse. With power input to the generator it will operate as a motor and drive the induction machine as an induction generator thus pumping the excess power back into the mains.

CHAPTER III

TRANSMISSION DYNAMOMETERS OR TORQUE METERS

I. Description of some early Torquemeters.[1]

3.1. Fottinger's Torquemeter

Fottinger's torquemeter is one of the earliest types of torque meter. It is a mechanical device and many meters are working on the principle on which this meter operates. The meter is as shown in fig.3-1. It consists of two split clamps a and c, encircling the shaft whose torque is to be measured. These clamps are rigidly fixed (by pins or screws) to the shaft between definite gauge points on the shaft, a distance apart. A sleeve is fixed to the clamp c, which transfers the motion of the gauge point c on the shaft to a disc b, close to the disc on clamp a. The relative angular displacement of the disc a and b is a measure of the torque acting on the shaft. This angular displacement is magnified by the link system and recorded by a pencil d on suitable paper wrapped round the co-axial cylinder e, which is stationary and can be moved clear of the pencil when required. When there is no torque on the shaft, the pencil traces a circumferential line and this is the zero line of the diagram. When the torque is transmitted by the shaft, the pencil moves to the right or left, according to the direction of rotation and traces a more or less wavy line at some distance from the zero line. The micrometer screw f allows the ordinates to be calibrated in angular movement.

Forttinger's meter was developed for the measurement of torque transmitted through the propeller shaft of a ship.

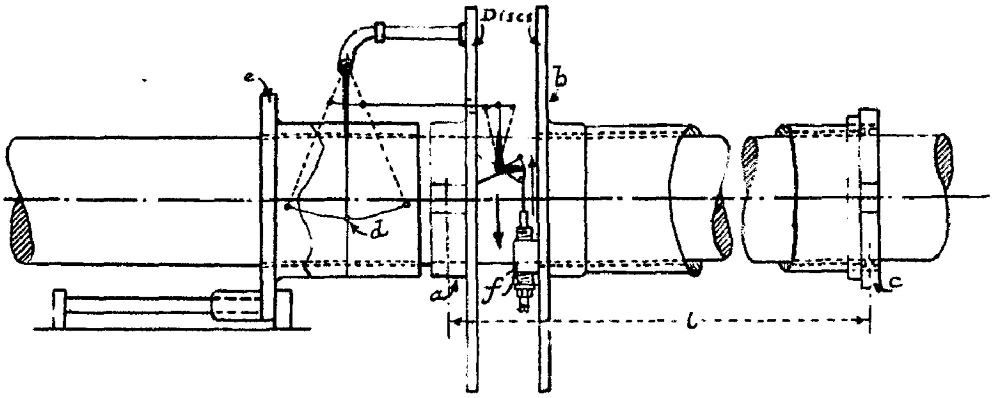

Fig. 3-1

Fottinger's Torsion Meter.

Disadvantages

The main disadvantage of this meter is that a large free length of the shaft is required, which may result into the bending of the shaft. It can only be used for slow moving shafts and record of rapidly varying torque is not possible.

3.2. The next development was Collie's torsionmeter. Two light co-axial shafts are mounted in bearings parallel to the main shaft and driven from it by gearing with a high ratio. This increases the gauge length and hence large angular twist is obtained which increases its sensitivity. The meter is shown in fig.3-2 and fig.3-3. The end of one of the shafts, a, is screwed and carries a nut b, which is splined to the other shaft, c, and can slide upon it for a limited distance. The motion of the nut is transmitted to a pointer, which measures a mechanical magnification of the movement. When the main shaft twists under load, one of the shafts advances or retards in angular position with regard to the other, so screwing the nuts one way or the other by an amount proportional to the torque transmitted.

The instrument is not applicable where the space is limited. Also the accuracy of measurement is not high. The only advantage is that a direct reading on the pointer is obtained.

The meters described so for were in use before 1910 and possess the following disadvantages:

1. A long length of shaft is required in most cases; in most of the machines, today such a length is not available. Also spurious effects are introduced through the bending of these long shafts.

2. Most of the devices are only applicable to slow-running shafts, and in general, the degree of accuracy is not high.

3. The readings are non-continuous.

4. In some cases there is no pointer reading and in others no permanent record.

5. The instruments need skilled operation and interpretation of the results.

For the present-day application the torquemeters should be compact, having high degree of accuracy, higher response, a permanent record, a pointer reading, robustness and stability. To achieve this electrical means of transmitting and magnifying the angular strain of a gauge length have been used.

We have a relation between the torque and the total angle of twist as

$$\frac{T\,L}{G\,I_p} = \theta.$$

Thus the relationship between the applied torque and the angle of twist produced is linear and so if the angle of twist is measured, it is as good as measuring the applied torque.

An electrical strain gauge could be made use of in order to measure the torque by the above method.

The principle reason for the popularity of electrical gauges is their ability to record data at a station remote from the point of application of the gauge, thus allowing the gauges to be attached in position which would be inaccessible for direct measurement by mechanical or optical means and high dynamic response of the electrical gauge which renders the gauge invaluable for dynamic work.

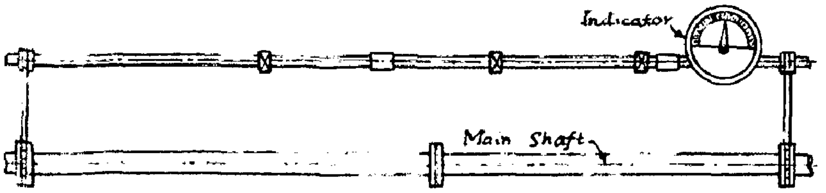

Fig. 3-2.

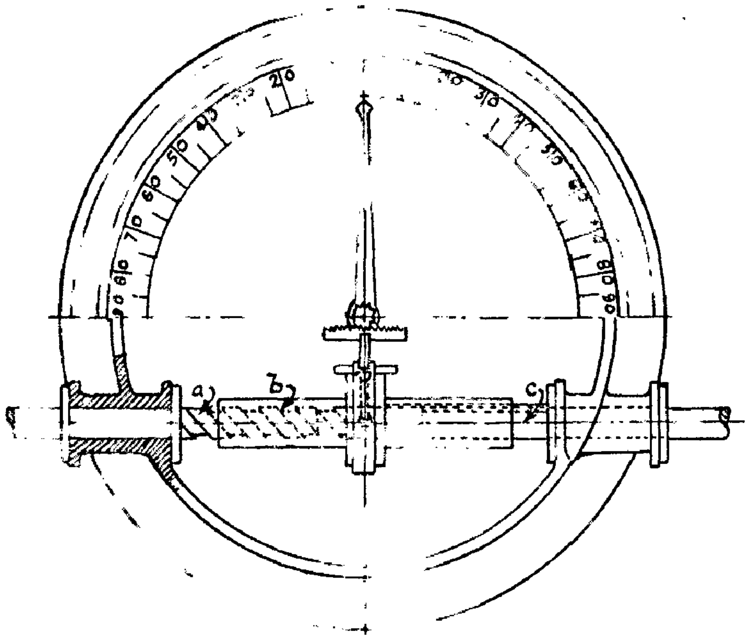

Fig. [illegible]

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An electrical gauge has been defined as a device which converts a physical magnitude into an electrical magnitude. All electrical circuits for magnification and measurement of small movements involve some or all of the three basic electrical units of inductance, capacitance and resistance. Therefore, obviously, any circuit component whose value can be changed by a mechanical phenomenon can be used for measuring purposes. Electrical gauges are therefore classified according to the principle of operation such as variable inductance, variable capacitance and variable resistance types.

II. Capacitance strain-gauge torque meters.[1-4]

Variable capacitance strain-gauge - The capacitance strain gauge is composed of a condenser, the capacity of which can be made to vary with strain. A capacitance is fundamentally two plates seperated by an insulator (often air). The impedance to an alternating current depends upon the capacity of the condenser, which in turn depends upon the distance between the plates and the area of the plates. Either variable can be used as a strain transducer.

The capacitance of a capaciter may be varied by changing either the gap or the effective area of the electrodes or by changing the dielectric constant of the material seperating the plates. Assuming that there is no change made in the dielectric, the capacity can therefore be varied by altering the seperation of the plates or the area of the overlap.

For parallel plate condenser the relation-ship between the capacitance and the seperation of plates is given by the relation $$C = \frac{\eta K A}{3.6 \pi t} \quad uuF.$$

3.3. Torque meter with variable-gap capacitance type strain gauge[2,3].

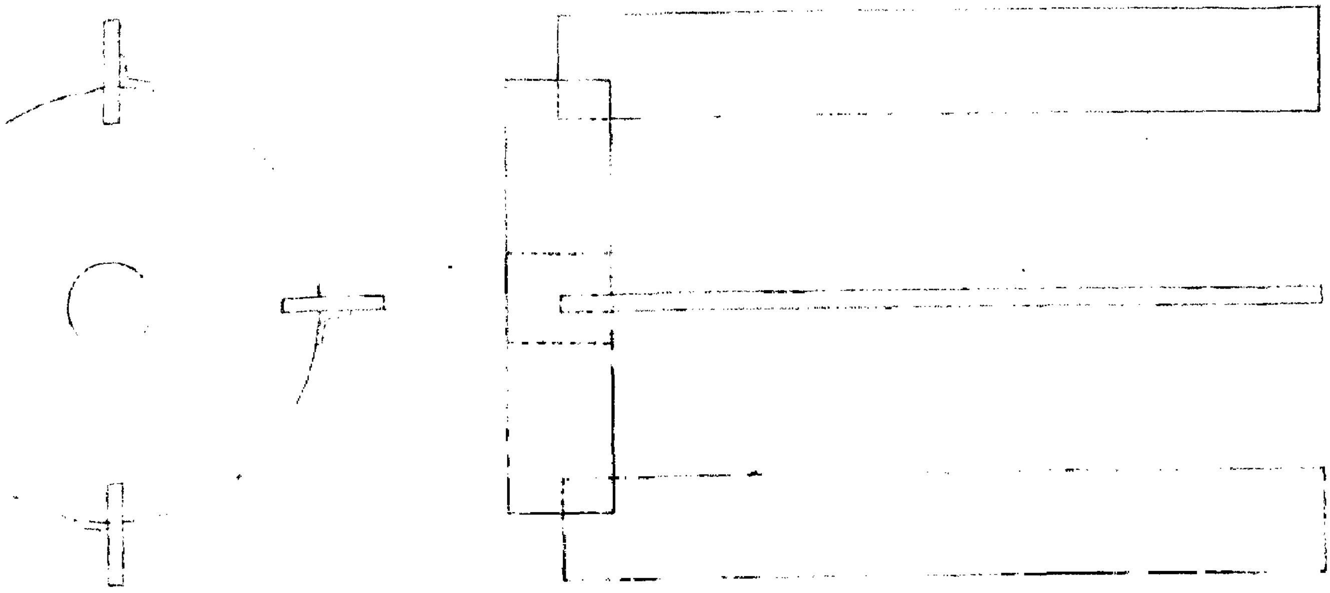
It is usual for the capacitance changes to be caused by changes in the gap, the changes in gap being restricted to small fraction of the total gap in order to prevent undue departure from linearity. Since the relation between the capacitance and seperation between plates is hyperbolic, it is necessary to use very small gaps and a small range of movement to obtain approximately linear relationship.

Description of the gauge[4].

The capacitance strain gauge consists of four parallel plates condensers connected in parallel. Four plates are fitted to one ebonite circular disc symmetrically as shown in fig.3-4. Two such pieces are mounted on a circular shaft so that the two ebonite discs are seperated by a distance andthe plates of one half are placed parallel to the plates of the other forming small air gaps. Thus four capacitors are formed. These capacitors are connected in parallel. An R.F. potential is applied across the terminals of the condensers. One terminal is brought through a slip-ring connection and the other (ground) terminal is the body of the machine itself.

The torque unit is coupled to the shaft of the motor under investigation. When the power is transmitted the shaft gets twisted. Thus the plates get nearer or go further away depending upon the direction of the applied torque, causing a change in capacitance of the unit. This change in capacitance is a measure of

[illegible] motor.



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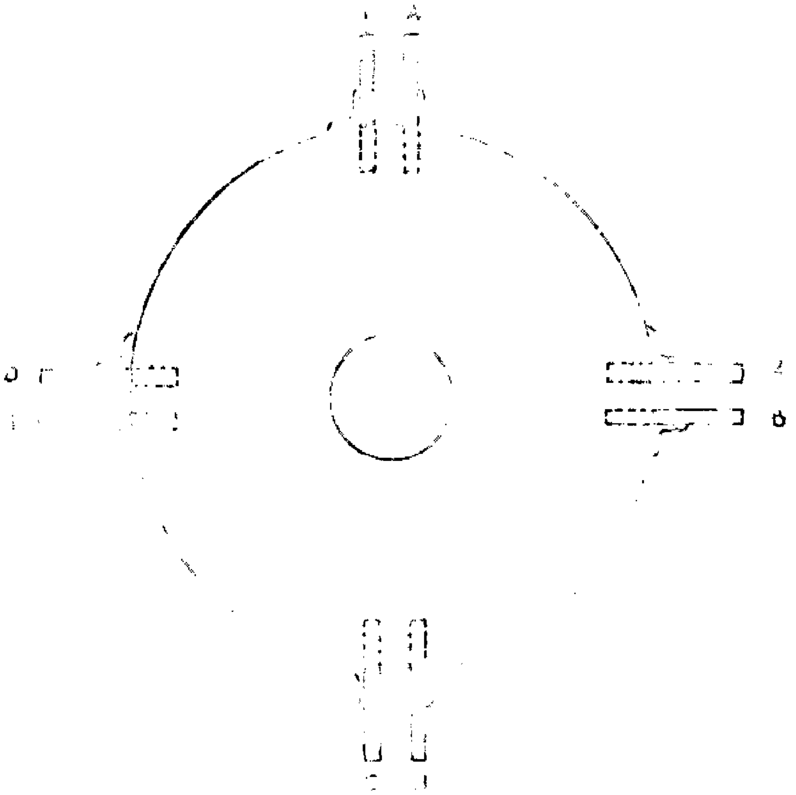

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the applied torque.

The application of this type of torque meter is at places where it is required to measure the torque of small magnitude. Care should be taken to avoid contamination of the gauge by oil, oil vapour, or water vapour, since they may appreciably alter its capacitance by changing the dielectric constant.

The serious disadvantage of the meter is that the temperature changes in the shaft open the gap between the plates.

3.4. Torquemeter with varying-area type capacitance type strain-gauge[1,2].

A convenient method of varying the area of overlap is by the help of serrated-condenser gauge. The gauge was developed by Carter, Shannon and Forshaw, and is as shown in fig.3-5. Tubular member a is of mild-steel and has fine longitudinal internal serrations in the region of the smaller bore. These serrations are formed by cutting rectangular slots, using a small slotting machine having an accurate indexing arrangement. The inner tubular member b, is also of mild steel and has corresponding external serrations, formed by using a milling cutter. Between a and b there is a fine air gap which is accurately maintained by preloaded ball bearings and these members constitute a condenser. The capacity of the condenser changes with relative angular displacement of the members as shown in fig. 3-6 and 3-7. The members a and b are registered to the shaft at a certain distance, which represents the gauge length. Under the full load torque the twist of the shaft between the two points should be enough to give a fairly large deflection on the oscillograph record. This has been achieved by the use of an amplifier.

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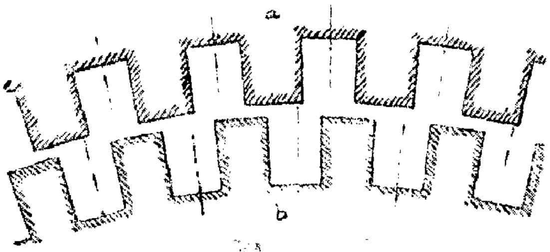
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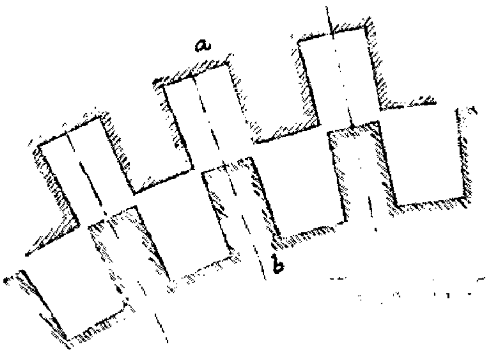
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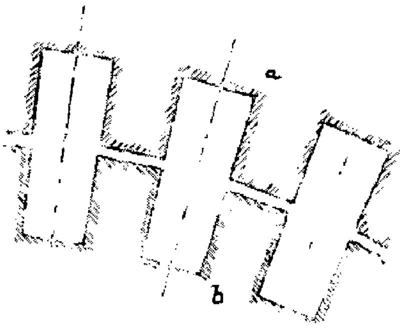
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The sensitivity of the instrument should be constant for the full range of movement due to the shaft twist. This means, that the capacity displacement relationship should be linear over this range, this condition can be met by designing the serrations suitably. In the variable-gap condenser type torquemeter, excessive movement will cause contact of condenser elements or of corresponding stops, where as in the present case there is no limit for mechanical movement and hence no stops are necessary. The pick up unit is normally fitted so that inner and outer teeth half over-lap when the shaft is transmitting approximately full mean-torque, this gives the fullest range of linearity for positive or negative torque.

<u>Theory</u>.

The capacitance of a long plain annular condenser is proportional to the area, the dielectric constant, and the logrithim of the ratio of outer to inner radius. In this particular case, since the gap between outer and inner cylinders is very small compared to the gap radius, the curvature of the condenser surfaces can be ignored, and the calculation can be done on the basis of single plate condenser formula

$$C = \frac{n \, K \, A}{3.6 \pi t} . \quad uuF$$

If the charge distributes itself uniformly, the change of capacity with relative position of the teeth would be linear, but, due to end effects the actual sensitivity and the range of linearity is to be determined experimentally.

Typical units have 60, 90 or 180 teeth and can be from $1\frac{1}{4}$" in diameter by 3/4" long. Slip-ring trouble is not serious in general, since high-frequency high-impedance circuits are used for energising the condenser and for detecting and amplifying the signal.

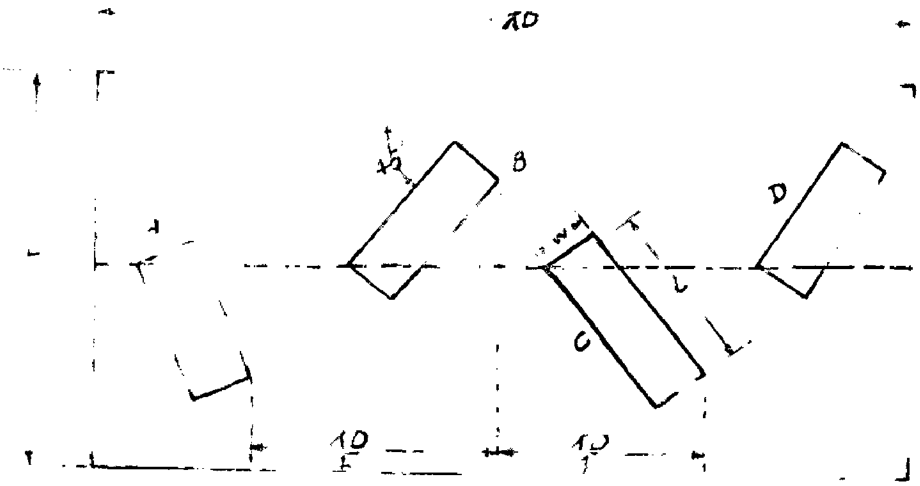
Capacity pick-ups require special care with details of the circuit. This gauge was developed before the advent of the resistance strain gauge; and so they can now have their useful application only in special cases. These gauges are most suitable in cases where the temperature is beyond the limit for wire-resistance gauges. In the capacity type pick-ups, the range of linearity is not intimately associated with the properties of the material, as in the wire resistance gauge and thus the capacity type may serve for measurements under extreme conditions where the wire resistance type would be over strained.

III. 3.5. The Bonded wire Gauge Torque-meter[6,8].

The resistance strain gauge, unlike other instruments based on the elastic twist of a shaft, makes use of the point-to-point stretch or compression of the surface of the shaft. The gauge exhibits a linear relationship between the change in its electrical resistance and the strain applied to it. If properly constructed and applied, it is free from hysteresis. When the material on which it is fixed is worked within the strain limits, then its properties do not change measurably with time or number of cycles of operation.

When a shaft is subjected to torsion, the principal stresses occur at 45° to the axis of the shaft, the stresses being at right angle and equal in magnitude but opposite in sign, that is, they are tensile and compressive. If a single bonded wire gauge is so placed that it follows a 45° helix on the surface of the shaft, the gauge will be subjected to maximum strain due to the torque. A single gauge could therefore be used for the measurement of torque. However, any bending or thrust applied to the shaft would obviously also affect the gauge response, and any change in temperature would cause false gauge readings unless the temperature coefficient of the gauge were zero. Moreover, unless the resistance of the gauge were very high, it would not be practical to employ slipring and brush connections to the external measuring circuit, since the erratic and variable brush contact resistance can easily be at least as large as the total resistance change of the gauge of usual resistance value.

The above mentioned limitations of the single gauge can be removed by the use of the arrangement of the gauges as shown in fig. 3-8. Four gauges are now used and are placed along 45° helices on the shaft surface. The gauges subjected to the strains of the same sign due to the torque, form opposite arms of the wheat stone bridge. The bridge is unbalanced due to the torque and the unbalance is additive by all the gauges. Therefore, the output of this arrangement is four times that of the bridge with only one active arm.



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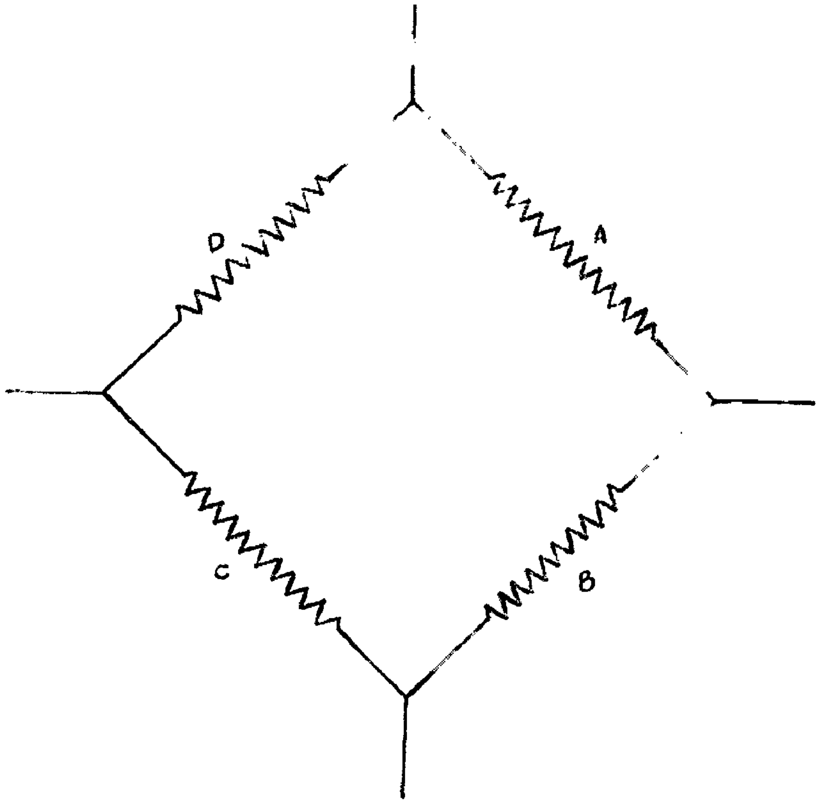


Fig. 3-3

Strain gauges connected in a bridge.

If a thrust force is applied along the shaft axis, it is evident that all four bridge arms will change by equal amounts; therefore the bridge balance is not responsive to thrust. If a bending moment acts about the vertical axis of the section, gauges A and B undergo strains equal and opposite to those undergone by gauges C and D. The result is that the balance of the bridge is not disturbed at all. Bending moment about the horizontal axis of the section would obviously cause no unbalance of the bridge, since the net change induced in each arm would then be zero. These considerations show that if the bridge is initially balanced, it will remain balanced despite the action of thrust and bending on the shaft. This is an extremely important advantage of the construction of the resistance strain-gauge torquemeter, and not shared by other types of torquemeters without elaborate precaution.

The meter is *temperature compensated*[7,8.] because of the proximity of the gauges. As the gauges are rotating with the shaft, sliprings and brushes are necessary for feeding to the bridge and for measuring the unbalance of the bridge. The requirements for a slipring and brushes are that their contact potential and resistance should be small and constant over a wide range of rubbing speeds and that the " noise" induced by them in amplifying system, which is normally used for amplifying the output signal, should be negligible. Silver is most suitable for sliprings because of its high conductivity and easily removable oxide, and carbon brushes for their anti-frictional properties. The contact potential of carbon on silver is greater than that of many other combinations recommended for this purpose, but, since the terminals of the strain-gauge network are not connected through thermionic valves or condensers, the contact potential will not affect the measurements, provided that all the rubbing contacts are at the same temperature. Where the slip-rings and collectors are both metallic there is usually a rubbing speed beyond which the temperature of the contacts will increase rapidly and will substantially affect the torque measurements. The low frictional resistance of the carbon brushes prevents this localised heating, and it has been found that the noise imparted to the amplifier by a silver-carbon combination is low.

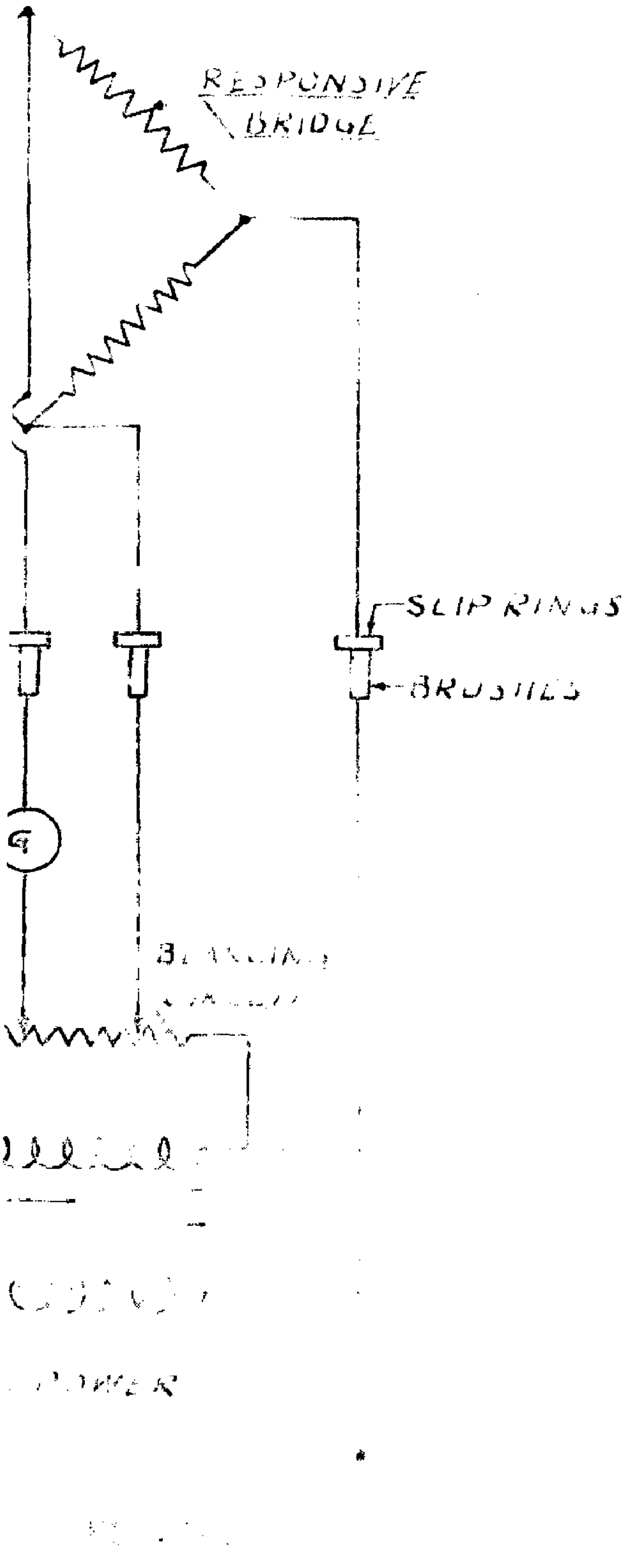
Measuring Circuits[7,8]

The circuits used for the measurement are shown in Figs.3-9 and 3-10. Circuit shown in Fig. 3-9 is used effectively for d.c. null balancing. It is suitable for operating directly from the mains. It provides a convenient means of feeding the balancing circuit so that variations in line voltage have no effect upon the measurement. The galvanometer G can be used as an accurate deflection-type of torque indicator when the more precise null-balancing system is not essential.

Fig.3-10 shows a circuit diagram for the measurement of dynamic torques. By dynamic torque is meant the alternating or fluctuating component of torque such as would be found in the output of an internal combustion engine. The bridge is fed by a battery and the dynamic components of torque are carried to the input of an amplifier by a condenser coupling.

Accuracy[5,6]

The accuracy of the meter depends primarily upon the magnitude of the shaft strain, hence it is desirable to employ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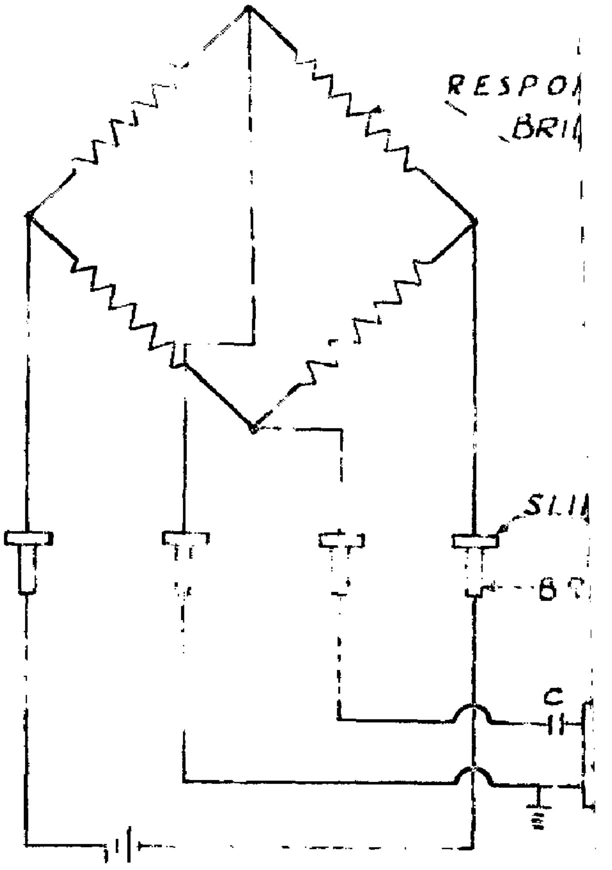
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working stresses as high as safety requirements permit when highest accuracy is essential.

As a general rule the stress should be at least 6000 lbs/in^2 when the accuracy of measurement is to be ± 1% of full scale. Preferably the stress should be 8000 to 10,000 psi. When one torquemeter is to cover several ranges of measurement, such that the smallest range is 1/3 of full scale, then it is desirable to use a shaft stress of about 16000 psi for full scale. High-strength alloy steel should be used for such pick-up shafts to provide sufficient safety-factor.

Limitations[5,8].

The resistance changes for strains corresponding to maximum allowable stresses in both the shaft and the wire-resistance elements seldom exceed 1% of the initial resistance. Therefore, use of sensitive potentiometer and balancing bridge is required with wire resistance strain-gauges, or high gain amplifiermust be used with direct indicating instruments. A further disadvantage is the relatively large temperature coefficient of resistance of most of the wire resistance strain gauges. It is therefore not of much use for air craft engine torquemeters where temperature variation is high.

IV. 3.6. Torquemeter using microwaves for the measurement of strain[9].

The cavity resonators used as frequency-stabilizing units or wavemeters are very sensitive to small changes in their dimensions. This method can therefore be used for any purpose requiring a sensitive method for measuring such small changes.

It has been used for the construction of a very sensitive strain gauge for torque measurement. Although the gauge is comparatively complicated than the resistance strain gauge, but sometimes it becomes necessary to use it where the accurate measurement is essential.

Microwave Principle of displacement measurement.

A cavity is a space totally enclosed by walls of high electrical conductivity, the cavity enabling the excitation of high-frequency alternating electromagnetic fields within the enclosed space. The condition of resonance exist at fixed frequencies, and it is the extreme sharpness with which these points are defined, or what is known as the high Q factor of the cavity, which makes it so useful. The points at which resonance occurs are a function of the dimensions of the cavity. Fig.3-11 shows a cavity formed by a cylinder closed at one end with an adjustable plunger at the other, so that the length of the cavity can be changed. Input and output points are provided near the base. If the power at fixed frequency is fed into the cavity and the output connected to a crystal detector, which measures the power transmitted through the cavity, then by varying the distance X, between the base and the plunger, the curve as shown in fig.3-12 is obtained.

Two methods are used for the measurement. The first is the comparison method which is useful only for steady state recording. The direct-reading method is used for transient torque recording.

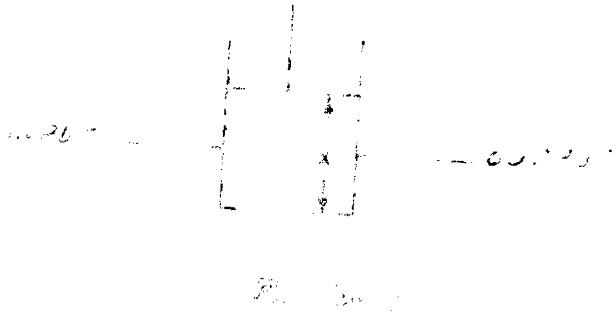
Accuracy: Provided that a displacement of 10 mil for full load torque can be obtained, an accuracy of ± 1% can be realised with cavities that are readily constructed. The instruments will give reasonable output without the use of sensitive indicating instruments or high-gain amplifiers.

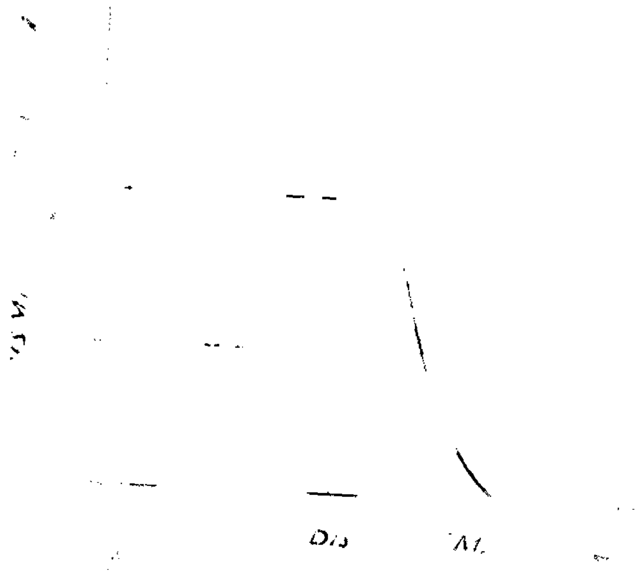
Apart from the measurement of torque there are several applications of displacement measurement to which the microwave method can be applied with its maximum sensitivity.

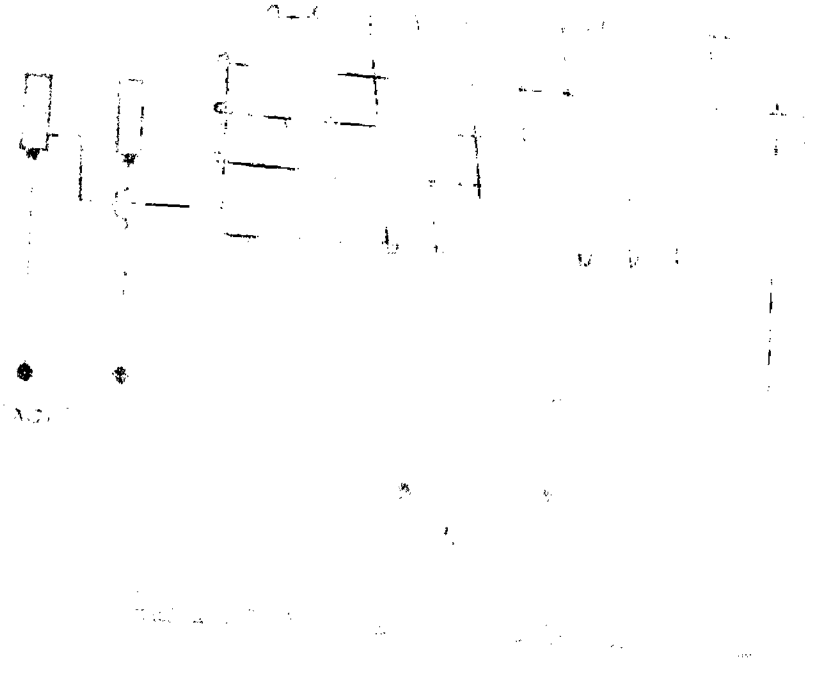
V. 3.7. Shaft mounted meters without sliprings[1,14].

Several experimenters have made attempts to utilize various coupling schemes to permit the use of strain-resistive or strain-capacitive gauges mounted directly upon the rotating shaft without using sliprings. Strain sensitive capacitors have been mounted directly on the torque loaded shafts with their terminals connected to the secondary coils of transformers, these coils completely encircling the shaft and rotating with the shaft the primary coils of the transformers are stationary and also encircle the shaft assemblies and the rotating coils. Mutual inductance between the primary and secondary coils of the rotating transformers thus formed constitute the link between the stationary instruments circuit elements and the strain sensitive capacitor on the load shaft.

It has been proposed by F.D.Smith and C.S. Wright that the effect of pressure on the magnetic properties of some ferromagnetic materials could be used for the measurement of torque. When the shaft made of nickel or nickel alloy is twisted, its permeability is modified. This change in permeability is proportional to the applied torque on the shaft. If a coil is wound around the shaft and is fed from an a.c. source then the change in permeability will result in the change of inductance of the







circuit and hence the change in the current. This change in current can be amplified and calibrated on the meter. The application of this is limited because the shaft has to be of a material showing good amount of magneto-strictive effect. The power is to be limited by the stresses which these materials can withstand. The magneto-skin effect method of torque measurement is sensitive to temperature, shaft bending, mechanical and magnetic hysteresis, and thrust loads.

Relatively high frequency k/cs. power supplies are required for the above mentioned two schemes, and amplifiers are required between the shaft unit and the indicating instrument. The magnetic skin effect or magneto striction torque-instrument shaft element approaches the ultimate in design simplicity, and if means of eliminating temperature errors and hysteresis effects can be found, the simplicity of the shaft element may offset the disadvantages and difficulties of high frequency supplies and amplifiers.

Torque-meter based on Mutual-Coupling.

The recent development in the design of torquemeters, has produced a simple and sensitive meter. The torque of the machine is transmitted along a steel tube that is magnetized circumferentially by a toroidal winding fed from slip rings at about 1000 c/s. The effect of torque on the magnetic properties of the tube is to cause the flux, previously passing a concentric circles around the axis of rotation, to take a spiral path, and a component appears in the space around the tube. A stationary pick up coil surrounds the rotating tube and has induced in it a voltage closely proportional to torque. A small unit has been fabricated and tested in the laboratory. The unit has not given good results due to the trouble in slipring contacts and brushes. Also as it is coupled with 1/4 H.P. m/c . the variation in flux around the tube with load is extremely small and so the variation of the output signal with load is very little. The unit is shown in fig.3-13.

CHAPTER IV

MAGNETIC COUPLED TORQUEMETER

Strain-magnetic elements lend themselves to the measurement of displacement much more readily than do any of the aforementioned strain-sensitive devices when it is desirable to connect direct-indicating instruments to the strain sensitive circuit without interposing amplifiers. Magnetic strain-gauges operate at sufficiently high energy level and so its output can be utilized to drive an indicating instrument directly. The gauges are small and operate at normal supply frequency.

4.1. Magnetic-strain gauge type torque-meter.[1,10]

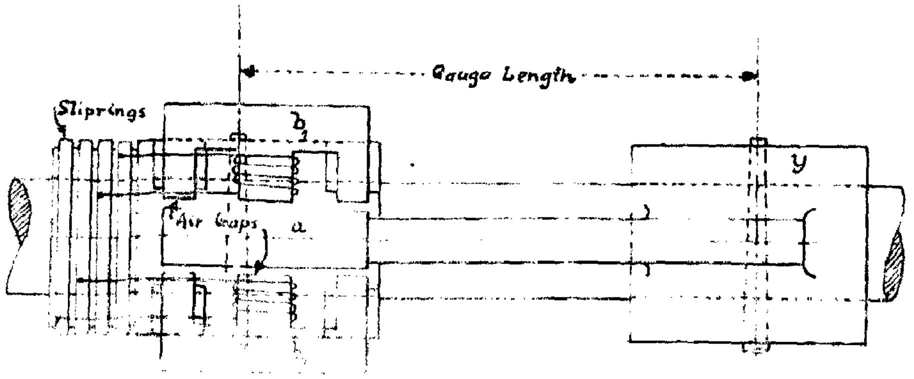
In 1922, instruments were developed depending upon a change in the number of linkages between the flux in a magnetic path and the coil generating the flux. This change in the linkages produces a change in the current, which is a measure of torque.

When a coil, in which a current flows, is wound on an iron core which form a part of a magnetic circuit, a flux is set up in the core. If the core is split up into two parts so that there exists a small air gap between the two parts, then the magnetic flux is forced to pass through the air gap. The reluctance offered by the gap is many times more than the reluctance offered by the iron part of the magnetic circuit. Even a small change in this gap will result in an appreciable change in the flux linking the circuit. If the power fed to the coil is from an a.c. source, then the change in the flux linkages will cause the change in the inductance of the circuit. This will result into the change of current drawn ~~drawn~~ by coil, and the change of current will be proportional to the change in air gap, provided the magnetic circuit is not saturated. The indication can be easily amplified if necessary.

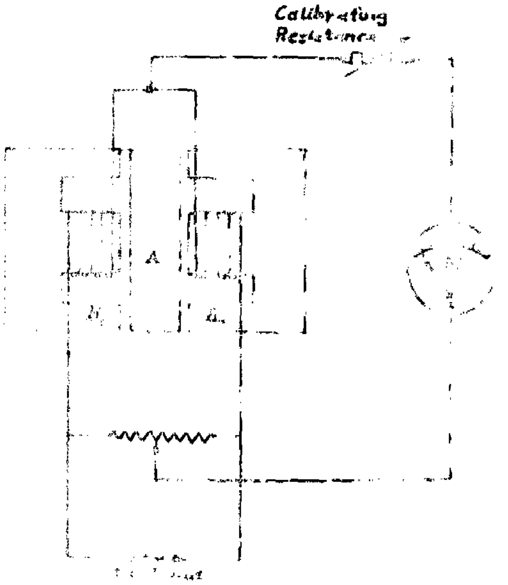
The above mentioned principle has been used for the measurement of torque as shown in fig. 4-1. The scheme consists of a laminated armature or movable part of the core a, which is carried by one of the clamps y. Two identical and opposite electromagnetic circuits b_1 and b_2 are held by another clamp x. When the torque transmitted by the shaft is zero, the gaps on the two sides are equal. With the application of torque one air gap is increased and the other gap is decreased. In order to have a linear response of the meter, the change in the air gap should be about 10 % of the original gap for rated output. It has been found that even by 20 % change in the air gap the deviation from linearity is small. The circuit used for the measurement is shown in fig. 4-2. The meter M is of rectifier type and the output is measured without any amplification.

4.2. Reasons for selecting Magnetic-coupled torque-meter.[12,13]

Of the gauges described so far, most of them require slip rings and brushes to energize the elements which rotate with the shaft. In many cases, the sliprings cannot be tolerated due to the presence of oil in the region surrounding the shaft or due to the high speed of the shaft. For example, in measuring the torque delivered to an airplane propeller in flight the propeller shaft is usually enclosed in the reduction gear housing and any instruments attached to it are subjected to a


Gauge Length
Sliprings
b
Air Gaps
a
y

[illegible]

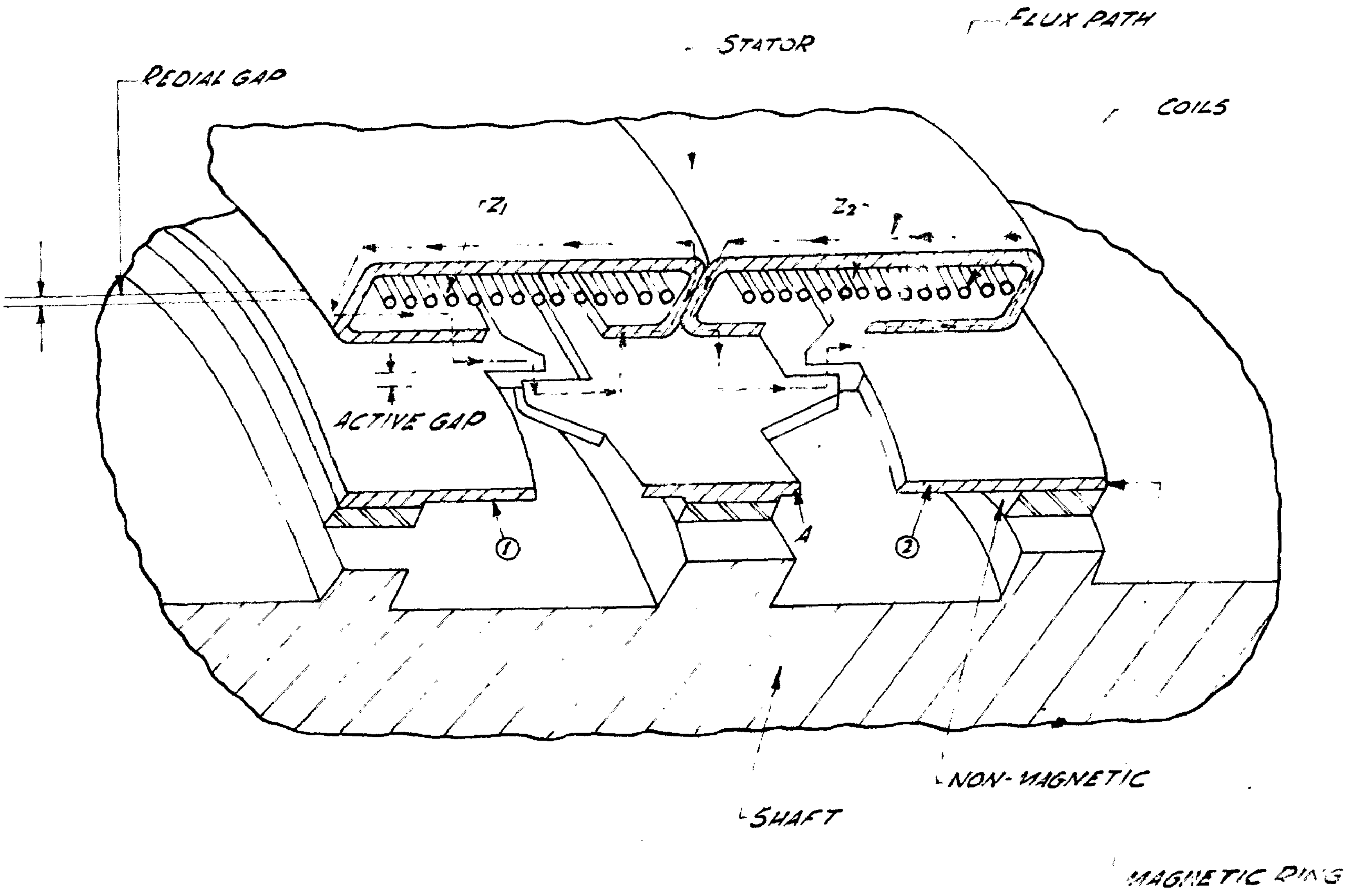

Calibrating
Resistance
A
B
a

[illegible]

continuous spray of hot oil. In testing gas turbines, speeds approaching 40,000 r.p.m. are sometimes encountered. Slip-rings are practically inoperative under such conditions, and instruments attached to the shaft are apt to be damaged by centrifugal force. The slip ring design is also likely to be difficult from the stand point of service trouble and contact resistance. The magnetic-coupled torquemeter has been developed and designed to eliminate sliprings and to get a continuous record of the torque which is being transmitted by the shaft. The design is most suitable for air craft engines where the engine output is to be known at every instant of its operation.

4.3. Principle of operation of Magnetic-coupled torquemeter.[11-14]

Fig. 4-3. shows the isometric view of the torquemeter. The device consists of a shaft of steel, this shaft is provided with three flanges on which are mounted three toothed rings of magnetic material, but seperated from contact with the shaft by means of non-magnetic spacers. The spacers are made of a metal such as Bronze or Brass. Overlapping teeth or projections from each of the three magnetic rings form two sets of active airgaps. One set of gap is formed between the outer ring 1 and the middle ring A, and the other set is formed between the outer ring 2 and the middle ring A. When the torque is transmitted by the shaft, one set of air gaps are shortened and the other set of air gaps are lengthened depending upon the direction in which the shaft is twisted. Two stationary coils Z_1 and Z_2 are provided which completely encircle the shaft assembly. When the coils are energized from an a.c. source, the flux flows across the two sets


FLUX PATH
STATOR
REDIAL GAP
COILS
Z1
Z2
ACTIVE GAP
1
A
2
NON-MAGNETIC
SHAFT
MAGNETIC RING

[illegible]

[illegible]

of air gaps. The magnetic flux completes its path as shown by the dotted lines in the diagram. The flux completes its path through the encasing shells of magnetic material for the stationary coils and across the radial air gaps between the coil assembly and the rotating-shaft assembly. The area offered for the flux by the radial gaps is very large compared to the area offered by the active gaps. As the length of the radial gap is small, the permeances offered by these radial gaps are quite large compared with the permeances of the active gaps between the toothed rings. Consequently, the insertion of the radial air gaps in the magnetic circuit has but small effect upon the characteristics of the strain-gauge, The effect of eccentric movement of the shaft in its bearings relative to the stator has got a very little effect on torquemeter calibration. The response of the meter is independent of bending and thrust loads on the shaft.

When strain-gauge elements are mounted on a rotating shaft, precautions must be taken to avoid errors due to bending moments and compression or tension loads on the shaft so that only pure torque is measured. This requires that a balanced magnetic circuit be used with both Z_1 and Z_2 responsive to shaft torque loads, and it also requires that the sensitive air gaps be distributed uniformly around the circumference of the shaft.

If the coils Z_1 and Z_2 are connected in such a fashion that they form the two sides of a measuring bridge, then with the application of torque, the bridge is thrown out of balance. This out of balance effect is the desired response,and the device may be calibrated to record this response which is proportio-

-nal to torque. The method adopted for calibration in this case is slightly different and is discussed in Chapter VI.

In effect, the magnetic-coupled torquemeter consists of a magnetic strain-gauge in which the portion of the magnetic circuit which carries the coils remains stationary while the variable air gaps are mounted on the rotating shaft. The magnetic flux is transmitted from the stator to the rotor through radial air gaps. On the rotating shaft the flux goes through a magnetic path reluctance distribution of which varies with torque transmitted through the shaft. Thus the torque meter requires no sliprings and the rotating part does not contain electric coils or other elements which might be damaged by centrifugal force.

CHAPTER V

DESIGN CONSIDERATIONS

One of the most important parts of the torque meter is its shaft. The design of the shaft influences the working and sensitivity of the meter to a large extent. Fig. 5-1 shows a solid shaft and fig. 5-2 shows a shaft which is hollow at the test section. The hollow shaft improves the sensitivity with a possible larger diameter at the test section. The hollow shaft is therefore selected for the meter.

The following calculation will show that with a given torque to be transmitted, the twist in a hollow shaft is more pronounced than in a solid shaft and thus the hollow shaft is more suitable for the proposed torque meter.

For a hollow circular shaft, we have

$$I_p = \frac{\pi}{2} (R_2^4 - R_1^4)$$

$$\frac{T}{I_p} = \frac{G \theta}{L}$$

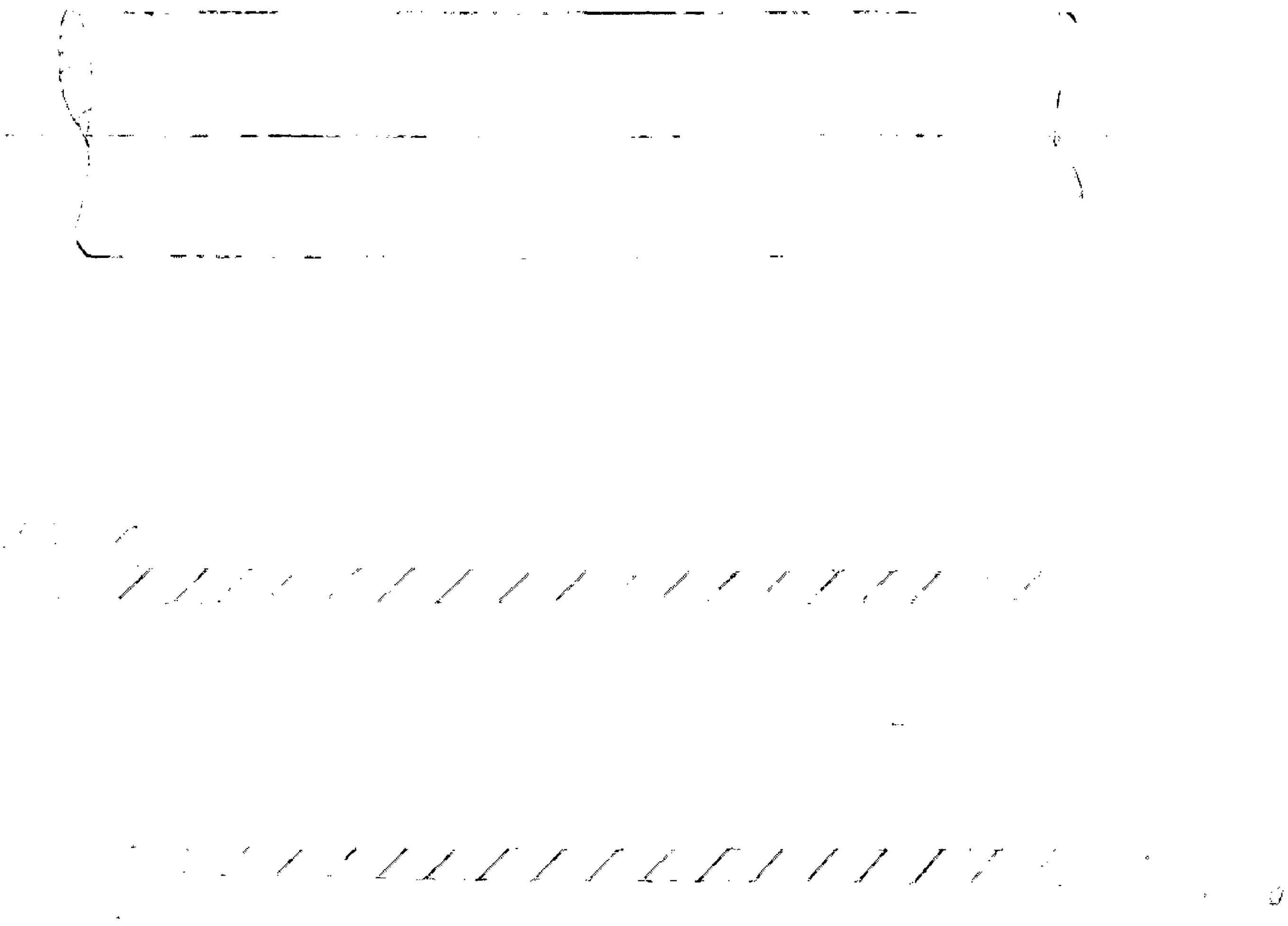
$$\therefore \theta = \frac{T L}{I_p G}$$

For a particular value of torque, larger the value of θ, the angle of twist, more will be the sensitivity of the meter. Therefore, in order to obtain larger output and so increased sensitivity of the meter we must have:-

(i) G, as small as possible.

(ii) Section modulus as small as possible.

(iii) The gauge length as large as possible.



Therefore a hollow shaft of diameter suitable from the stress considerations and section modulus reduced to obtain maximum sensitivity is used.

However, care must be taken to see that the stressing of the shaft should be within the elastic limit, otherwise plastic deformation of the shaft might result. Therefore, we must select suitable material having high yield point stress and good strainability (lower value of ω). From these considerations ordinary mild steel is quite suitable. It has been found that mild steel gives satisfactory results, especially if the shaft is subjected to a twist well above the value corresponding to the maximum designed torque before calibration, without exceeding the elastic limit.

This torque meter has to be interposed between the drive and the driven-member. Therefore, it should not materially affect the performance of the equipment under test. This requires that it must have a very low inertia and high stiffness. This implies that the shaft should be light and small in diameter. All parts including the couplings should be made light. High stiffness requires smaller length of the shaft, thus economising in length. But we should be liberal in choosing the length as it increases the sensitivity of the device. Therefore a compromise is to be made.

<u>Design of the shaft:</u>

The meter is to be coupled with a 7.5 H.P. 960 r.p.m., 400 V, 3 ph. induction motor. The meter is to be designed in such a way that it can be used up to the above rating only. So the design will have to be an optimum one for the above rating.

This rating was chosen because of the facilities available for testing its viability, though it is arbitrary otherwise. Ofcourse the design consideration noted herein for this particular meter will be applicable to meters of similar type but of different ratings.

$$H.P. = \frac{2\pi NT}{3300}$$

$$\therefore \; 7.5 = \frac{2\pi \times 960 \times T}{3300}$$

$$\therefore \; T = \frac{33000 \times 7.5}{2\pi \times 960} = 41 \text{ lb.ft.}$$

The drawing of the shaft is shown in fig. 5-3. The maximum twist is contributed by the sections a and b, the maximum shear stress will also occur at these sections. Therefore, if the twist in these sections are within safe limits, other sections will automatically be safe under most severe condition.

Chosing the bore of the shaft = $\frac{3}{4}$" throughout, and the thickness of the sections a and b = $\frac{1}{16}$". We have, the outer diameter of sections a and b = $\frac{7}{8}$".

Polar moment of inertia of the sections

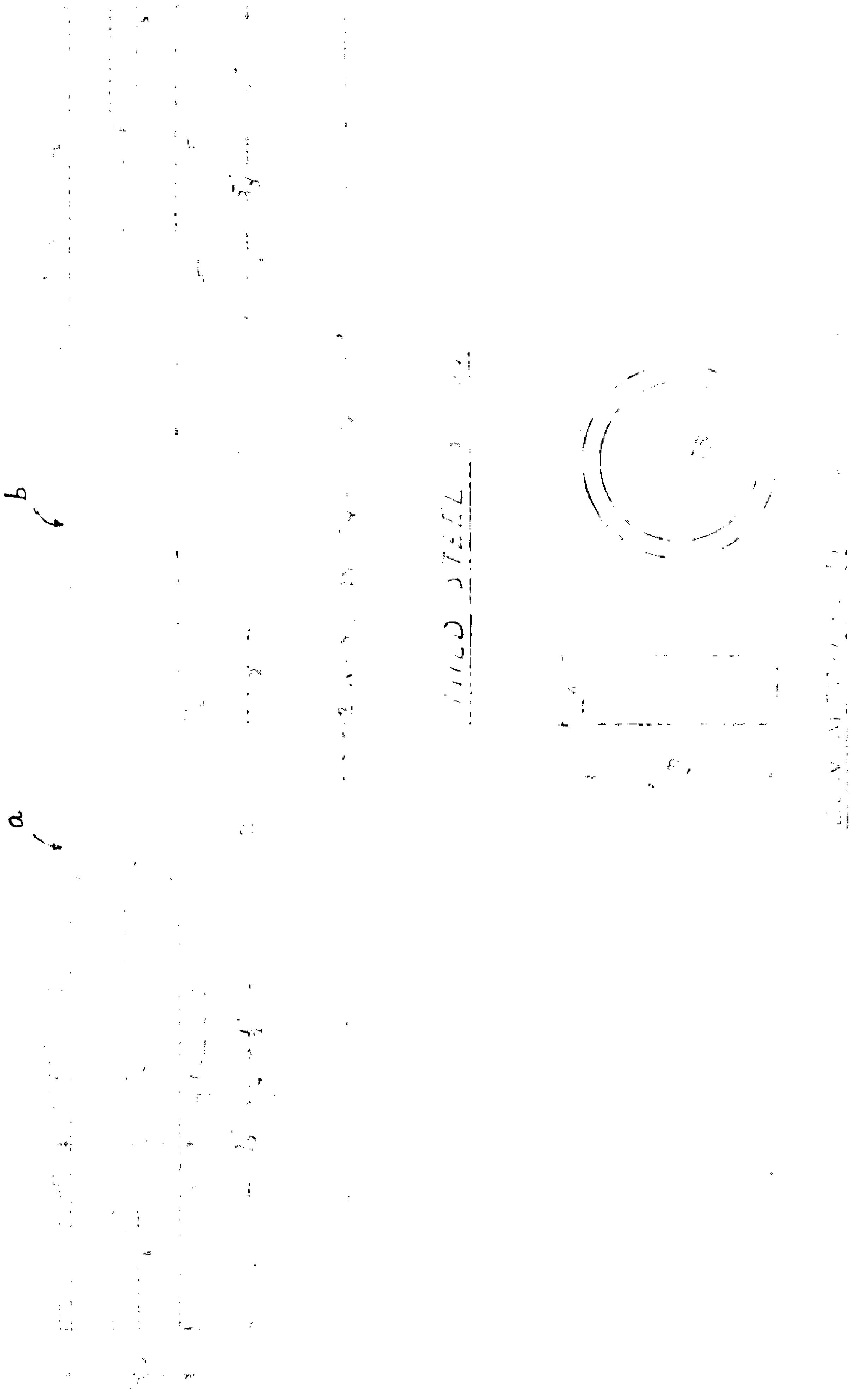
$$= \frac{\pi}{32}\left[\left(\frac{7}{8}\right)^4 - \left(\frac{3}{4}\right)^4\right] = \frac{\pi}{32}(\,0.585 - 0.314\,)$$

$$= 0.0266 \text{ in}^4.$$

Maximum shear stress at these sections

$$\frac{T}{I_p} = \frac{f_s}{R}$$

$$\therefore \; f_s = \frac{41 \times 12 \times 7}{.0266 \times 16} = 8100 \text{ lbs/in}^2.$$


a
b
MILD STEEL

The ultimate shear stress for mild steel is 20,000 lbs/in^2

Choosing a factor of safety of 2, the allowable maximum shear stress = 10,000 lbs/in^2.

Allowing for the stress concentration etc., the maximum shear stress in the material will be about the maximum allowable shear stress. Hence the design is optimum and safe.

A bore of $\frac{3}{4}$" is chosen to keep down the polar moment of inertia as small as possible. The bearings used are N.B.C. 120, having a bore diameter of 1". Considering the horse-power capacity of the set these bearings are not suitable. But as they are just supporting the length of the motor only and most of the load is coming on the main bearings of the I.M. and D.C. machine, these bearings can be used. Another reason for using these bearings is to reduce the diameter of the shaft. Hence $\frac{3}{4}$" bore diameter is quite suitable.

To avoid bending the total length of the shaft should be as small as possible with higher stiffness. But this will reduce the twist resulting in lower sensitivity. Extension of 1" is provided on both sides for couplings. Bearings are supported in their place by $\frac{1}{4}$" collars. The shaft carries three $\frac{1}{2}$" collars for supporting non-magnetic spacers with toothed rings over them. Narrow collars may not give the rigid support to the rings. The length of the sections a and b is decided entirely by the required twist of the shaft which changes the active air gap length. This change in the active gap should be about 10-20% of the original gap. This limitation of change in air gap will depend on the degree of saturation of the magnetic path and also on the original gap. Provisionally the length of the sections a and b is chosen as 2" each, so that the total length of the unit is not large.

Non-magnetic spacers are to be set on the collars. With thin spacers there is a possibility of flux leakage into the shaft from the rings through the spacers. The increase in their thickness will result in reduction of twist contributed by the three collars. As has been stated earlier, the twist is mainly contributed by the sections a and b, and therefore, the increase in thickness of the spacers will affect the twist very little. From these considerations, the spacers are taken as $\frac{1}{8}$" thick.

The magnetic toothed rings, which are placed above the spacers are to be designed for carrying a particular value of flux. The flux density in the toothed portion will depend upon the thickness of the rings and the length over which the teeth overlap. Assuming the thickness of the rings as 1/8", the outer diameter at collar sections is $1\frac{5}{8}$".

Total twist in the shaft

Polar moment of inertia of the collar sections

$$= \frac{\pi}{32}\left[(1\tfrac{5}{8})^4 - (\tfrac{3}{4})^4 \right]$$

$$= \frac{\pi}{32}(7 - 0.314) = 0.655 \text{ in}^4.$$

Polar moment of inertia of sections a abd b

$$= \frac{\pi}{32}\left[(\tfrac{7}{8})^4 - (\tfrac{3}{4})^4 \right]$$

$$= \frac{\pi}{32}(0.585 - 0.314) = 0.0266. \text{ in}^4.$$

Total twist in the gauge length will be the sum of the twists of the three collars and that in sections a and b. There will be very slight error introduced in assuming the same value of G for mild steel and for non-magnetic spacer's material (Gun-metal in this case).

$$\theta = \frac{T.L}{G\,I_p} = \frac{T}{G}\left(\frac{L_1}{I_{p_1}} + \frac{L_2}{I_{p_2}} + \ldots.\right)$$

$$= \frac{41 \times 12}{12 \times 10^6}\left(\frac{3 \times 0.5}{0.655} + \frac{4}{0.0266}\right) \quad \text{radians}$$

$$= \frac{41}{10^6}\,(2.3 + 150) \times \frac{180}{\pi}.\ \text{degrees.}$$

$$= 0.358^\circ.$$

Twist for half gauge length = 0.179°.

The active gap between the teeth should be as small as possible. Under extreme loading conditions with the proviso that the teeth should not touch each other. The gap is therefore initially kept 1/64".

Mean diameter of the rings = 1.5"

Mean circumference = π x 1.5 = 4.7".

360° correspond to 4.7".

$\therefore$ 0.179° correspond to $\frac{4.7}{360} \times .179$

= 0.00234".

$\therefore$ Change in the active gap = 0.00234".

Original active gap = 0.0156".

$\therefore$ Change in gap as percentage of original gap

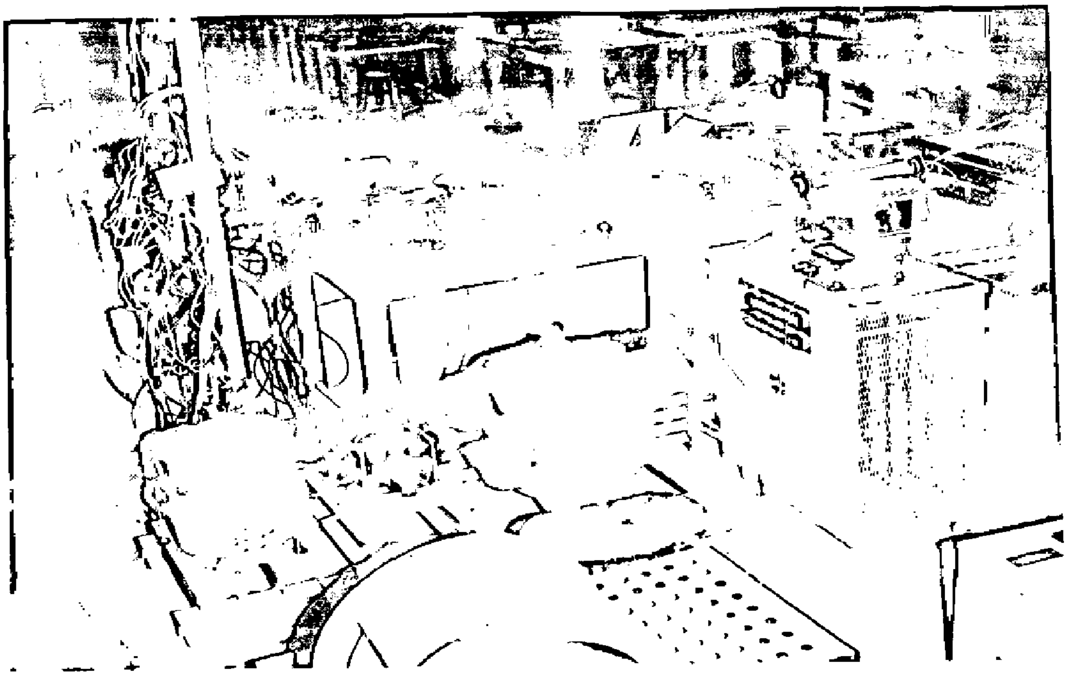
$$= \frac{0.00234}{0.0156} \times 100 = 15\ \%.$$

This change in gap will occur under the desired full load conditions, therefore the variation in the gap will normally be in the linear region.

Number of teeth on the ring

The number of teeth on the rings is a matter of choice within close limits for meter to be used in laboratory. However, the large number of teeth is very effective in averaging out bending and thrust loads on the propeller shaft in the case of air-craft engine torque meter, but leads to excessive magnetic leakage around the teeth and also to increased manufacturing difficulties. With smaller number of teeth, the sensitivity of the instrument will increase due to the better magnetic design and the reduction in the leakage flux around the rotor.

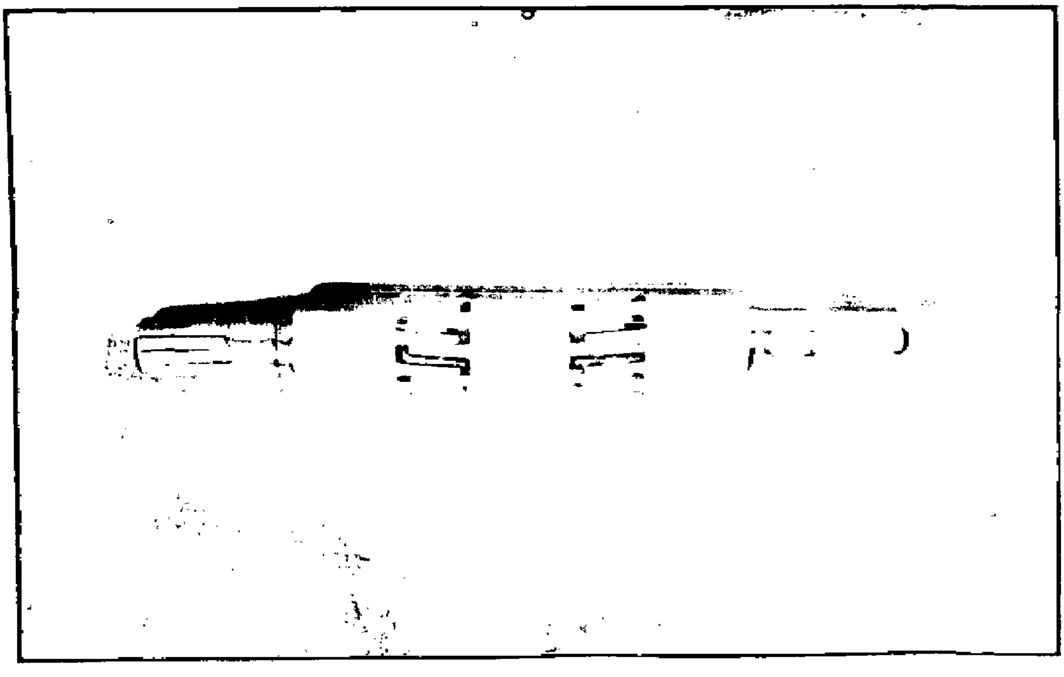
In this design, two sets of rings are used. The first set is having 10 teeth on each ring and the other set is with 5 teeth on each ring. This is done to see the effect of number of teeth on the sensitivity and performance of meter. The number of teeth is chosen such that the gap between the two consecutive pairs of overlapping teeth is large enough so that there is no flux(leakage) flowing along the circumference of the rings. The teeth provided are tapered slightly to have maximum utilization of material with an eye on proper flux density at the neck sufficiently below the saturation level. The rings are shown in fig.5-4. Their position shown is same as will be in the unit in operation. The detailed drawings of the rings are shown in figs. 5-5 and 5-6. The three rings are to cover a gauge length

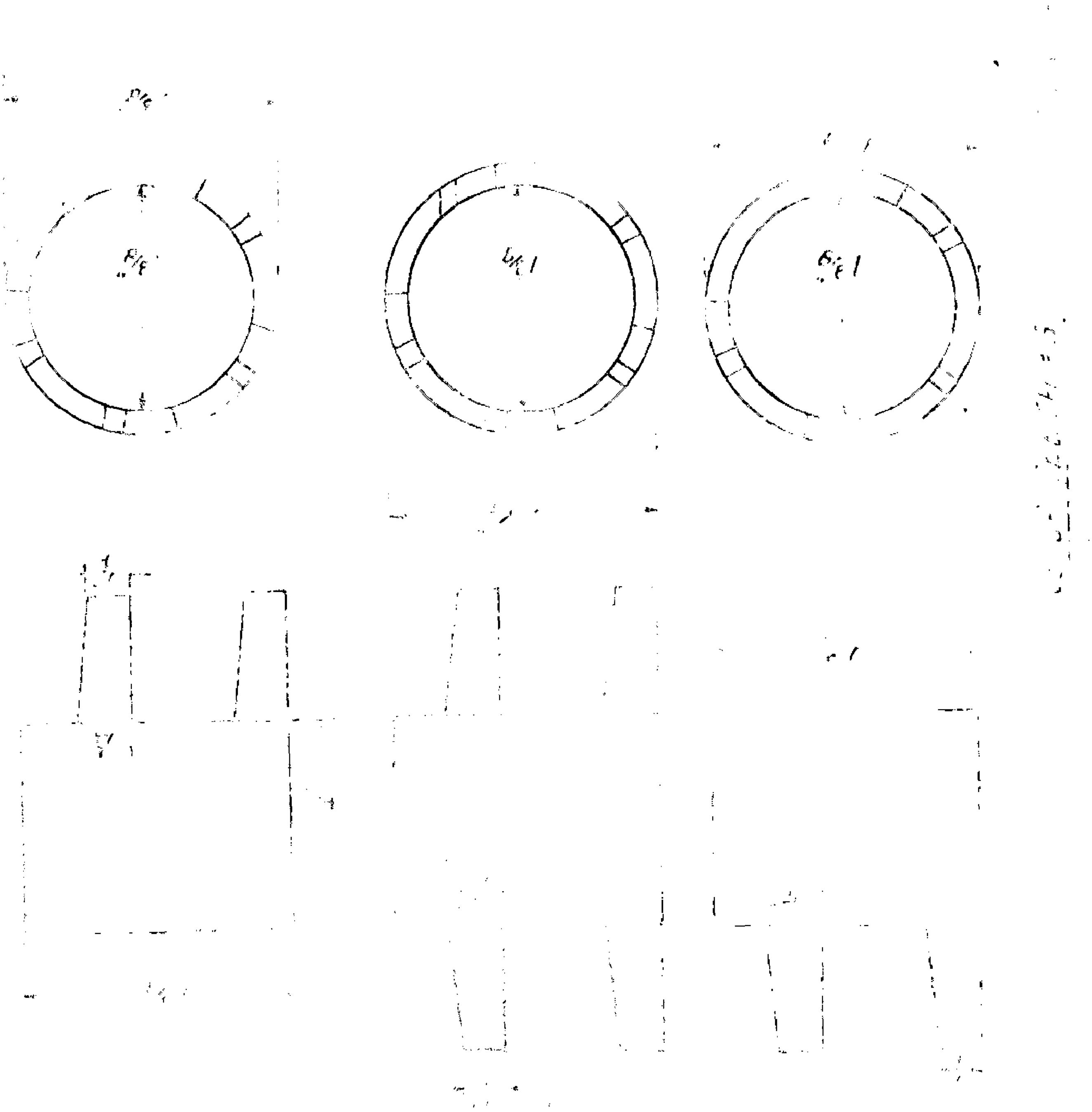


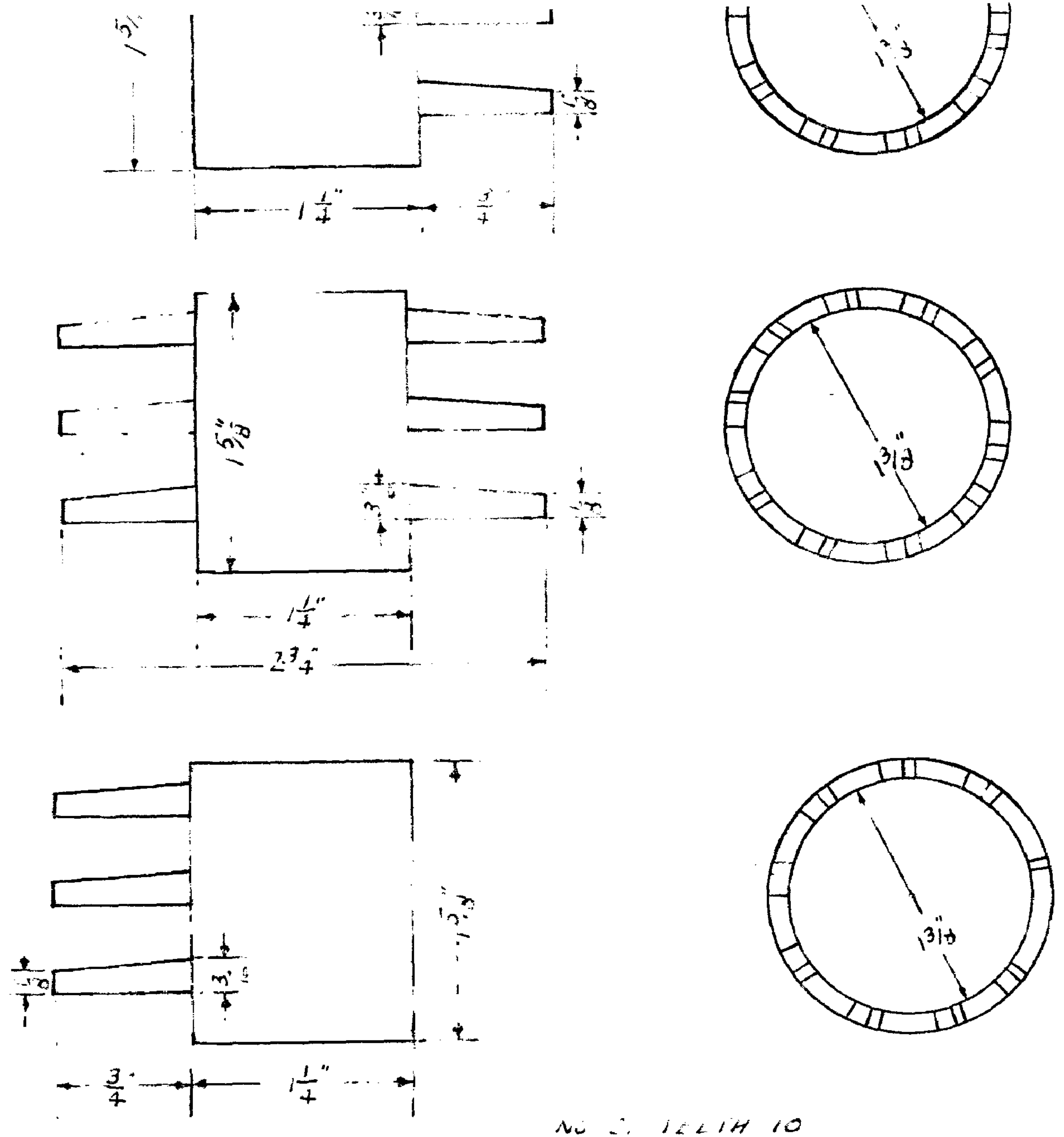
Torquemeter Interposed

Above:- between I.M.[illegible] Generator set.

Below:- Rotor Ring: with [illegible].

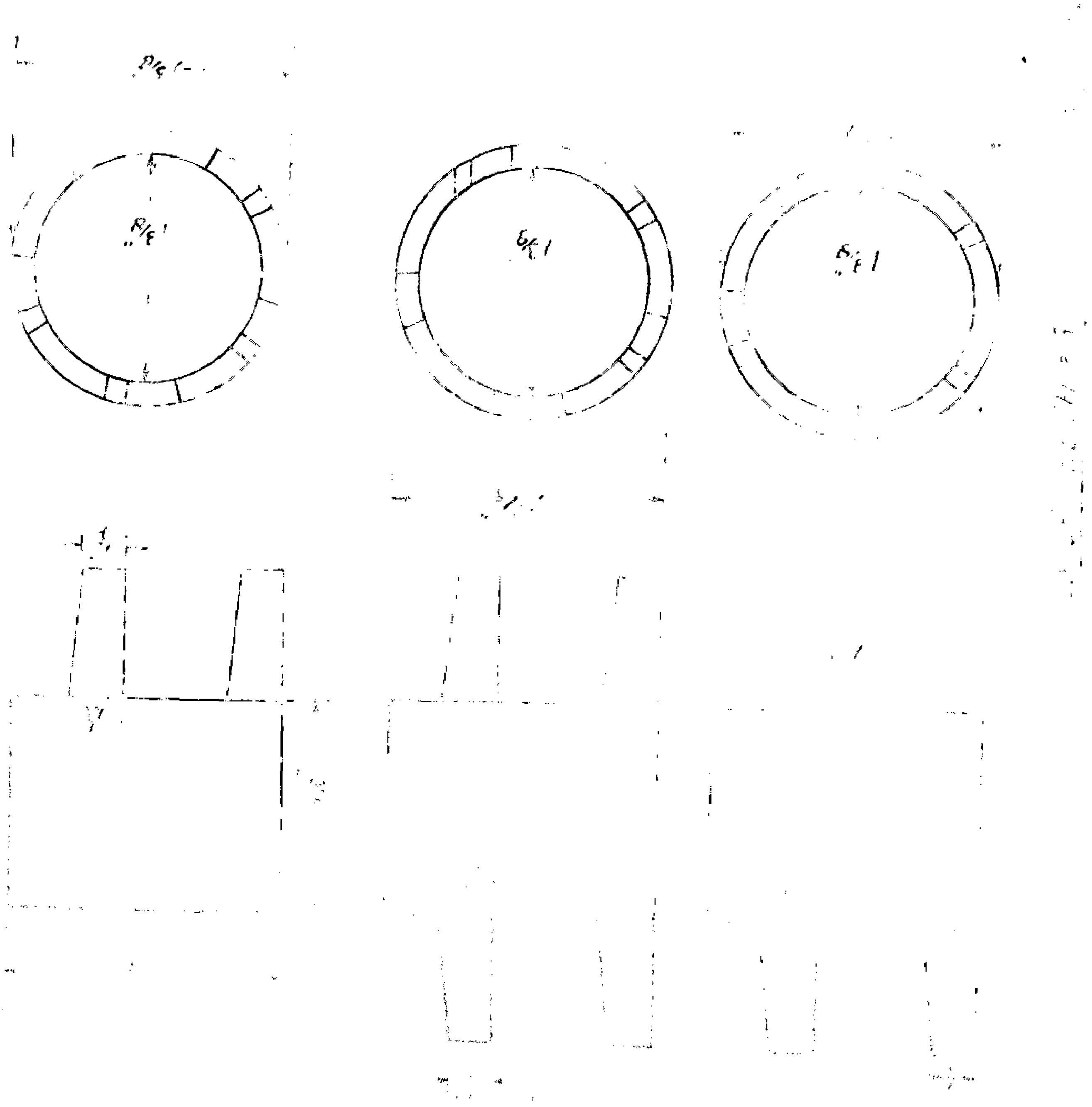






No. of TEETH 10

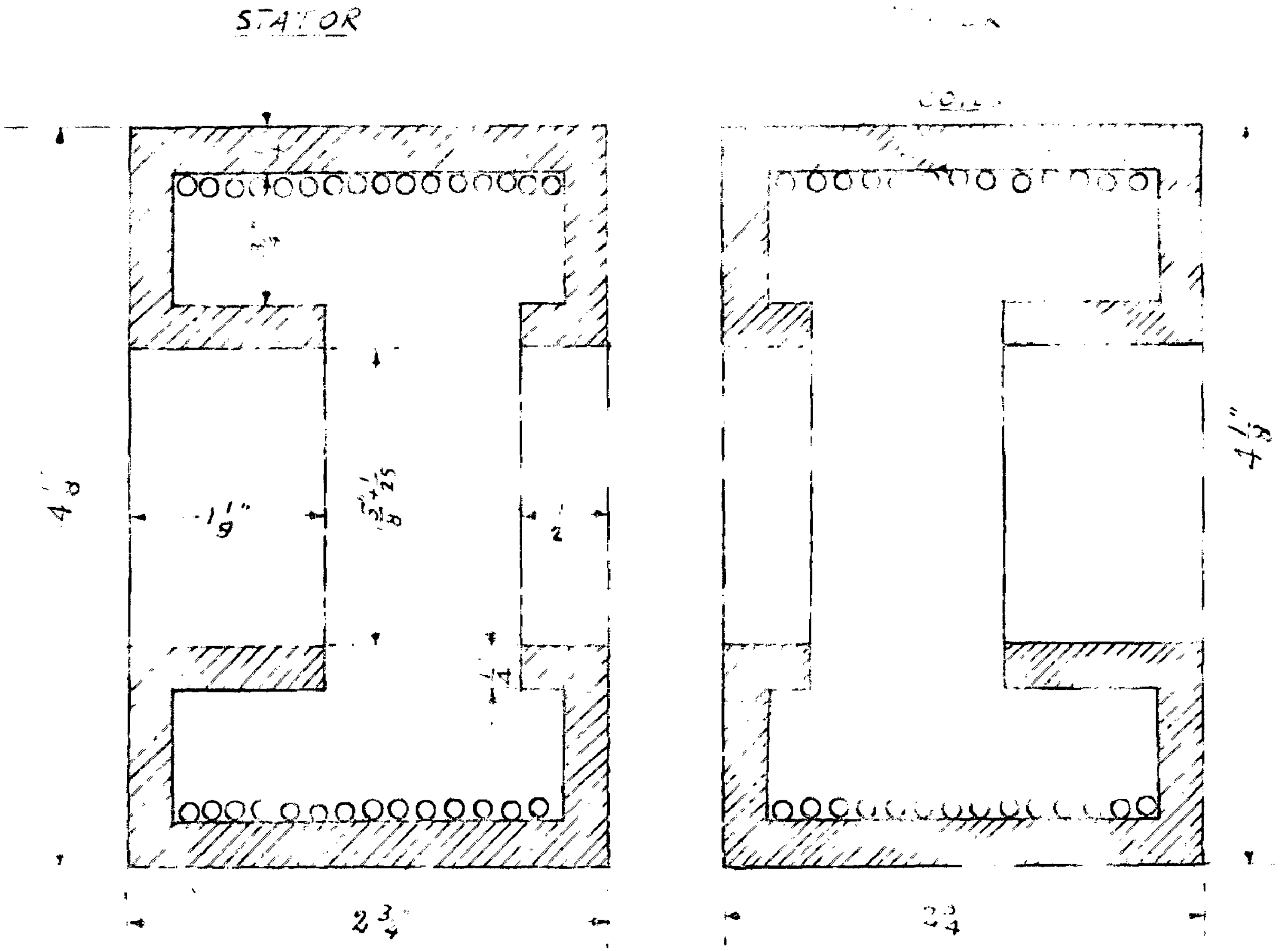
TOOTHED RINGS FOR MAGNETICALLY COUPLED
TORQUE METER



of $5\frac{1}{2}$". As the middle ring will have teeth on both the sides its ~~all~~ overall dimensions are to be higher than the other two rings. The teeth length is 3/4". The axial gap between the two rings is 1/8". This is intentially kept high to avoid flux leakage. This gap provides a large reluctance and so the flux is forced to cross the active air gaps. The area of overlapping of teeth is 5/8" x 1/8". In case of 10-teeth rings, the width of the teeth at one section is 3/16" and at the other section it is 1/8". In the case of 5-teeth rings, the width of teeth is 5/16" at one section and 1/4" at the other. This is because the flux carried by each tooth will be increased for the same value of stator ampere-turns.

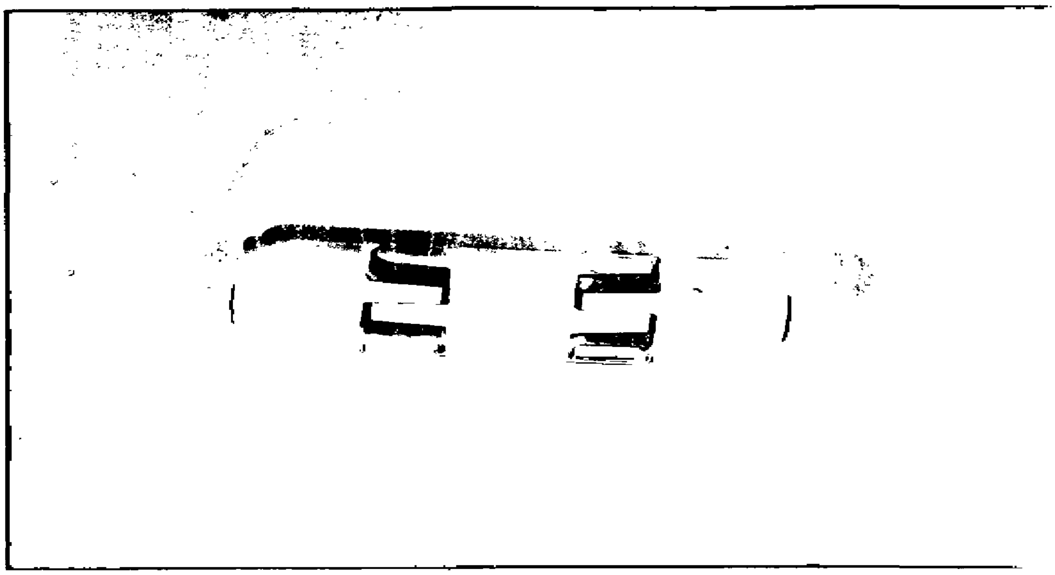
Stator

The stator consists of two similar parts. One extends from the ring 1 to the middle of the ring A, and the other from the middle of the ring A to the end of the ring 2. As has been indicated earlier, the radial air gap between the stator and the rotor has a very little effect on the reluctance of the magnetic path, so radial gap of 1/50" is provided. The end covers of the two parts of the stator are so designed that they leave a space of 1/8" axially on the rings, so that the flux is forced to pass through the active air gaps. The drawings of the stator parts are shown in fig. 5-7. The depth of the stator housings is taken to be large enough so that two coils of sufficiently large number of turns can be conveniently accommodated. The idea of using two coils is to use the second set of coils in the two halves connected differentially for measuring response while the first set of coils is used to provide the excitation for the device.



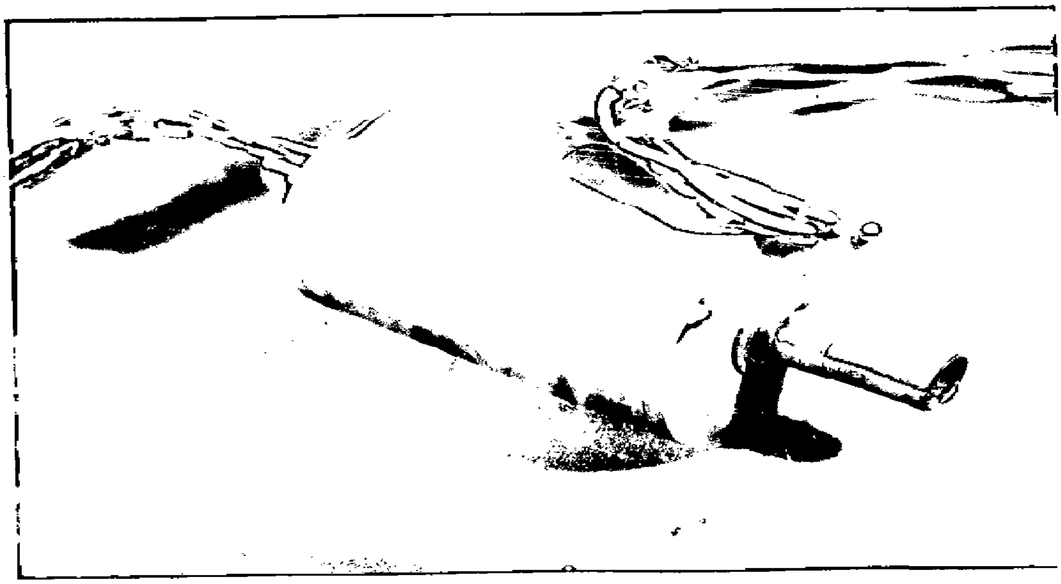
[illegible]ATOR FOR MAGNETICALLY COUPLED [illegible] METER

[illegible]



Above:- Rotor Rings with 8-tooth.

Below:- Complete Assembly of the
Torquemotor.



As there is no data available on the design of these meters, so to start with any suitable values for various quantities has to be assumed. Regarding the number of turns to be provided in each coil, a fairly large value is chosen. The current in the primary coils is varied and the voltage induced in the secondary coils is noted. The current is adjusted to such a value that the magnetic circuit is not saturated. Incomplete layers are avoided in the windings. As the current is not expected to be large, 26 S.W.G. wire is chosen and six layers of it are provided in each of the stator coils. The total number of turns in each coil is 585. The primary and secondary coils in the two stators are wound in such a fashion, that when the current is passed with the primaries connected in series, the flux produced by them flows in the same direction in the two halves of the stator. Now if the secondaries are connected in series opposition then the voltage between the terminals available will be the out-of-balance.voltage of the two halves of secondary. The stator section is taken 1/4" thick throughout. As iron path of the magnetic circuit is not laminated the flux densities in it should be as low as possible to reduce eddy current losses.

Flux densities of various sections

Reluctance calculations - For the calculation of reluctances of various paths, it is assumed that the iron part is of infinite permeability, so that all the ampere-turns are utilized by the air-gaps in the magnetic path.

There are two radial air-gaps and one active air-gap for the flux to complete its path. The area of cross section provided by the stator end covers is different for two radial gaps.

From the drawings of the stators:

Area for the radial flux on one side

$$= \pi \left(1\frac{5}{8} + \frac{1}{25} \right) \times 1\frac{1}{8} . \text{ sq.in.}$$

$$= \pi \times 1.665 \times \frac{9}{8} = 5.89 \text{ sq.in.}$$

Area for the radial flux on the other side

$$= \pi \times 1.665 \times \frac{1}{2} = 2.62 \text{ sq. in.}$$

length of the radial gap = 1/50"

R = reluctance of the path

$$R_1 = \frac{l_1}{a_1 \mu} = \frac{1 \times 2.54}{50 \times 5.89 \times 2.54 \times 2.54} \text{ ./cm.}$$

$$= 0.00134.$$

$$R_2 = \frac{l_2}{a_2 \mu} = \frac{1 \times 2.54}{50 \times 2.62 \times 2.54 \times 2.54} = 0.00312.$$

<u>Gears</u> - Area of overlapping of one teeth = $\frac{1}{8} \times \frac{5}{8}$ sq.in.

Length of active air gap = 1/64".

∴ Reluctance of each active air gap

$$R_3 = \frac{1 \times 2.54 \times 8}{64 \times 0.125 \times 5 \times 2.54 \times 2.54} = 0.0786$$

There are 10 teeth on the ring and so there are 10 active gaps. The total flux from the stator distributes itself into ten different paths. As all the teeth are identical and the area of overlapping etc. is same all over, we can assume that there are ten similar paths in parallel.

$\therefore$ Reluctance of all the active-gaps

$$= \frac{1}{10} \times 0.0786 = 0.00786.$$

Total reluctance of the path

$$= 0.00134 + 0.00312 + 0.00786$$

$$= 0.01232.$$

The current in the exciting coils in series is 0.16 ampere. This current is allowed so that saturation does not occur at points of magnetic circuit where the flux density is comparatively high.

$$\text{Flux} = \frac{\text{M. M. F.}}{\text{Reluctance}} = \frac{0.4 \pi NI}{R}.$$

$$= \frac{0.4 \pi \times 585 \times 0.16}{0.01232} = 9550 \text{ lines}.$$

The voltage induced in one of the secondaries has been measured and is found to be 12 volts.

Now

$$E = 4.44 \Phi f N \times 10^{-8}.$$

$$12 = 4.44. \Phi .50 \times 585 \times 10^{-8}.$$

$$\therefore \Phi = \frac{12}{4.44 \times 50 \times 585 \times 10^{-8}} = 9250 \text{ Lines}.$$

The value of flux calculated from the dimensions of the meter and from the voltages induced in the secondary coils, is slightly different, because the leakage flux has not been taken into account. Comparison of the calculated and experimental values shows a leakage of nearly 3% which is within allowable limits.

The value of useful flux is taken for the calculations of flux density in the rotor teeth, and the total flux is taken for the calculation of flux density in stator. The amount of flux assumed to be passing through the rotor body is the maximum possible under the physical disposition of the different parts of this device.

$$\text{Flux through each active gap} = \frac{9250}{10} = 925 \text{ lines}$$

$$\therefore \text{ Flux density in the rotor teeth at overlapping section} = \frac{925}{\frac{5}{8} \times \frac{1}{8}} = 11830 \text{ lines/in}^2.$$

The value is quite low and can therefore be allowed.

The above flux passes through the base of the tooth at a section 3/16" x 1/8" as shown. At this section the flux density is expected to be maximum.

Flux density at above section

$$= \frac{925}{\frac{3}{16} \times \frac{1}{8}} = 39400 \text{ lines/in}^2.$$

Area of cross section of stator core

$$= \frac{\pi}{4}(4.165^2 - 3.665^2) = \frac{\pi}{4}(17.35 - 13.4) = \frac{\pi}{4} \times 3.95$$

$$= 3.1 \text{ sq.in.}$$

Flux density in the stator core

$$= \frac{9550}{3.1} = 3{,}080 \text{ lines/in}^2.$$

The value is quite low.

In the end covers of the stators, the flux density will be maximum at a section where the supports for the windings starts.

Area of cross section at that section

$$= \pi \times 2.165 \times \frac{1}{4} = 1.7 \text{ sq. in.}$$

$$\text{Flux density} = \frac{9550}{1.7} = 5600 \text{ lines/in}^2.$$

<u>Flux densities at various sections with 5-teeth rings</u>

Length of the radial gap = 15/1000"

Area for the radial gap flux on one side

$$= \pi \left(1\tfrac{5}{8} + \frac{3}{100} \right) \times 1\tfrac{1}{8} \text{ sq.in.}$$

$$= \pi \times 1.655 \times 9/8 = 5.85 \text{ sq. in.}$$

Area for the radial flux on the other side

$$= \pi \left(1\tfrac{5}{8} + \frac{3}{100} \right) \times 1/2 = 2.6 \text{ sq. in.}$$

$$R_1 = \frac{l_1}{a_1\,\mu} = \frac{15 \times 2.54}{1000 \times 5.85 \times 2.54 \times 2.54}.$$

$$= 0.0010$$

$$R_2 = \frac{l_2}{a_2 \mu} = \frac{15 \times 2.54}{1000 \times 2.6 \times 2.54 \times 2.54} = .00228$$

As the overlapping area of the gears is same as with 10-teeth rings, the reluctance of each active air-gap

$$R_3 = 0.0786.$$

Reluctance of all the active gaps

$$= 1/5 \times .0786 = 0.01572$$

Total reluctance of the path = .0010 + .00228
+ 0.01572 = 0.019

The current in the exciting coils = 0.16A

$$\therefore \quad \text{Flux} = \frac{\text{M.M.F.}}{\text{Reluctance}} = \frac{0.4\,\pi\,NI}{R}$$

$$= \frac{0.4\,\pi \times 585 \times 0.16}{.019} = 6200 \text{ lines}$$

The voltage induced in one of the secondaries is measured and is found to be 7.9 volts.

Now $E = 4.44\,\Phi\,f\,N \times 10^{-8}.$

$$7.9 = 4.44 \times \Phi \times 50 \times 585 \times 10^{-8}.$$

$$\therefore \quad \Phi = 6100 \text{ lines.}$$

The difference between the calculated and measured values of flux is very small. This indicates the reduction in leakage flux with 5-teeth rings.

$$\text{Flux through each active gap} = \frac{6200}{5} = 1240$$

Flux density in rotor teeth at overlapping section

$$= \frac{1240}{5/8 \times 1/8} = 15900 \text{ lines/in}^2$$

This value is well within the limits.

Area of cross-section at the neck of the teeth = 5/16 x 1/8 sq.in.

Flux density at the neck

$$= \frac{1240}{5/16 \times 1/8} = 31800 \text{ lines/in}^2.$$

Area of stator core = 3.1 sq.in.

Flux density in the stator core

$$= \frac{6200}{3.1} = 2000 \text{ lines/in}^2$$

Area of cross section at the stator end covers where the supports for the windings starts.

= 1.7 sq.in.

$$\text{Flux density} = \frac{6200}{1.7} = 3650 \text{ lines/in}^2.$$

Temperature effects in magnetic strain gauges

The effects of ambient temperature changes upon magnetic strain gauges can be divided into those originating in the instrument circuit and those originating in the shaft pick-up unit. The temperature effects in the instrument circuit are readily corrected by conventional means. The temperature changes in the shaft element are more difficult handle ordinarily, particularly since temperature may change from -60°F to +200°F, for air-craft application. The changes in the modulus of elasticity of the shaft material are usually small over the normal temperature ranges. Serious unbalances of the impedance bridge may result from large ambient temperature changes around the shaft pick-up unit; this may be particularly noticeable when large temperature differentials appear from end of the shaft unit to the other. These calibration changes can be held to small limits with proper care in design to prevent large hysteresis and eddy current losses in the magnetic parts of the shaft unit. These losses are highly temperature sensitive, so that torque instrument accuracy suffers from temperature changes. Those temperature effects can be held within acceptable limits by the proper care in design and application.

CHAPTER VI

CALIBRATION AND RECORDING

6.1. The circuit for the calibration of the torquemeter is to be sensitive and accurate. As the energy level at which this meter operates is high, calibration can be done without the use of an amplifier.

The circuit used originally by Langer[12] in his paper is no doubt an extremely simple one, fig.6-1. But the out-of-balance signal being very small, a modified circuit is used which is comparatively more sensitive than used by Langer. The idea of putting two similar coils in each stator is actually to improve the sensitivity of this meter. The output signal is measured by both the circuits, first by using circuit suggested by Langer and then by connecting two secondaries in opposition and finding the out-of-balance signal. It has been observed that modified circuit is more sensitive to changes.

As there are two seperate stators sending flux through two different sets of active air gaps, there is always a possibility of slight unbalance in the two magnetic circuits. Due to this unbalance, some out-of-balance voltage (or current) is obtained even without any torque transmission. Number of things have been tried to eliminate this zero-error, as we call it, but it could not be eliminated. This is taken as the initial reading or the "zero-error" of the meter. It depends upon the exciting current in the primary coils and the degree of assymmetry in the two sections of the device.

Calibration of Torquemeter with rings having 10 teeth.

6.2. Calibration by Milli-ammeter.

The calibration of this meter has been done by various methods. The first method adopted is by reading the output directly. The secondaries are connected in series opposition through a milli-ammeter. The initial reading of this meter is noted for an exciting current of 0.16 A. The connections are shown in fig.6-2.

The meter is interposed between an I.M.-D.C. generator set. The D.C. machine works as a seperately excited generator and for various values of load current, the readings on the milli-ampere meter are noted. The torque transmitted by the shaft is calculated for different loads and the calibration curve is shown on graph 6-3.

But for the zero error which may cover a large portion of the meter scale, the above method is quite simple. The output of the meter varies linearly with the torque transmitted by the shaft.

6.3. Calibration with the help of Zener Diode.

With a linear relation between signal and response it is desirable to read torque directly from the calibration curve with initial zero reading corresponding to zero signal. But in this particular meter the initial reading for zero torque is not zero due to flux leakage and unbalance in magnetic circuit.

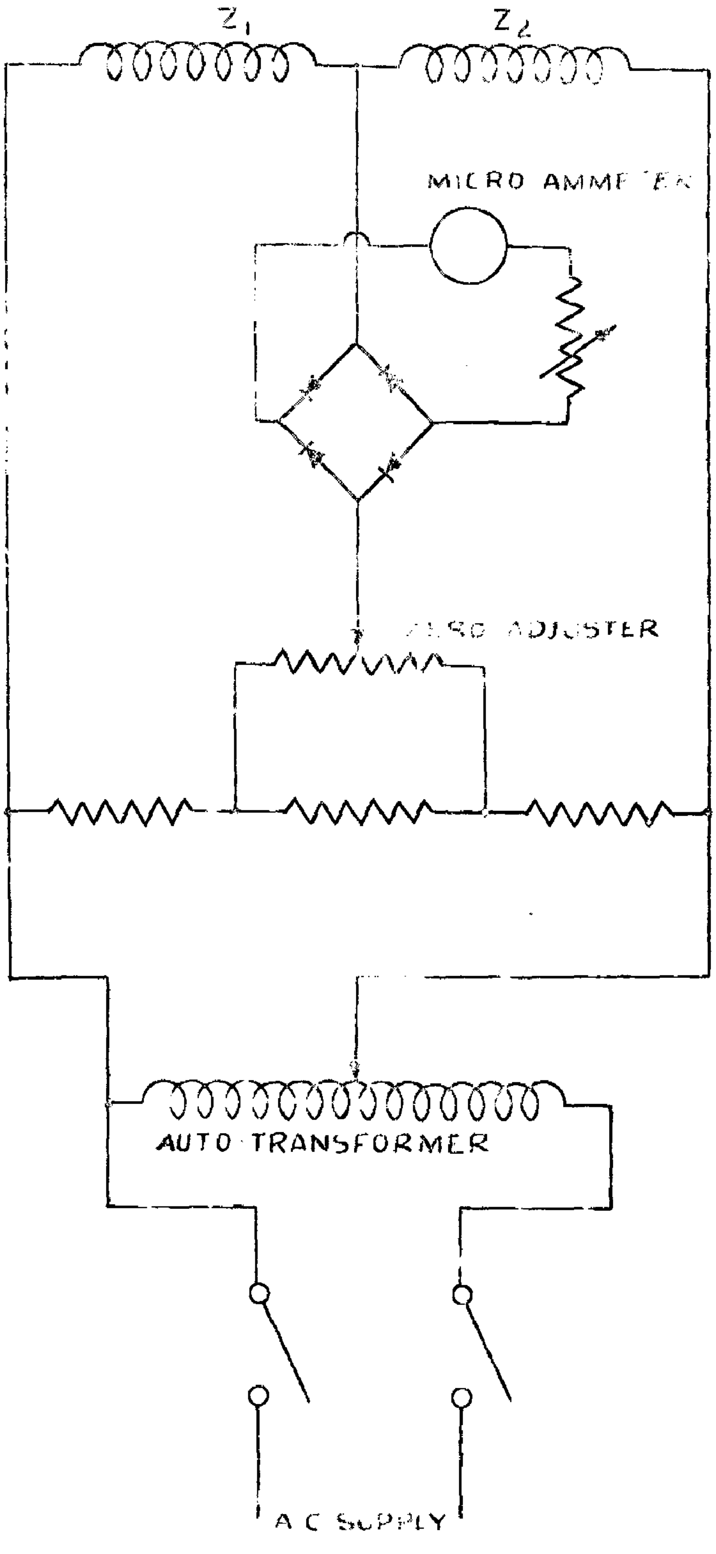
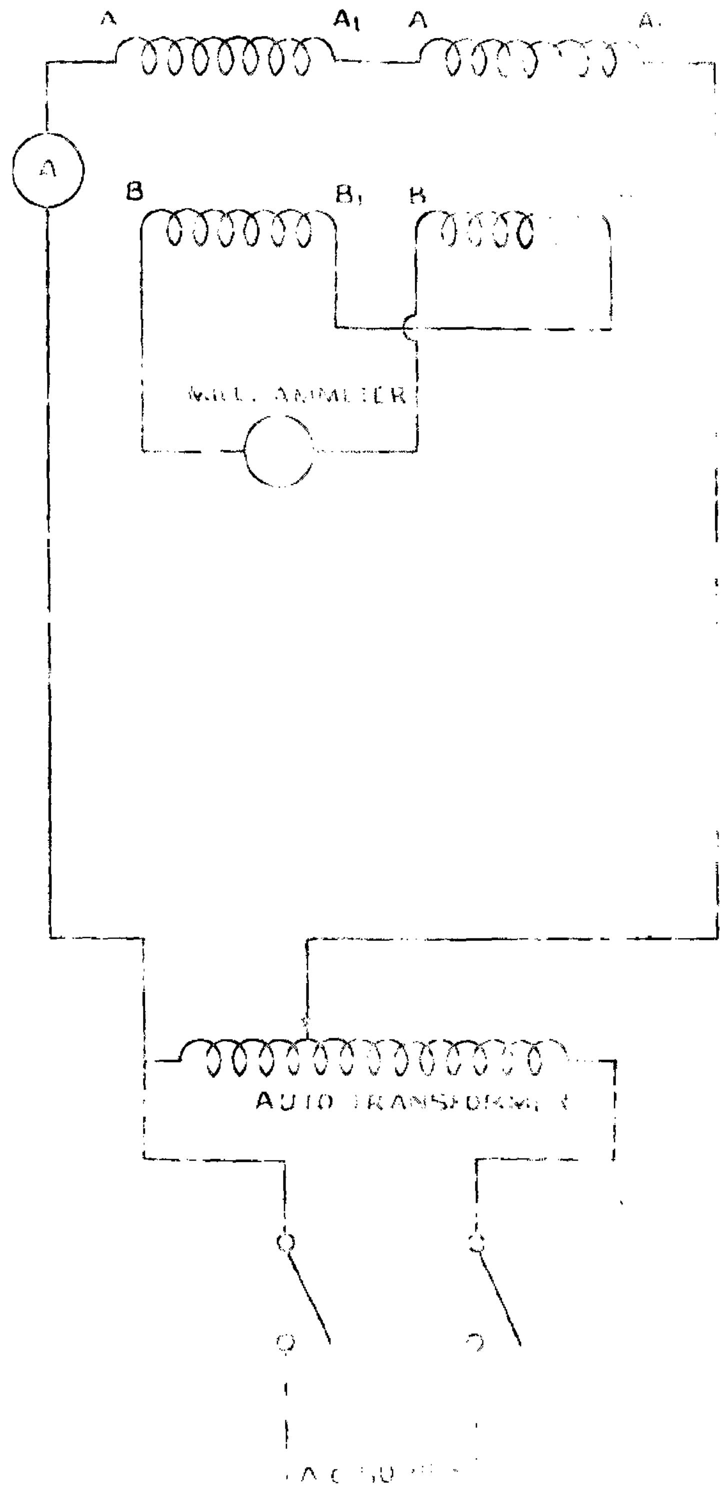

Z1
Z2
MICRO AMMETER
ZERO ADJUSTER
AUTO TRANSFORMER
A C SUPPLY

FIG 6 I


A
A1
A
A.
A
B
B1
B
MILLIAMMETER
AUTO TRANSFORMER
A C SUPPLY

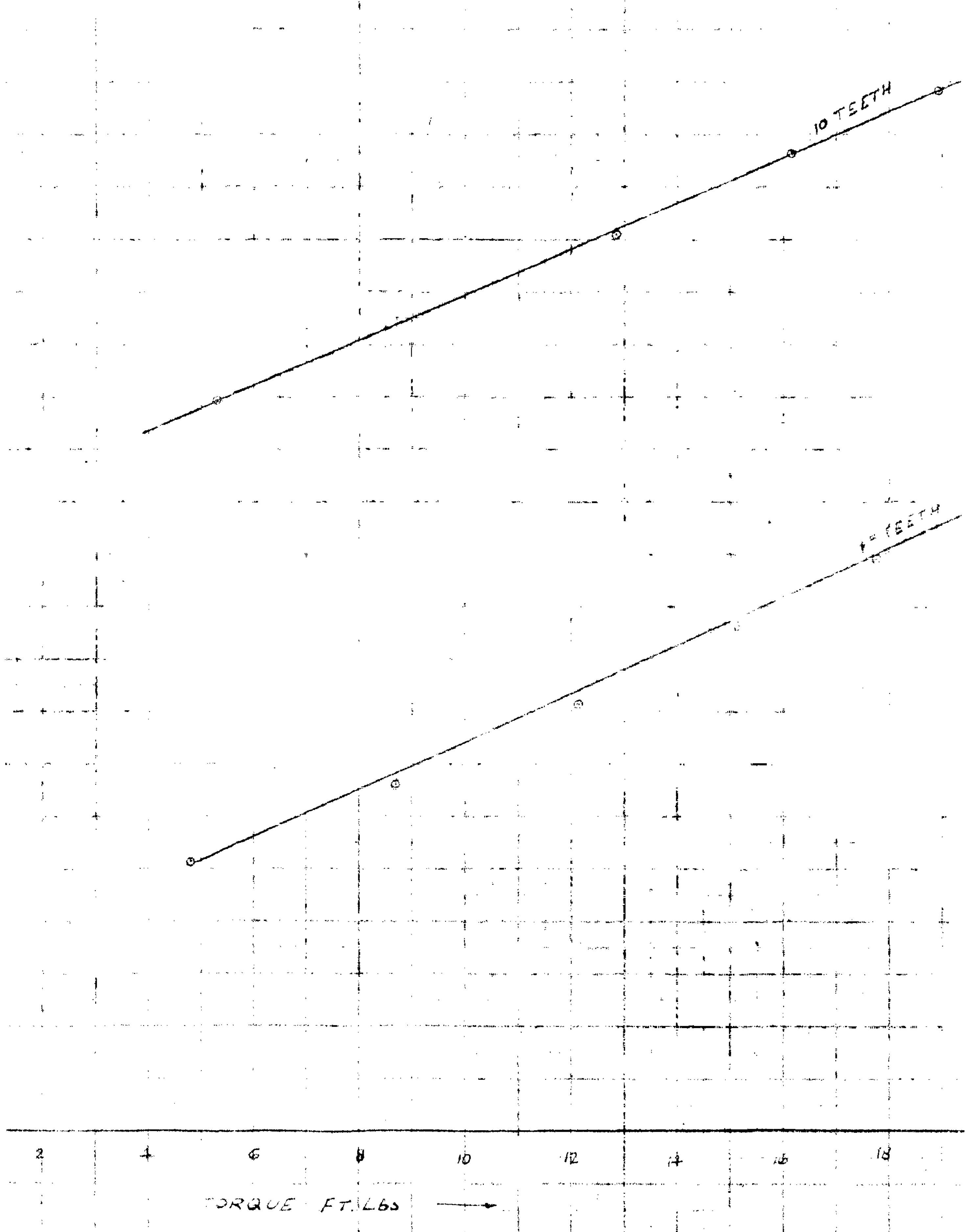
Zener Diodes[18.] are best suited to work as reference potential under above conditions. The characteristic of a zener diode is shown in fig.6-4. Once the breakdown voltage has been reached, the voltage across the diode is almost independent of the current through it. Even in the forward direction large changes of current result in only small changes of voltage. The voltage at which the sudden increase in current occurs is called the zener voltage and is sometimes referred to as the break down voltage. In this case we are not very much interested in a constant voltage across the zener, and so even the diode can be put in forward direction. The voltage required for the operation of the diode in the forward direction is comparatively small.

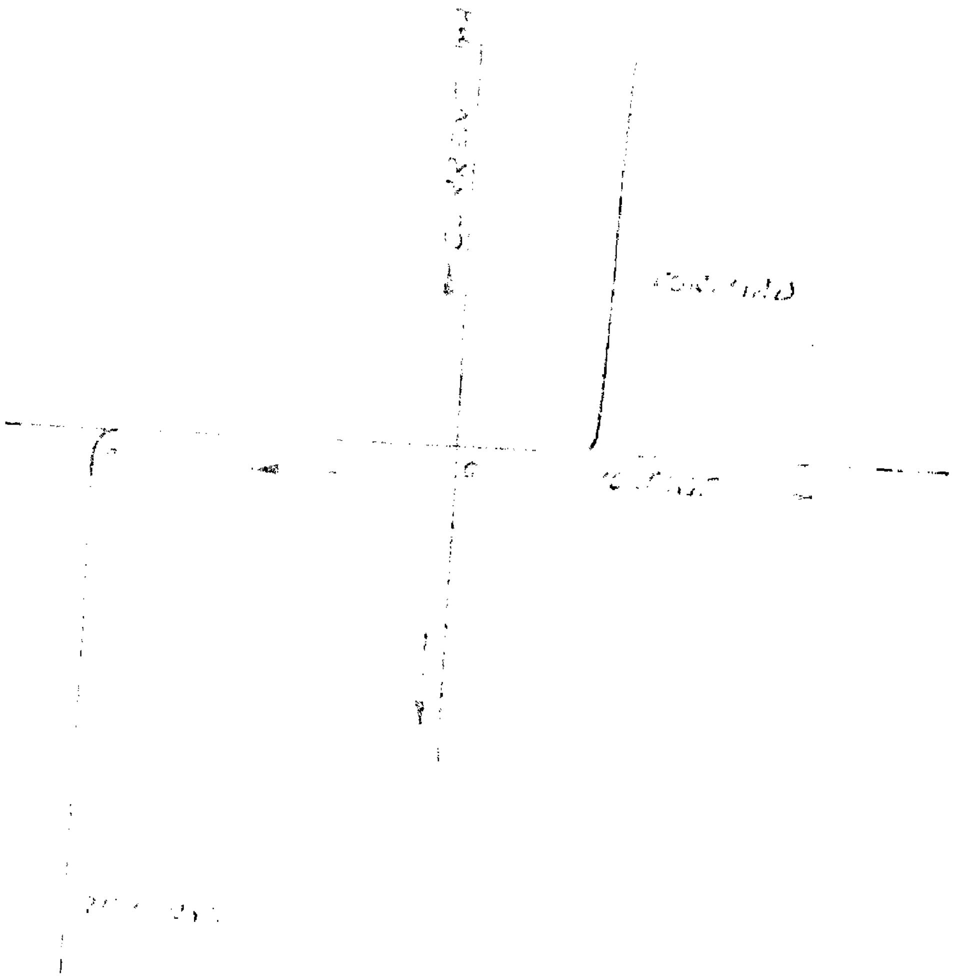
As the out-of-balance voltage is very small, the signal is amplified with the help of a transistor amplifier. The out put of the amplifier is rectified and then smoothed. A bridge is formed, one arm of which contains a zener diode and is supplied from the d.c. output of the circuit. The bridge is balanced for the initial reading of the meter output. A d.c. micro-ammeter is used to measure the out-of-balance signal with load. The connection diagram is shown in fig.6-5; and the calibration curve on graph 6-6. This method of calibration is quite good, as it gives the zero initial reading and also the micro-ammeter is very sensitive to the changes occuring in the circuit due to the torque.

6.4. The nature of the variation of the output signal with load is also seen on oscilloscope. The rectified output of the meter is given to x-plates and a signal proportional to

Graph C-2

Calibration of the [illegible] Dynamometer




0

Connection diagram for calibration with Zener diode

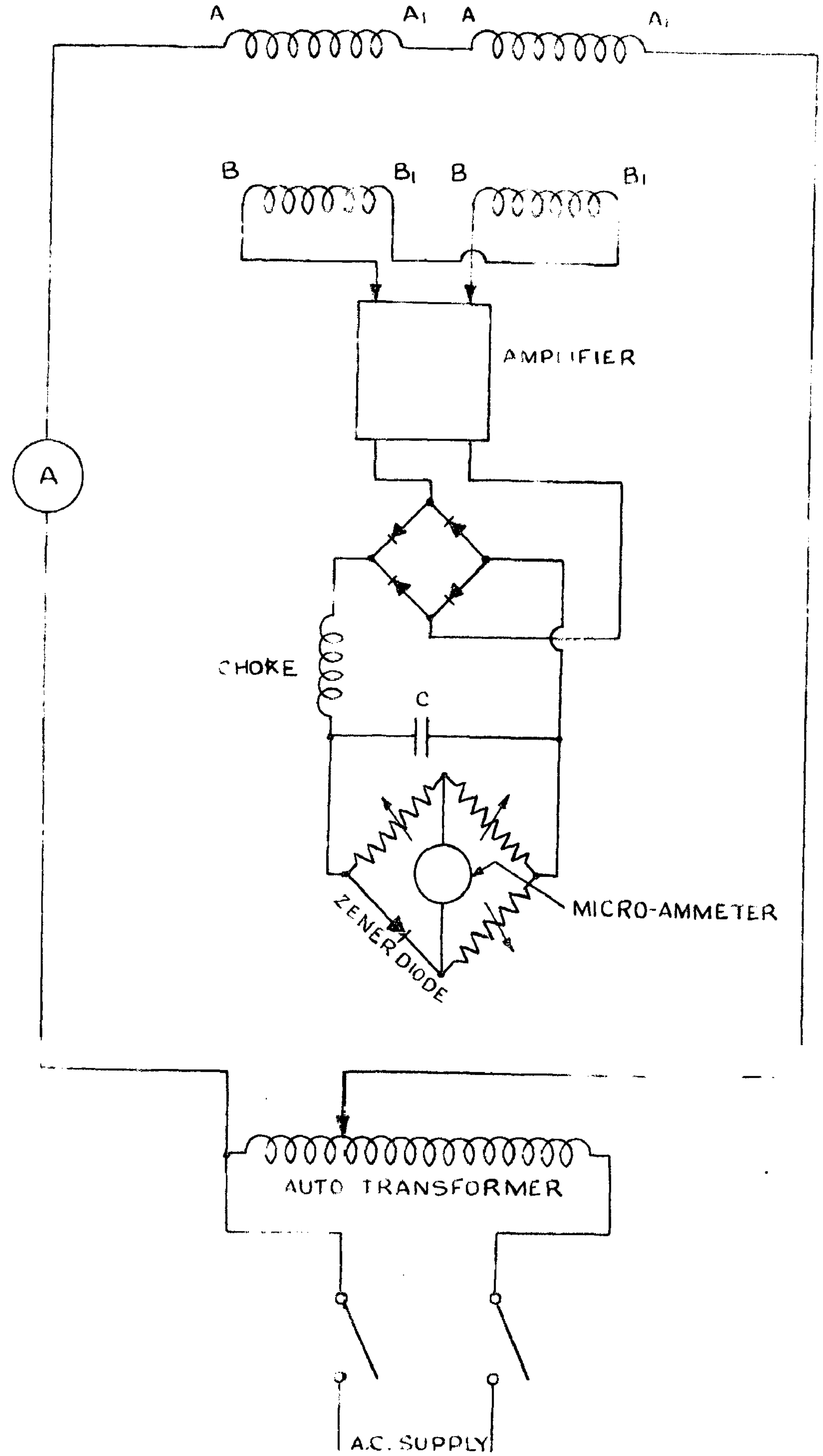
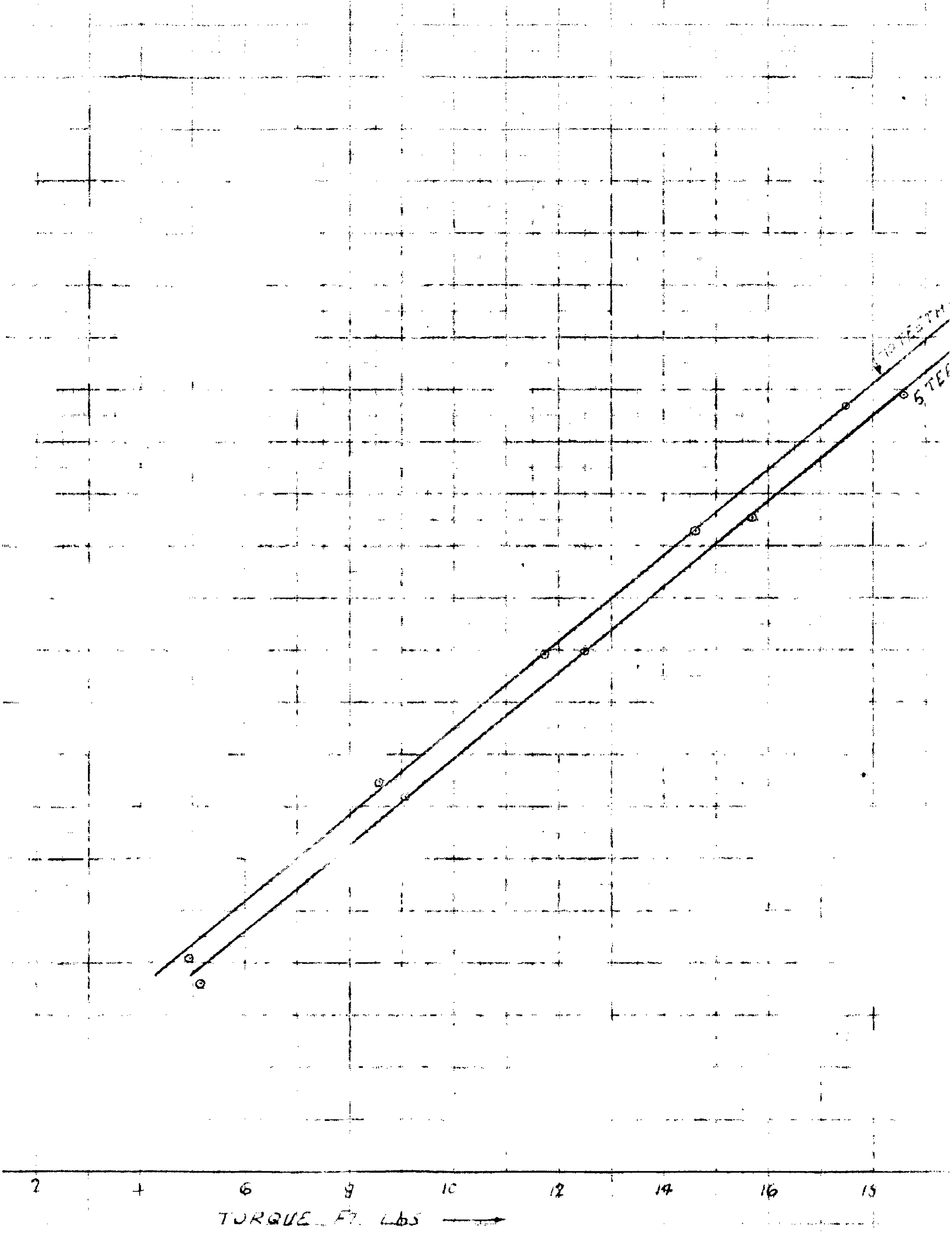


FIG. 6-5

Graph C-

Calibration Curves with Zener-diode and Micro-ammeter



the load current of d.c. generator is given to y-plates. It has been found that the response recorded on scope for the change in the load is slow. However, this slowness does not affect the steady state readings.

Calibration of torquemeter with rings having 6-teeth.

As indicated earlier, the sensitivity of the meter increases with lesser number of teeth on rings with same overlapping area. The excitation current through the primaries connected in series is kept same as in the first case. The out-of-balance signal is less for no-load conditions. This is firstly because of the lower total flux owing to the increase in the reluctance of the circuit and secondly due to the reduction in the leakage flux around the rotor. The meter is again calibrated first by the use of milli-ammeter and then by the help of zener-diode and micro-ammeter. The calibration curves are shown on the graphs C-3 and C-4. The variation obtained on the indicating meters with 6-tooth rings is approximately the same as with 20-tooth rings, which shows the increase in the sensitivity of the device with lesser number of teeth.

Recording - Records of transient torque are taken on C-beam oscilloscope. The starting torque is recorded with line voltages of 40% and 60% of the normal voltage. Plugging torque is taken only at 80% of the supply voltage. The starting of the motor and the recording are done simultaneously by the help of a relay. The block circuit diagram is shown in fig. C-7.

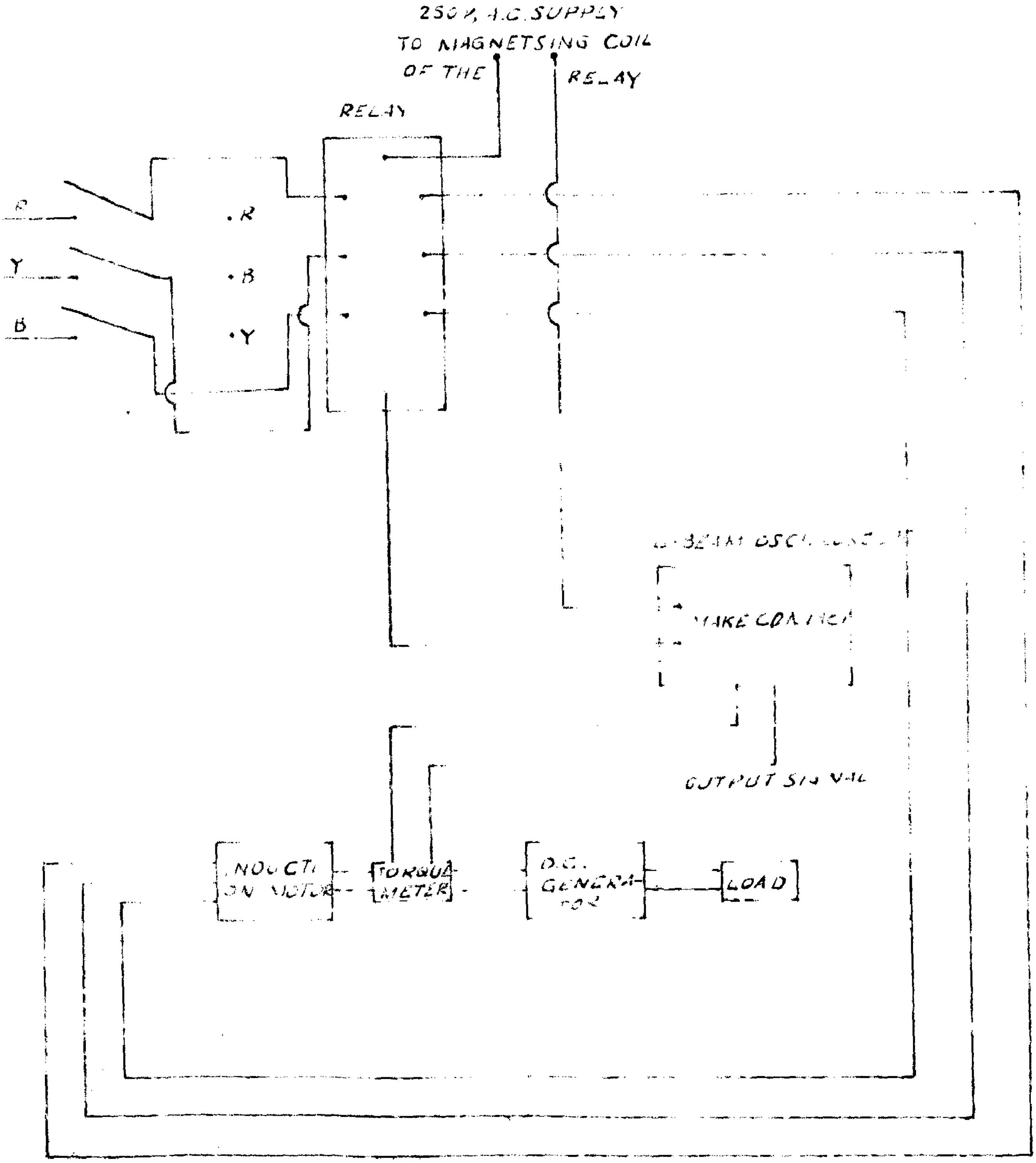
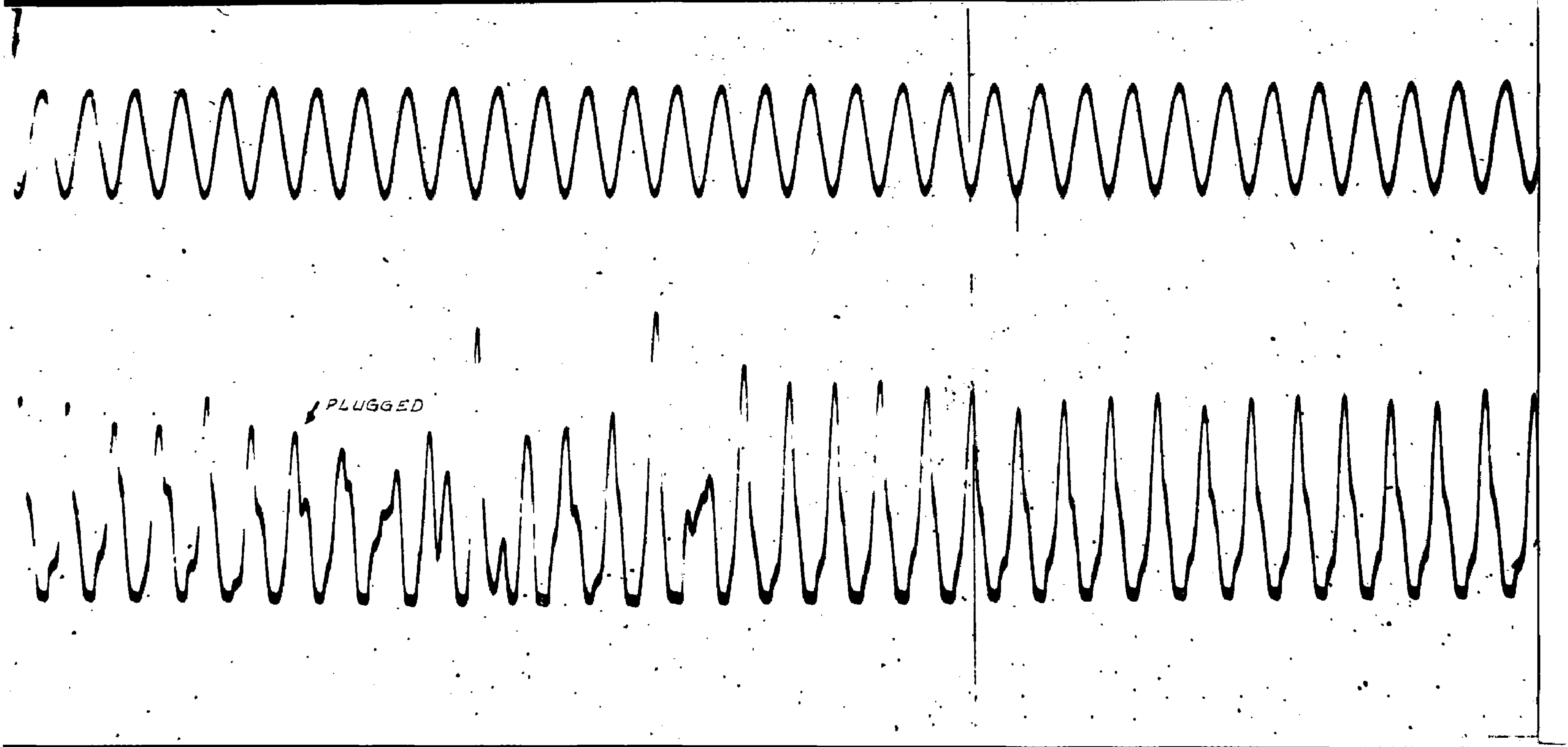
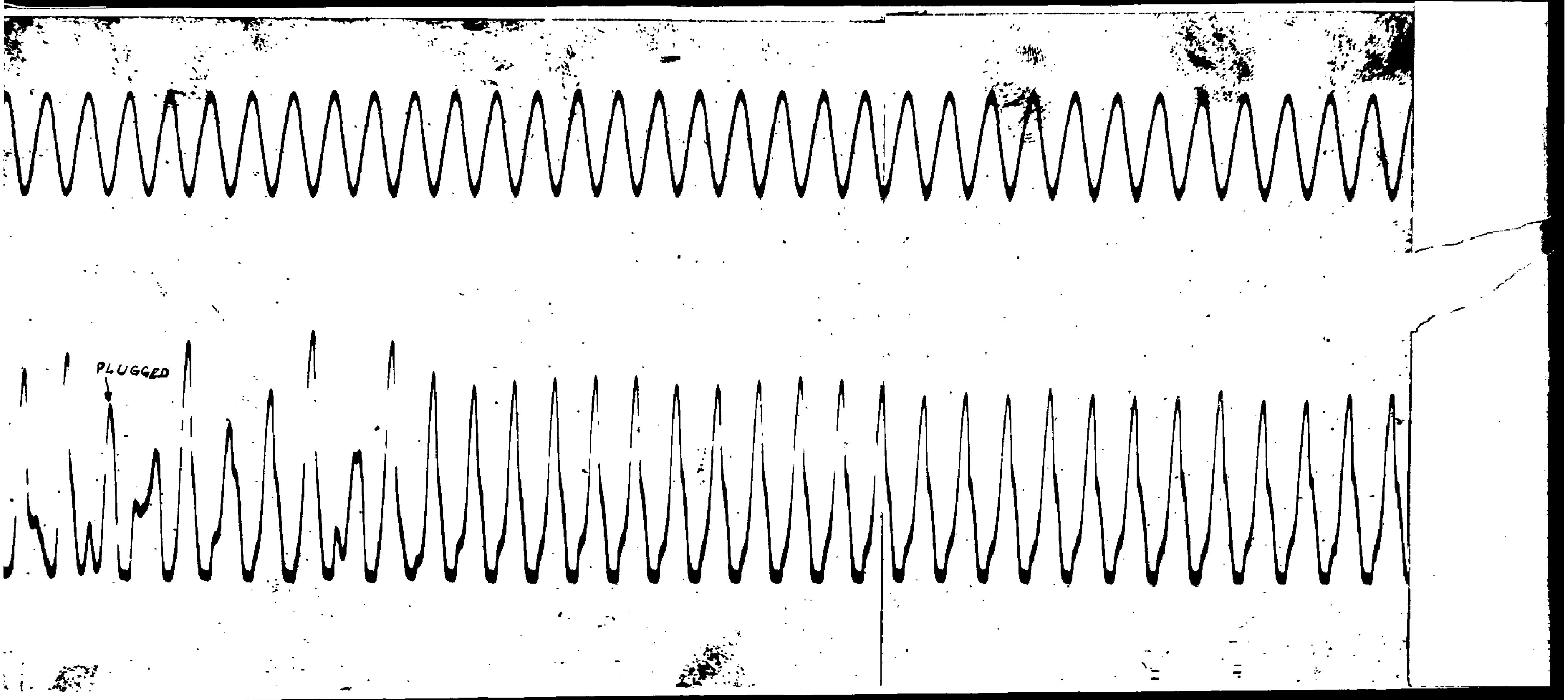


Fig. 6-7

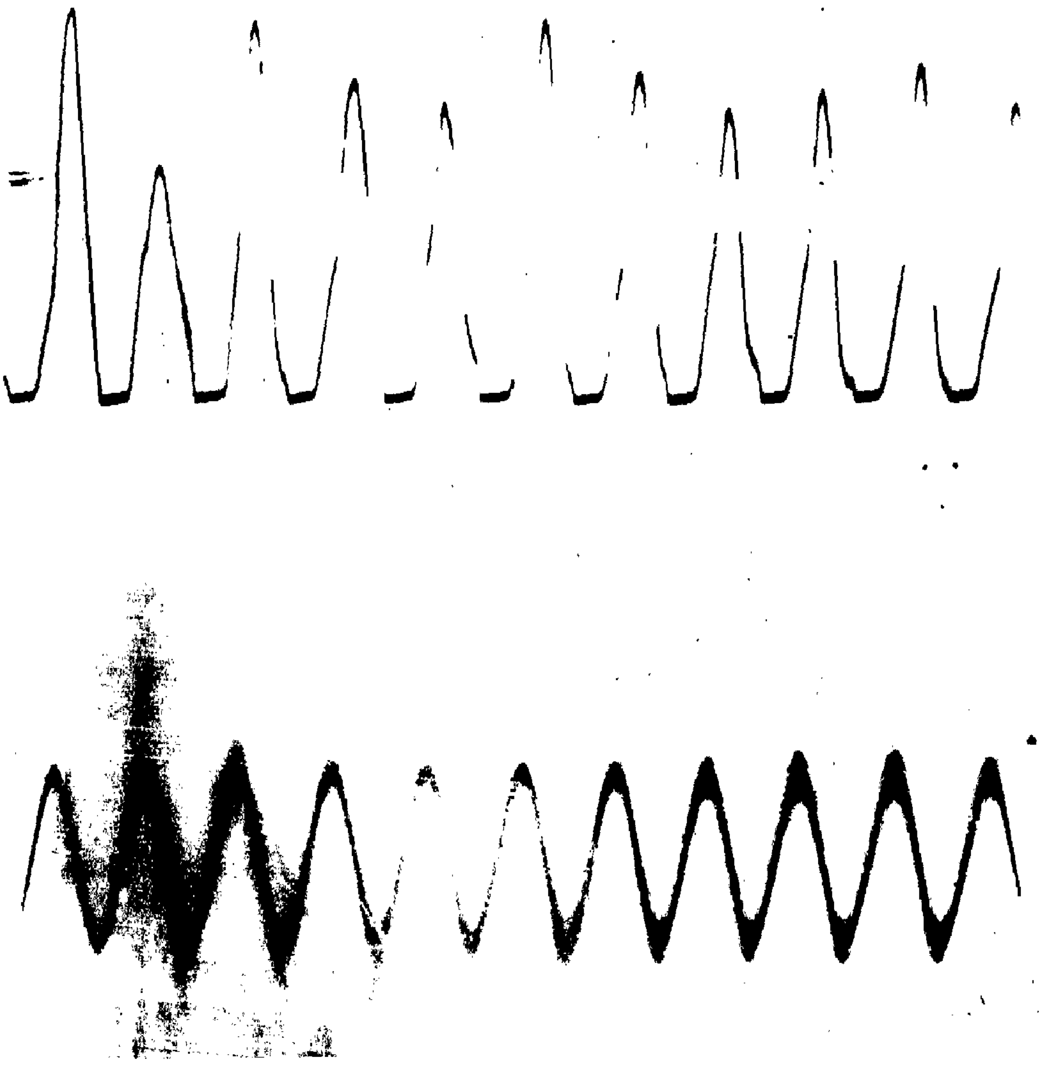
Block circuit diagram for transient recording



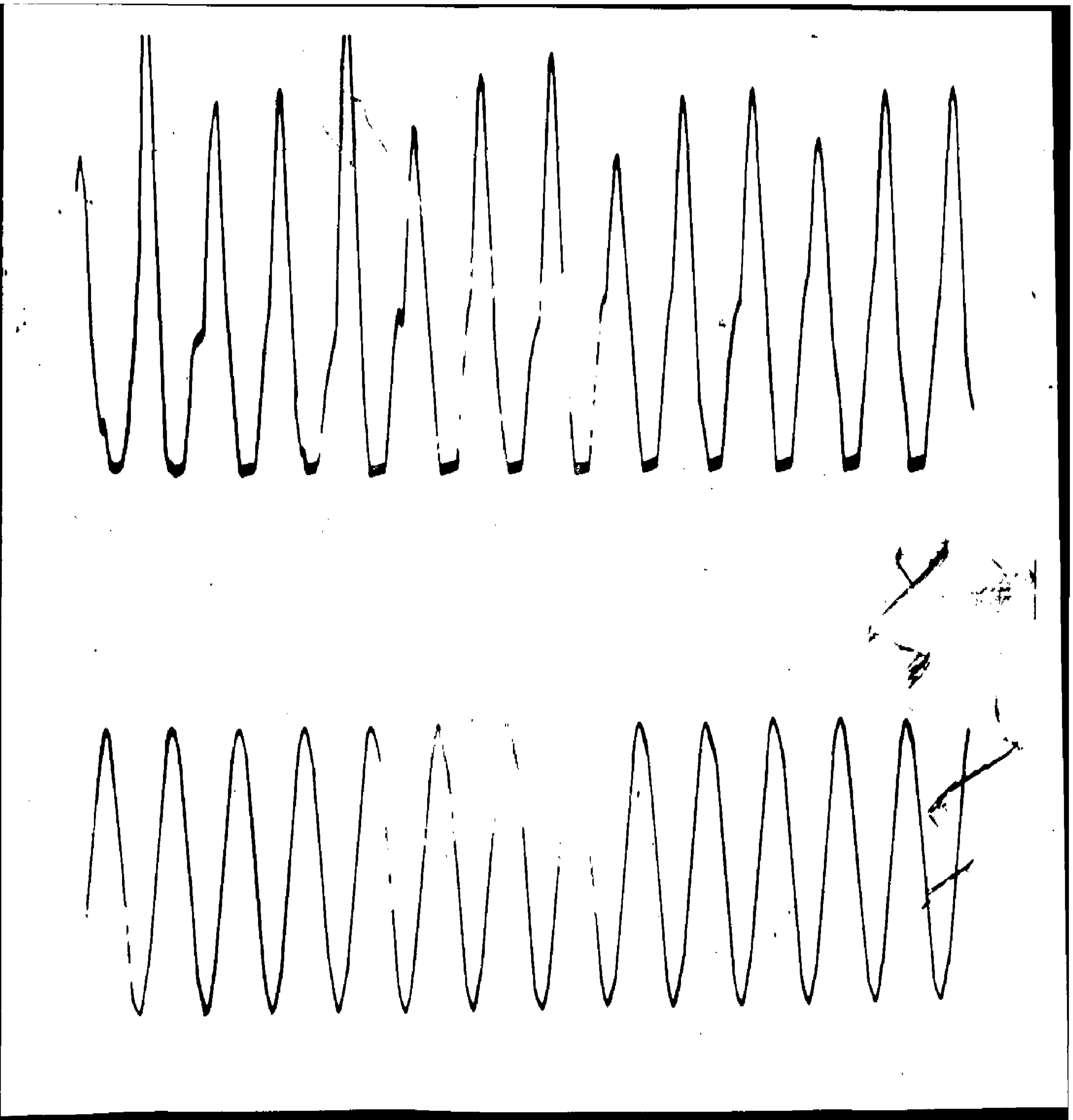
Plugging torque at 50 % Voltage.



Plugging torque at 80 % Voltage.



Starting torque at 40 % Voltage.



Starting torque at 50 % Voltage

CHAPTER VII

CONCLUSIONS

The Magnetic-coupled torquemeter which has been fabricated and tested is a very useful device for measuring both steady and transient torques. Excepting the toothed rings, other parts are very simple and so there is not much difficulty in fabricating the unit.

The modifications introduced in the stator for measuring the response has resulted into higher sensitivity compared to the arrangement used by Langer. The reduction in the number of teeth on the rotor rings has reduced the leakage flux around the rotor, which results in smaller zero error and reduction in noise. But reduction in the number of teeth may result in lesser sensitivity of the meter because of the reduction in total change of flux due to torque.

The calibration has been done by means of very simple circuits. The response of the meter to transient conditions is good. Transient records of starting and plugging indicate that the device is quite suitable for transient recording.

From the transient record it will be seen that there is nonuniformity in the wave shape, even under steady state condition of running of the machine. The probable cause of this nonuniformity is the nonuniform radial air-gap and nonuniform teeth gap on the rotor. Transient torque record for plugging shows high plugging torque and also the increased torque when motor starts to run in the opposite direction.

Preceding the plugging torque record there is a slight depression in the response wave form. This is due to momentary decrease in torque when for the purpose of plugging the supply to motor is broken for a brief while.

In addition to plugging torque starting torque of an induction motor has also been recorded. The records brings out the expected nature of torque variations during starting up period of an ordinary induction motor.

The sensitivity is high even for small values of torque and so the accurate measurement of torque is possible even with machines of lower ratings.

The accuracy with which the measurements are possible with magnetic-coupled torquemeter is of course dependent on the limitations of the circuit used to measure the response of the torquemeter.

Field of application

It is expected that the magnetic-coupled torque meter will find its main field of application in permanent installations such as (1) Laboratories where rotating machinery is being developed, (2) test floors where rotating machines are being given acceptance tests and (3) air craft and marine power plants where a continuous check on the performance of the plant is desired. In these fields it fills several gaps which can not be handled by any other device and often can be substituted for much more expensive equipment.

In some applications it has been found desirable to split the stator axially so that it can be removed from the rotor without slipping it over an open shaft end.

All this shows that with better workmanship in fabrication and proporting in design, the meter with the modification suggested in this work will prove to be more useful and popular whenever there is a necessity for recording torque under static as well dynamic conditions of operation.

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LIST OF SYMBOLS

T = Torque transmitted by the shaft, ft-lbs.

G = Modulus of rigidity of the shaft material-lbs/in^2.

I_p = Polar moment of inertia of the section - in^4.

L = Length of the shaft - in.

θ = Angular twist of the shaft - radians.

A = Area of overlap of plates of a condenser.

K = The dielectric constant.

t = Width of the gap between the plates.

= Coefficient to allow edge effects.