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Design of a photoelectric transient torque and speed meter

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DESIGN OF A PHOTOELECTRIC TRANSIENT TORQUE AND SPEED METER

by

RAOJIBHAI A. PATEL

A

THESIS

Submitted to the faculty of the
UNIVERSITY OF MISSOURI AT ROLLA, ROLLA, MISSOURI
in partial fulfillment of the requirements for the
Degree of
MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

ROLLA, MISSOURI

1965

Approved by

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125321
ABSTRACT

There are many situations in which it is desirable to know the speed of the shaft and the torque it is transmitting, when it is equally undesirable to make any mechanical connection to the shaft. This thesis describes the development and design of a device for measuring the torque and speed by photo-electric means. The basic principle is that a light beam parallel to the shaft may be used to pick up the desired information without adding friction to the system. The deflection of a torque tube inserted in the shaft opens or closes a set of apertures arranged in a circle concentric with the shaft. A beam from a light source is directed parallel to the shaft and focused on a light sensor through the apertures. As the shaft rotates, a flickering light reaches the light sensor. The size of the apertures depends on the torque, the average light intensity reaching the light sensor is a measure of the torque. The frequency of the light fluctuations is a measure of the speed.

The design of the torque tube and variable-aperture assembly is discussed. The design of the electronic circuits which convert the light sensor output into signals proportional to speed and torque is shown in detail.

Suggestions are given for future improvement of operation and expansion of the range capabilities.
ACKNOWLEDGEMENT

The author expresses his appreciation to Professor George McPherson, Jr. for his guidance throughout the entire program of study and research and to Professor Lyle G. Rhea for his assistance in the construction work involved in preparing all mechanical components.

Thanks also go to Mr. David Smith for his assistance in the photographic work involved in this thesis.
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CHAPTER I
INTRODUCTION

A. Problem

The major objective of the thesis was to design, construct and evaluate a system capable of measuring torque and speed over a useful range. The system was conceived by Professor George McPherson, Jr., of the University of Missouri at Rolla.

The basic idea used to measure the torque and the speed is as follows. A beam of light from a light source passes through two concentric circles of apertures, in two discs attached to the ends of a torque tube. (Fig. 4.3) In the presence of torque, one disc moves angularly with respect to other. The two discs are placed in such a way that the area of the apertures lying on outer circumference will increase, while the area of the apertures lying on inner circumference will decrease, or vice versa. Since the effective areas of the apertures will change, the average light energy passing through the apertures will change. The light energy passing through apertures is converted into electrical energy by means of two light sensors. Feeding the output of the two light sensors to a differential amplifier, the effective change in area will be obtained as an output of the differential amplifier in terms of an electrical quantity. The frequency of the light fluctuations, due to the set of apertures on the disc, will determine the
This thesis involves the design of all suitable mechanical components and electronic circuitry forming a system which is capable of collecting all the information concerning the speed and the torque of a rotating shaft.

B. Importance of Study

There are many situations in which it is desirable to know the speed of shaft and the torque it is transmitting, when it is equally undesirable to make any mechanical connection to the shaft. There are also situations in which there is considerable axial drift or end play of a shaft, making it difficult to make electrical connections to a shaft-mounted torquemeter or to maintain mechanical contact with a tachometer. The torquemeter and speedmeter described in this thesis is able to measure the torque and the speed without making any mechanical connection to the shaft.
CHAPTER II
REVIEW OF THE LITERATURE

The design and construction of a useful torque-speed meter at high rotational speed involves consideration of several important factors.

At low speeds, strain gage torque meters and other types with sliprings work satisfactorily.\(^1\) Above 20,000 R.P.M., noise and rapid wear of the brushes makes sliprings undesirable.\(^2\) Magnetic types are sensitive to axial or radial displacements of the torque shaft.\(^1\) Electric dynamometers, which absorb power, are also unsuitable for certain high-speed measurements, such as some phases of turbine-pump research. An optical torque meter which has been developed for this application is not compact in size. When space problem is important, it is unsuitable.\(^1\)

A remote-reading torque meter and speed meter can be developed by use of the photoelectric pick-off system as the original idea of Prof. George McPherson, (University of Missouri at Rolla). This device is compact and more precise in the measurement of speed and torque. By the use of this system, problems of axial drift or "end play" of a shaft for measuring the torque can be solved. This method also allows limited radial displacement of the shaft.

\(^1\)Superscripts refer to literature references listed in the Bibliography.
CHAPTER III
PRESENTATION OF BACKGROUND MATERIAL

The torque and speed-measuring device developed for this thesis consists of a torque tube, aperture disc assembly, optical system and electronic circuitry. The electronic circuit converts the output of photoelectric light sensors into torque and speed data. This chapter presents the theoretical background necessary for the design of the component parts.

A. Torsion in a Circular Shaft

To establish a relation between the internal torque and the stresses it sets up in members with circular and tubular cross sections, it is necessary to make the following assumptions:

(1) A plane section of material perpendicular to the axis of a circular member remains plane after the torques are applied.

(2) In a circular member subjected to torque, shearing strains vary linearly from the central axis.

(3) Shearing stress is proportional to shearing strain.

Fig. 3.1 Variation of Stress in a Circular Member
In the elastic case, on the basis of the above assumptions, since stress is proportional to strain, and the latter varies linearly from the center, stresses vary linearly from the central axis of a circular member. The stresses induced by the assumed distortions are shearing stresses and lie in the plane parallel to the section taken normal to the axis of a rod. The variation of shearing stress is illustrated in Fig. 3.1. The maximum shearing stress occurs at points most remote from the center O and is designated $\tau_{\text{max}}$. These points, such as point A in Fig. 3.1, lie at the periphery of a section at a distance $C$ from the center. While, by virtue of a linear stress variation, at any arbitrary point at a distance $r$ from 0, the shearing stress is $\frac{r}{C} \tau_{\text{max}}$. Once the stress distribution at a section is established, the resistance to torque in terms of stress can be expressed. The resistance to the torque developed must be equivalent to the internal torque

$$\int \left[ \frac{r}{C} \tau_{\text{max}} \right] \text{d}A \frac{r}{C} = \tau$$

(stress) (area)

(force) (arm)

(torque)

Where $C$ is the radius of the circular member.

$r$ is a radial distance between an arbitrary point B and O.

$\tau_{\text{max}}$, the maximum shearing stress occurs at the periphery of a cross section of a circular member.
T is resisting torque.

The integral sums up all torques developed on the cut by infinitesimal forces acting at a distance \( r \) from a member's axis. At any given section \( \tau_{\text{max}} \) and \( C \) are constant hence the above relation may be written as

\[
\tau_{\text{max}} \frac{C}{J} \int_{\text{area}} r^2 \, dA = T \quad (3-2)
\]

However, \( \int_{\text{area}} r^2 \, dA \), the polar moment of inertia of cross-sectional area, is also constant for a particular cross-sectional area, which will be designated by \( J \). The polar moment of inertia of circular cross-sectional area is \( \pi d^4 / 32 \) where \( d \) is diameter of solid circular shaft. Therefore torsion formula is

\[
\tau_{\text{max}} = \frac{TC}{J} \quad (3-3)
\]

Fig. 3.2 An Element From Solid Shaft

Consider an element from solid shaft when torque is applied. In the element shown, a line or "fiber" such as AB initially is parallel to the axis of the shaft. After torque is applied, it assumes a new position AD. At the
same time, by virtue of Assumption 2, radius OB remains straight and rotates through a small angle $d\phi$ to the new position OD. Denoting the small angle DAB by $\gamma_{\text{max}}$, from geometry:

$$\text{arc } BD = \gamma_{\text{max}} \, dz \text{ or } \text{arc } BD = d\phi \, C$$

where both angles are small and are measured in radians. Hence

$$\gamma_{\text{max}} \, dz = d\phi \, C \quad (3-4)$$

$\gamma_{\text{max}}$ applies only in the zone of an infinitesimal "tube" of a uniform maximum shearing stress $\tau_{\text{max}}$. In the elastic range, according to Hooke's law, this angle is proportional to $\tau_{\text{max}}$; i.e. $\gamma_{\text{max}} = \frac{\tau_{\text{max}}}{G}$, where $G$ is modulus of rigidity. Moreover by Equation 3.3

$$\tau_{\text{max}} = \frac{T C}{J} \quad (3-5)$$

hence

$$\gamma_{\text{max}} = \frac{T C}{J G} \quad (3-6)$$

Whence upon substituting the latter expression into the Equation 3-4 and cancelling out $C$:

$$d\phi = \frac{T d z}{J G} \quad (3-7)$$

Assuming $T$, $J$, $G$ are constant, for particular shaft, along the $z$ axis.
\[ \phi = \int_{A}^{B} d\phi = \int_{A}^{B} \frac{Tdz}{JG} \]  

(3-8)

hence

\[ \phi = \frac{Tz}{JG} \]  

(3-9)

This formula is useful in the design of a torque tube.

**B. Differential Amplifier**

Measurement of relative displacement of two ends of the torque tube, due to torque transmitted by the torque transmitting system, can be detected by means of a differential amplifier.

![Differential Amplifier Diagram](image)

**Fig. 3.3 Differential Amplifier**

Two transistors are necessary to perform the subtraction operation. If they are matched, the various temperature-dependent signals tend to cancel, as can be seen. For
example, by symmetry, it is clear that similar signals at both inputs will cause similar signals at the collectors and so the output signal will be zero. Thus if there is any change in the voltage $V_{be}$ of both transistors, there will be no output.

It is desirable to make the change of current in the transistors as small as possible so that variation of alpha (for the common-base configuration $\alpha$ is defined as, $\alpha = \frac{\Delta i_C}{\Delta i_E} |V_{CB} = \text{constant}$) with temperature will have small effect. On the other hand, it is desirable to make the quiescent current large compared with the signal current because this makes for a minimum of unbalance of differential amplifier when signals are present. This latter effect is very important one. Consider for example, the case where everything in the amplifier is ideally balanced. Then, when there are ambient temperature changes and both transistors change by the same temperature, all the temperature effects will balance out. But if there is a signal present, then one of the transistors will carry a different current and voltage. The power dissipated in it will be different from the other. Thus uneven heating takes place and amplifier will become unbalanced because of the unequal temperatures of the transistors. Nothing can be done about such heating except to make it small compared with the quiescent dissipation.

An a-c equivalent circuit of the differential amplifier is shown in Figure 3-4.
In analysis, $r_c$ is assumed to be much larger than $R_L$. The transistor parameter $r_b$ is lumped with generator resistance $R_g$ to form a composite which is termed $R_s$.

Writing the Kirchhoff equation for the a.c. equivalent circuit of the differential amplifier:

$$e_1 = i_{b1}R_s + i_{e1}r_e + ixR_x \quad (3-10)$$
$$e_2 = i_{b2}R_s + i_{e2}r_e + ixR_x \quad (3-11)$$
$$i_x = i_{e1} + i_{e2} \quad (3-12)$$
$$(\beta + 1) \ i_{b1} = i_{e1} \ \text{and} \ \ (\beta + 1) \ i_{b2} = i_{e2} \quad (3-13)$$

Substituting Equation 3-13 in Equation 3-12

$$i_x = (\beta + 1) \ i_{b1} + (\beta + 1) \ i_{b2} \quad (3-14)$$

Substituting values of $i_x$, $i_{e1}$ and $i_{e2}$ in equation 3-10 and
3-11 and simplifying, we will have

\[ e_1 = i_{b1} [R_s + (p+1) r_e + (p+1) R_x] + i_{b2} [(p+1) R_x] \]

(3-15)

\[ e_2 = i_{b1} [(p+1) R_x] + i_{b2} [R_s + (p+1) r_e + (p+1) R_x] \]

(3-16)

Solving for \( i_{b2} \) from Equation 3-15 and 3-16

\[ i_{b2} = \frac{e_2 [R_s + (p+1) r_e + (p+1) R_x] - [(p+1) R_x] e_1}{[R_s + (p+1) r_e + (p+1) R_x]^2 - [(p+1) R_x]^2} \]

(3-17)

But \( e_o = -\frac{P R_L i_{b2}}{} \)

\[ e_o = \frac{-P R_L}{[e_2 [R_s + (p+1) r_e + (p+1) R_x] - [(p+1) R_x] e_1]} \]

\[ [R_s + (p+1) r_e + (p+1) R_x]^2 - [(p+1) R_x]^2 \]

(3-18)

By imposing following restrictions

\[ R_x \gg r_e \quad \text{and} \quad (p + 1) R_x \gg R_s \]

\[ e_o = \frac{P R_L (e_1 - e_2) (p+1) R_x}{2R_s (p+1) R_x} \]

\[ = \frac{P R_L}{2R_s} (e_1 - e_2) \]

(3-19)

For perfect subtraction operation it is necessary that circuit must satisfy the following restrictions.

1. \( r_C \gg R_L \)
2. \( R_x \gg r_e \)
3. \( (p + 1) R_x \gg R_s \)

(3-19a)
C. High Input Impedance Amplifier

To have a signal to measure the speed of rotating system, it is necessary to have high input impedance amplifier to isolate the differential amplifier from the frequency-measuring circuit.

A high input impedance amplifier can be obtained from the emitter follower connection or from the common-emitter connection with large unbypassed emitter resistance. The latter method is widely accepted. It must be borne in mind that the input impedance of a particular stage is reduced by base-bias schemes. Fixed-biasing, single battery biasing, emitter-biasing and self-biasing tends to reduce input impedance by paralleling the transistor input with resistive elements. For maximum input impedance, emitter-biasing with transformer coupling or cut-off biasing present the most satisfactory circuitry.

For the transistor, high input impedance always rules out high power gain. The a-c equivalent circuit of a transistor for low frequency analysis, in terms of the hybrid or h parameters, will be considered here.

Analysis for high input impedance, voltage gain and output impedance will be performed, using a self-biased amplifier.
Consider the a-c equivalent circuit for common-emitter configuration with source and load terminations, in terms of common-base parameters.

Fig. 3.5 High Input-Impedance Amplifier.

Fig. 3.6 A-C Equivalent Circuit for the Common-Emitter Configuration with Source and Load Terminations.
$R_E$ and $Y_f$ are respectively in series and parallel with $h_{ib}$ and $h_{ob}$. Simplifying the above circuit: ($\frac{h_{fb}}{1+h_{fb}} i_b$ has been substituted for $i_e$).

![Simplified A-C Equivalent Circuit](image)

Fig. 3.7 Simplified A-C Equivalent Circuit

Writing the Kirchhoff equations:

$$V_i = i_1 \left[ h_{ib} + R_E - \frac{h_{fb} h_{rb}}{h_{ob} + Y_f} \right] + i_2 \left[ h_{ib} + R_E - \frac{(1+h_{fb}) h_{rb}}{h_{ob} + Y_f} \right]$$

$$0 = i_1 \left[ h_{ib} + R_E + \frac{(1-h_{rb}) h_{fb}}{h_{ob} + Y_f} \right] + i_2 \left[ h_{ib} + R_E + R_L \right]$$

$$+ \frac{(1-h_{rb})(1+h_{fb})}{(h_{ob} + Y_f)}$$

(3-20)

(3-21)

Input resistance is defined as

$$R_i = \left| \frac{V_i}{I_1} \right|$$

(3-22)

and voltage gain

$$A_V = \left| \frac{V_o}{V_i} \right| = \left| \frac{i_2 R_L}{V_i} \right|$$

(3-23)

Solving for input resistance and voltage gain from Equation 3-20 and Equation 3-21:
By using a series RC circuit, it is possible to have an output approximately proportional to the derivative of the input. These conditions may be determined by examination of circuit differential equation.

\[ e_2(t) = R \, i(t) = e_1(t) - \frac{1}{C} \int i(t) \, dt \]  

(3-26)

Maintaining the output voltage small with respect to input

\[ e_1(t) \approx \frac{1}{C} \int i(t) \, dt \]  

(3-27)

\[ i(t) \approx C \frac{de_1(t)}{dt} \]  

(3-28)
\[ e_2(t) = RC \frac{de_1(t)}{dt} \] (3-29)

The major portion of the circuit voltage drop is developed across capacitor only when the time constant is small compared with time range of interest. With sufficiently small time constant, the output waveshape is reasonably close, except at discontinuities, to the one found by assuming a perfect differentiator. A differentiator is necessary in the system because there will be different output waveform of the light sensor at no load and full load. To measure the speed it is necessary to have a sharp triggering pulse for the multivibrator at any torque.

E. **Monostable Multivibrator.**

On being triggered, a monostable multivibrator switches to its unstable state, where it remains for predetermined time before returning to its original stable state. This makes the monostable multivibrator useful in standardizing pulses of random widths. The introduction of a single energy storage element in the regenerative transmission path creates a circuit having one stable and one quasistable state. The circuit employed is shown in Figure 3-9.

The quasi-stable circuit state, \( T_2 \) cut-off, is contingent on the charge in the coupling capacitor maintaining \( e_{b2} < 0 \). However, a discharge path exists, and regardless of initial conditions, \( C \) must decay, with \( e_{b2} \) subsequently reaching zero. At this point \( T_2 \) turns back on.
Regeneration turns $T_1$ off, and multivibrator is back in its one "mono" stable state.

Analysis of this circuit will proceed on the assumption that it is designed for the maximum possible collector voltage variation, i.e., both transistors driven between saturation and cut-off. Assume initially that $T_1$ in cut-off region, and $T_2$ is saturated. The base current of transistor $T_2$ is

$$i_{b2} = \frac{E_{bb}}{R}$$  \hspace{1cm} (3-30)

The collector-emitter voltage of an ideal saturated transistor is zero. Substitution of this limit:

$$e_{ce2} = 0 = E_{bb} - \beta_{ib2}R_c$$  \hspace{1cm} (3-31)

To keep transistor $T_2$ in the saturation region

$$i_{b2} \geq \frac{E_{bb}}{\beta R_c}$$
substituting \( i_{b2} \) from Equation 3-30

\[
\frac{E_{bb}}{R} = \frac{E_{bb}}{\beta R_C}
\]  
(3-32)

\[
\therefore R \leq \beta R_C
\]  
(3-32a)

A positive trigger pulse injected at the base of \( T_1 \) turns this transistor on, and the change in its collector voltage is immediately coupled through \( C \) to the base of \( T_2 \), turning it off. The circuit has now entered its quasistable region, and the new models needed to define operation are those given in Fig. 3-10 as shown below.

We can determine the time elapsed before the circuit can return to its stable state from Fig. 3.10a. As the right-hand side of \( C \) charges from its original value of \(-E_{bb}\) towards \( E_{bb} \), the equation of the base voltage of \( T_2 \)
becomes
\[ e_{b2}(t) = E_{bb} - 2E_{bb}e^{-t/\tau} \]
where \( \tau = RC \)  

At \( t = t_1 \), \( e_{b2} = 0 \) and \( T_2 \) again conducts. Substitution of the boundary value into the equation defining \( e_{b2}(t) \) results in
\[ t_1 = RC \ln 2 \]  \hspace{1cm} (3-34)

To guarantee the saturation of \( T_1 \) during the unstable period, the following relationship must be satisfied
\[ i_{b1} = \frac{E_{bb}}{R_C + R_1} \geq \frac{E_{bb}}{R_C} \]  \hspace{1cm} (3-35)

After the circuit reswitches and recovery begins, we must consider the new problem posed shown in Fig. 3.11,

![Fig. 3.11 Recovery Circuit](image)

where \( C \) recharges toward \( E_{bb} \) from its initial value of zero. The collector of \( T_1 \) recovers toward its stable state, also \( E_{bb} \), with recovery time constant \( T_2 = R_C C \).

Within four time constants, recovery is virtually complete. Since the recovery time should be small compared
with the output pulse width,

\[ R_C \ll R \]  \hspace{1cm} (3-35a)

Output is taken at the collector of \( T_2 \) because this point is isolated from the single RC timing circuit. External loading, introduced by the coupling to the next stage, will not affect the pulse duration.
A. General

The photoelectric transient torquemeter and dynamometer was designed to measure the torque from 0 foot-pounds to 20 foot-pounds and speed from 60 rpm to 3600 rpm.

Two mechanical mountings (Fig. 4.2) are placed at the two ends of the torque tube to hold two photographic plates close together. Each plate has two concentric rings of rectangular transparent areas, produced photographically. The two photographic plates are designed and positioned in such a way (discussed on the page 26) that for increasing torque in a given direction, the transparent area (through which light is passing) in the one set of apertures enlarges, while the transparent area of apertures in the other set closes down. Twice the effective change in area is obtained by using this scheme, and the direction of the torque transmitted by the torque transmitting system is detected. Two beams from stationary light sources are directed parallel to the torque tube and focused on the light sensors through the apertures. The change in transparent area of the two sets of the apertures is detected as changes in the outputs of a light sensors. An effective change in area, in terms of an electrical quantity, is obtained by feeding the output of two light sensors to the input terminals of the differential amplifier. The output is obtained between the
Fig. 4.1 Block Diagram of Photoelectric-Transient Torque And Speed Meter
the two collector terminals of differential amplifier. (Fig. 4.1)

A light beam reaching the light sensors is alternately passed and obstructed by the transparent and non-transparent areas on the photographic plates. When the torque tube is rotating, the frequency of the light fluctuations is a measure of the speed.

A signal from the one light sensor is fed to a high-input-impedance amplifier. The high-input-impedance amplifier is used to avoid the unbalance of the differential amplifier and loading of the light sensor. Output of the high input impedance amplifier drives a differentiator and clipping circuit. The output of the differentiator and clipping circuit is a series of positive pulses clipped at +5 volts. These pulses are the trigger input for the monostable multivibrator. The monostable multivibrator is used as a pulse generator producing output pulses with standard amplitude width. The d-c or average value of the output pulses of the monostable multivibrator is proportional to the speed of the torque tube.

B. Mechanical Mounting for Holding the Photographic Plate on the Torque Tube

The mechanical mountings were constructed by the Mechanical Engineering Department, at University of Missouri at Rolla. Aluminum was used to construct the mountings (Fig. 4.2). They were made symmetrical to facilitate dynamic balancing.
Fig. 4.2 Cross Section of a Mechanical Mounting to Hold The Photographic Plate.
Fig. 4.2a Picture Showing The Mechanical Assembly

1 Mechanical Mounting  b,b Light Source  2 Ground
aa Light Sensors  3, 3 To Light Sensors  4, 4 To 2.5 Volt A.C. Supply
C. **Design of Photographic Plate**

Two sets of sixty, equally-spaced black rectangles were drawn on drawing paper at 6° intervals, to form two concentric circles. The black rectangles are 3° wide and 0.15" high, radially. Those lying on the inner circumference are advanced in a clockwise direction by 1.5° (Fig. 4.4). Heights and widths of all the black rectangles are identical.

A photograph of the drawing (Fig. 4.4) was made. On negative film, the black rectangles will appear as transparent regions, while the white area will appear as a non-transparent region. Two such plates were made. When attached to the torque tube, the one plate was reversed with respect to the other. Thus the apertures on the inner circumference will be displaced in the counter-clockwise direction. (One can realize this by looking at Fig. 4.4 from the back side). The initial positions of two photographic plates are adjusted in such a way that the transparent portions of the apertures, lying on both the inner and outer circumferences, are same, as shown in Fig. 4.3C.

![Fig. 4.3 (a) Photographic Plate: A](image1.png)  ![Fig. 4.3 (b) B](image2.png)  ![Fig. 4.3 (c) A and B](image3.png)
Fig. 4-4. Drawing Showing Two Sets of Sixty, Equally-Spaced Black Rectangles.
Fig. 4.4a Close View Of the Photographic Plate.
Fig. 4.3 a and b show the apertures on two plates. The cross-hatched area represents non-transparent area and also distinguishes the two plates in Fig. 4.3 c. Both the plates are placed together as shown in Fig. 4.3 c in such a way that all transparent regions of the apertures are the same.

If plate B moves clockwise with respect to the plate A, the transparent area on the outer circumference will increase while the area on the inner circumference will decrease.

This arrangement also detects the direction of the torque because change in transparent area of the apertures lying on the outer circumference and inner circumference will decrease or increase depending upon the direction of the torque.

D. Selection of Light Sensor

A Texas Instrument product, LS 400, was selected as a light sensitive element. This light sensor works as a photoresistor. When a beam of light falls on a light sensor, the resistance of the light sensor changes from infinity to $38 \Omega$ at low frequencies.\textsuperscript{13} It has a flat frequency response from 0 c.p.s. to 7 k.c.p.s. Rise time is 1.5 msec., which is very small.

E. Selection of Light Source

G. E., optically-refined, high output, lens end,
subminiature lamps (No. 253x) were used as light sources. Average life of this lamp is 10,000 hours. Minimum illumination over 1/16" spot is 750 foot-candles, which is what was required by the light sensors. The light beam of the 253x lamp falls within a 5/16" x 3/8" rectangle. The lamp is rated at 0.35 amps at 2.5V, a-c or d-c.

F. Design of Torque Tube

The torque tube was made of aluminum alloy 2024 T3 for the following principal reasons:

1. The use of aluminum results in a considerable reduction in weight with no loss of strength.
2. Aluminum structures require a minimum of maintenance.
3. Aluminum is economical to use because of cost per pound is advantageous.
4. Easy to work with.
5. A low modulus of elasticity gives aluminum extra ability to resist impact without deforming permanently.

Composition of the aluminum alloy is 4.5 per cent of manganese, 1.5 per cent of magnesium, and 93.4 per cent of aluminum. Minimum mechanical properties of this alloy are as follows at room temperature:

<table>
<thead>
<tr>
<th></th>
<th>Ultimate Strength</th>
<th>Yield Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension</td>
<td>64 Kips per sq. in</td>
<td>42 Kips per sq. in</td>
</tr>
<tr>
<td>Shear</td>
<td>39 Kips per sq. in</td>
<td>24 Kips per sq. in</td>
</tr>
<tr>
<td>Shear Modulus of rigidity</td>
<td>$4 \times 10^6$ lbs. per sq. in</td>
<td></td>
</tr>
</tbody>
</table>
Data given:

1. Maximum torque transmitted 240 in.-lbs. (Design specification)

2. Deflection between two reference points 0.3° for 240 in.-lbs. torque.

3. Internal diameter of the torque tube, \( d_2 = 0.806" \) (Commercially available tube size.)

4. Length of the torque tube 8"

5. Factor of safety greater than 5.

Design of torque tube to meet the above requirements:

Using the torsion formula (Equation 3.9)

\[
J = \frac{TL}{2G} = \frac{240 \times 8}{0.0053 \times 4 \times 10^6} \text{ in.}^4
\]

\[
= 0.0906 \text{ in.}^4
\]

Now,

\[
J = \frac{\pi}{2} (R_1^4 - R_2^4)
\]

Substituting for \( J \) and \( R_2 \)

\[
0.0906 = \frac{\pi}{2} (R_1^4 - 0.403^4)
\]

Solving the Equation for \( R_1 \)

\[
R_1 = 0.539 \text{ in.}
\]

Therefore the outer diameter of torque tube is \( d_1 = 1.078 \text{ in.} \). Approximate ultimate torque, in.-Kips is given
where \( F_{Su} \) is the ultimate shear strength Kips per sq. in.

\[
T_u = \frac{2 \left( R_1^3 - R_2^3 \right) F_{Su}}{3}
\]

\[
= \frac{2 \left( 0.54^3 - 0.403^3 \right)}{3} \times 39
\]

\[
= 7.48 \text{ in} - \text{Kips}
\]

Factor of safety\(^6\) = \text{approximate ultimate torque} / \text{allowable torque transmitted}

\[
= \frac{7.48 \text{ Kips Per Sq. in.}}{0.24 \text{ Kips Per Sq. in.}}
\]

\[
= 31.2
\]

G. Design of Differential Amplifier

Selection of the transistor: The General Electric 2N3391A is an NPN silicon planar passivated device intended for low noise pre-amplifier applications. The planar

![Differential Amplifier Diagram](image-url)

**Fig. 4.5 Differential Amplifier**
passivated construction assures excellent device stability and life. Therefore, the above transistor with low noise and high gain was used in the design of the differential amplifier.

If the parameters of the two transistors are exactly alike and if the external base circuits are also alike, then there is a perfect balance.

It is then possible to separate the emitters and place a resistance $2R_x$ in each emitter, as far as d-c bias is concerned. A potentiometer is used in the emitter circuit of the differential amplifier for balancing.

![D-C Equivalent Circuit of One Transistor With Emitter Resistance Separated](image)

The voltage required at $V_B$ is 6 volts so that the output of light sensor can be connected directly to the base without using the power supply for biasing the light.
sensors. The assumed operating temperature for the differential amplifier is 25°C.

It is assumed that Ecc = 25V and RL = 4.7K. From the electrical specifications for the transistor, change in ICB0 vs. temperature is very small. So temperature effect is not considered in the design of differential amplifier.

Only voltage amplification is of interest, so the operating range of the collector current is limited by selecting large values of RL and Rx. Due to the low change of collector current, heating effect at junction is limited.

Neglecting Vce at saturation,

\[ I_c (\text{saturation current}) = \frac{Ecc}{R_L + 2R_X + \frac{R_p}{2}} \]  

(4.1)

It is assumed that Rp = .2K and Rx = 1.2K. A large value of Rx is chosen to obtain an stability close to unity. 

\[ I_c (\text{sat.}) = 3.48 \text{ mili-amps} \]

Quiescent collector current was chosen at 2.1 miliamps. This will produce a voltage drop of 10V from collector to emitter. Vce = 10V is chosen because the data of the transistor were given at this particular Vce. At quiescent collector current, the base current will be

\[ I_{BQ} = \frac{I_{CO}}{h_{FE}} \]

\[ = \frac{2.1 \times 10^{-3}}{290} \]

(4.2)

\[ = 7.25 \text{ micro-amps.} \]
The quiescent emitter current is
\[ I_{EQ} = I_{CQ} + I_{BQ} \]
\[ = (2.1 \times 10^{-3} + 0.00725 \times 10^{-3}) \text{ amps.} \]  \( (4.3) \)
\[ = 2.10725 \times 10^{-3} \text{ amps.} \]

It is assumed that the emitter cut-off current \( I_{CBO} \) is negligible in the operating range of temperature.

Voltage between emitter to ground,
\[ V_E = \left[ \frac{R_2}{2} + 2 R_X \right] I_{EQ} \]
\[ = \left[ 0.1K + 2 \times 3.2K \right] \times 2.10725 \times 10^{-3} \text{ volts} \]
\[ = 5.3 \text{ volts} \]  \( (4.5) \)

Normally, the voltage drop between base to emitter is approximately 0.7 volts. Therefore,
\[ V_B = (5.3 + .7) \text{ volts} \]
\[ = 6 \text{ volts} \]  \( (4.6) \)

Current flowing through \( R_2 \) assuming \( R_2 = 1.2K \)
\[ I_2 = \frac{6}{1.2 \times 10^3} \text{ amps} \]
\[ = 5 \text{ miliamps} \]  \( (4.7) \)

Current flowing through resistance \( R_1 \) is \( I_2 \) plus base current flowing in the transistor.
Therefore

\[ R_1 = \frac{E_{cc} - V_B}{I_2 + I_B} \]  \hspace{1cm} (4-8)

\[ = \frac{25 - 6}{(5 + .00725) \times 10^{-3}} \]

\[ = 3.78 \, k \]

3.5K is available as a standard value of resistance.

Stability:

Stability factor \( S \) can be defined as the rate of change of collector current with respect to the reverse saturation current or

\[ S = \frac{dI_C}{dI_{CO}} \]

The smaller the value of \( S \), the less likely the circuit is to exhibit thermal runaway.

The stability factor of one side of the differential amplifier will be

\[ S = \frac{R_P}{2} \left[ \frac{2 + 2R_X}{R_1 + R_2} \right] \left( R_1 + R_2 \right) + R_1R_2 \]

\[ \frac{[R_P - 2R_X]}{2} \left( R_1 + R_2 \right) + (1-\alpha) R_1R_2 \]  \hspace{1cm} (4.9)

\[ = \frac{(2.5K \times 4.7K) + 3.5K \times 1.2K}{(2.5K \times 4.7K) + .003 \times 3.5K \times 1.2K} \]

\[ = 1.352 \, \text{M.a.} / \text{M.a.} \]
Corrected, common emitter configuration $h$ parameters, from the electrical characteristics of the 2N3391A at $I_C = 2.1$ m.a and $V_{ce} = 10V$ are

1. $h_{ie} = 0.08 \times 60 \times 10^3 = 4.8 \times 10^3$ ohms
2. $h_{re} = 0.09 \times 4.1 \times 10^{-3} = 3.69 \times 10^{-4}$
3. $h_{oe} = 3.5 \times 14 \times 10^{-6} = 49 \times 10^6$ mhos
4. $h_{fe} = 1.7 \times 200 = 340$

It is necessary to have the parameters in terms of T-equivalent circuit to check the conditions for perfect subtraction operation, performed by the differential amplifier.

![Fig. 4.7 Common Emitter Configuration In Terms Of $h$ parameters](image)

![Fig. 4.8 The Grounded Emitter T Equivalent Circuit From the Characteristics of the 2N3391A Transistor](image)

Conversions are shown below:
\[ r_c = \frac{1}{h_{oe}} = \frac{1}{47 \times 10^{-6}} = 20.4k \]  
(4-10)

\[ r_b = h_{ie} - \frac{h_{re}}{h_{oe}} (1+h_{fe}) = 4.8 \times 10^3 - \frac{3.69 \times 10}{49 \times 10} \times 0.003 = 2230 \Omega \]  
(4.11)

\[ r_e = \frac{h_{re}}{h_{oe}} = \frac{3.69 \times 10}{47 \times 10^{-6}} = 7.55 \Omega \]  
(4.12)

Checking the conditions for perfect subtraction operation by the differential amplifier (using Equation 3.19a):

1. \( r_c \gg R_L \)
   
   \[ 20.4K \gg 4.7K \]
   
   \( r_c \) is 4.35 times greater than \( R_L \)

2. \( R_X \gg r_e + \frac{R_p}{2} \)
   
   \[ 1.2K \gg 7.55 \Omega + 0.1K \]

3. \( (\beta + 1) R_X \geq R_S \)
   
   \[ 341 \times 1.2K \geq 3.125K \]

All the conditions are satisfied up to limited extent. Large value of \( R_L \) was chosen in order to acquire high gain.

The low value of the transistor parameter \( r_c \), relative to \( R_L \), will cause a negative feedback, and the gain will be reduced. In the Appendix, a circuit analysis was made considering the transistor parameter \( r_c \) in the calculation of the gain.

Gain of the differential amplifier can be calculated by using Equation A-11. Before calculating the gain, it is necessary to simplify the a-c equivalent circuit of the differential amplifier (using Thevenin's and Norton's Theorems). The simplified circuit is shown in Fig. 4.9.
Referring to Equation A-11, differential voltage gain will be

\[
G_d = \frac{e_o}{e_1 - e_2} = \frac{R_L \beta r_C}{(r_E + r_X + r_E + r_C + r_L) - (r_C + R_L) [r_C + R_L + \beta r_C]}
\]

\[
x \left[ \frac{R_1 // R_2 // R_g}{R_g} \right]
\]

where \( R_g = 600 \)

\[
= \left[ \frac{-1.2K}{1.2K + .108K + 1.2K + 1.2K + .108K + 21.4K + 4.7K} - (21.4K + 4.7K) \right]
\]

\[
x \left[ \frac{1}{21.4K + 4.7K + 340 \times 21.4K} \right] \times \left[ \frac{1.2K // 3.5K // .6K}{.6K} \right]
\]

\[
= 13
\]
H. Design of High Input Impedance Amplifier

As described in Chapter 3, a high input impedance amplifier can be obtained from the common-emitter configuration with large unbypassed emitter resistance.

From the transistor specifications, corrected common emitter $h$ parameters at $I_{CQ} = 2.5$ mA are:

$h_{ie} = 60 \times 10^3 \times 0.08 = 4.8 \times 10^3$ ohms

$h_{oe} = 14 \times 10^{-6} \times 3.4 = 47.6 \times 10^{-6}$ mhos

$h_{re} = 4.1 \times 10^{-3} \times 0.09 = 3.69 \times 10^{-4}$

$h_{fe} = 200 \times 1.65 = 330$

Conversion from common emitter $h$ parameters to common base parameters gives:

$h_{fb} = \frac{-h_{fe}}{1 + h_{fe}} = -0.9975$ \hspace{1cm} (4.13)

$h_{ob} = \frac{h_{oe}}{1 + h_{fe}} = 0.144 \times 10^{-6}$ mhos \hspace{1cm} (4.15)
\[ h_{ib} = \frac{h_{ie}}{1 + h_{fe}} = 14.5 \text{ ohms} \quad (4.16) \]

\[ h_{rb} = \frac{h_{ie} h_{oe}}{1 + h_{fe}} - h_{re} = 3.21 \times 10^{-4} \quad (4.17) \]

A schematic diagram of the amplifier is shown in Fig. 4.10. It is assumed that load resistance \( R_L = 4.7 \text{ k} \), and \( V_{ce} = 10 \text{ volt} \). \( I_{CBO} \) is very small in comparison with \( I_{BO} \), so it is neglected.

Voltage drop across \( R_L \) is

\[ V_1 = 4.7 \times 10^3 \times 2.5 \times 10^{-3} = 11.8 \text{ Volts} \]

Therefore voltage drop across emitter resistance will be

\[ V_E = E_{bb} - V_1 - V_{CE} \quad (4.18) \]

\[ = 25 - 11.8 = 3.2 \text{V} \]

Assuming base current is very small in comparison with collector current,

\[ R_E = \frac{V_E}{I_{CQ}} = \frac{3.2}{2.5 \times 10^{-3}} = 1.275 \text{K} \quad (4.19) \]

Base current at quiescent point:

\[ I_{BO} = \frac{I_{CQ}}{h_{FE}} \quad (4.20) \]

\[ = \frac{2.5 \times 10^{-3}}{290} \text{ amps} \]

\[ = 8.65 \mu A. \]
Assuming that $V_{BE}$ is negligible,

$$R_f = \frac{V_{ce}}{I_{BQ}}$$

(4.21)

$$= \frac{10}{8.65} \times 10^6 \text{ ohms}$$

$$= 1.15 \text{ Megohms}$$

Fig. 4-10. High Input Impedance Amplifier


$$R_i = \frac{(h_{ib} + R_E) [1 + R_L (h_{ob} + Y_f)] - h_{rb} h_{fb} R_L}{(h_{ib} + R_E + R_L)(h_{ob} + Y_f) + (1 + h_{fb})(1-h_{rb})}$$

$$= \frac{(14.5 + 1.2 \times 10^3)[1 + 4.7 \times 10^3 (0.144 \times 10^{-6} + 1 \times 10^{-6})]}{(14.5 + 1.2 \times 10^3 + 4.7 \times 10^3)(0.144 \times 10^{-6})}$$

$$+ \frac{[3.21 \times 10^4 \times 4.7 \times 10^3 \times 9975]}{+ (1 - 0.9975)(1-3.21 \times 10^{-4})}$$

$$= 132.1 \times 10^3 \Omega.$$

Since the input impedance of the differential amplifier
is approximately .89K, an input impedance of 132.1 K will not load the differential amplifier.

Voltage gain will be (using Equation 3.25):

\[
A_v = \frac{R_L [(h_{ib} + R_E)(h_{ob} + Y_f) + (1 + h_{rb}) h_{fb}]}{(h_{ib} + R_E)[1 + R_L (h_{ob} + Y_f)] - h_{rb} h_{fb} R_1} \\
= \frac{4.7K[(14.5 + 1.2K)(.144 \times 10^{-6})]-(1-3.21\times 10^{-4})}{(14.5+1.2\times 10^3)[1+4.7\times 10^3(.144\times 10^{-6}) +3.21\times 10^4]} \\
= \frac{0.9975}{0.9975 \times 4.7K} \\
= 3.84
\]

I. Design Of Differentiator Circuit

Since there are 60 apertures passing the light sensor per revolution, the number of pulses/second is equal to R.P.M. The differentiator circuit is designed to trigger the monostable multivibrator up to 3600 c.p.s. Approximately, minimum pulse width up to 3600 c.p.s. will be

\[
t_1 = \frac{1}{3600 \times 4} = .0695 \text{ milisecond.}
\]

The time constant of the differentiator should be very
small in comparison with width of the input pulse. Let $t_1 = 25 \tau_1$ for good differentiation. R is taken to be 10K. The time constant of the differentiator circuit, $\tau_1 = RC$. Therefore,

$$C = \frac{0.0695 \times 10^{-3}}{25 \times 10 \times 10^3} = 0.2775 \times 10^{-9} \text{ farad}$$

A capacitor of $0.25 \times 10^{-9}$ farad was used.

To clip the negative component of the output of the differentiator, the circuit shown below is used. (Fig. 4.12)

![Clipping Circuit](image)

Fig. 4.12 Clipping Circuit

The resistance $R_1$ and Zener diode eliminate the negative pulses coming from the differentiation and clip the output trigger pulses at 5 volts.

When the output of a differentiator circuit (voltage across R) is a negative pulse, the Zener diode will be in the forward-bias condition. The equivalent circuit at that time, can be represented by Fig. 4.13, in which $r_f$ is forward resistance of Zener diode.

If $R_1 \gg r_f$, then voltage across the Zener diode will be approximately zero. So $R_1 = 4.7K$ was used, which is very large in comparison with $r_f$. 
The 5-volt zener diode also clips the positive output voltage at 5 volts.

![Equivalent Circuit of Clipping Circuit When Zener Diode Is In Forward-Bias Condition](image)

J. Design of the Monostable Multivibrator

The monostable multivibrator is used to generate standard pulses at the same frequency as the output of the light sensor. The 2N3391 NPN transistor is used in the design of the monostable multivibrator. (Refer to Fig. 4.14)

![Monostable Multivibrator](image)

To ensure that $T_2$ is to be saturated in the stable condition it must satisfy the condition 3.32a:

$$R \leq \frac{E_{bb}}{R_c}$$

It was assumed that $R_c = 1.5K$, $E_{bb} = 25V$ and $\beta$ of this
particular transistor is 200.

\[ R = 200 \times 1.5K \leq 300 \text{ K} \]

\[ R = 250 \text{ K} \]

To guarantee the saturation of \( T_1 \) during the unstable period, the following relationship must be satisfied (From Condition 3-35):

\[ R_c + R_1 \leq \beta R_c \]

\( R_1 \) was chosen to be 8.2K:

\[ 9.7K \leq 300 \text{ K} \]

To ensure that the recovery time is small compared with the output pulse width,

\[ R_c \leq R \]

(From Condition 3.35a)

\[ R_c = 1.5K \leq 250 \text{ K} \]

Since a maximum speed of 3600 R.P.M. was specified, the width of the output pulse of multivibrator was chosen to be \( t_1 = 0.173 \text{ msec} \). This will allow the speed to be measured up to 5800 R.P.M. Using Equation 3.34 to determine the width of pulses

\[ t_1 = RC \times \ln 2 \]

\[ 0.173 \times 10^{-3} = 250 \times 10^3 \times C \times 0.695 \]

\[ C = \frac{0.173 \times 10^{-3}}{250 \times 10^3 \times 0.695} = 0.001 \text{ Micro farads} \]

\( C_1 \) was also chosen to be 0.001 \text{ Micro farads}. 

Fig. 4.15 Complete Circuit Diagram Of Electronic Circuitry
K. Theoretical Calculations For Torque and Speed

A complete circuit diagram of electronic circuitry to measure the torque and speed is shown in Fig. 4.15. The capacitor $C_A$ is used to block d-c in order to avoid altering the original biasing of the stage.

The ranges of the voltmeter, (used to measure the torque at the two collector terminal of the differential amplifier) and the microammeter, (to measure the speed of rotating shaft) are chosen after the following calculations:

a. Torque:

When the torque of 20 foot-pounds is applied to torque tube, the deflection between the two ends of the torque tube will be $0.3^\circ$. An effective output at two collector terminals of the differential amplifier will be obtained for $0.6^\circ$ (as discussed in this chapter).

![Fig. 4.16 Output Between The Two Collector Terminals When Light Shines On Only One Light Sensor.]

When the light shines on any one of the light sensors, the output of the light sensor is such that one of the transistors of the differential amplifier will operate in the cut-off region while other will be in the saturation
region. Under these conditions, the maximum output between the collector terminals of the differential amplifier will be 19.6 volts.

The D-C, or average output voltage between the collector terminals of the differential amplifier will be

\[ V_{D-C} = \frac{19.6 \times 0.6 \times 60}{360} \text{ volt-degree} \]  

\[ = 1.96 \text{ volts} \]

1.96 volts will be available when 20 foot-pounds of torque is applied to the shaft. So a voltmeter having a range of 0-5 volt, was selected.

b. Speed:

The d-c output of the monostable multivibrator is linearly proportional to the speed. The output at the maximum specified speed of 3600 R.P.M. is calculated as follows. It is assumed that \( R_6 = 6.9K \) (See Figure 4.1). The average (d-c) output at 3600 R.P.M. will be

\[ V_{dc} = 3600 \left[ \frac{(R_1/R_6) \times E_{CC}}{(R_1/R_6) + R_C} \right] \times 0.173 \times 10^{-3} \]  

\[ = 11.1 \text{ volts}, \]

Where \( E_{CC} = 25 \text{ volts} \), and \( 0.173 \times 10^{-3} \) is the output pulse width, in seconds. Since there are 60 apertures passing the light sensor per revolutions, the number of pulses per second is equal to the R.P.M.
The current flowing through $R_6$ is, thus

$$I_B = \frac{V_{dc}}{R_6} = \frac{11.2}{6.9 \times 10^3} = 1.61 \times 10^{-3} \text{ amps}$$

The graphs between $I_B$ and the speed (Fig. 4.18) and the output between two collector terminals of differential amplifier vs. torque (Fig. 4.17) were plotted.
Fig. 4.17 The Graph Between Voltage Output Of Differential Amplifier And Torque
Fig. 4.18 Graph Between Output Of Multivibrator and Speed Of The Shaft
Fig. 4.19 Electrical Circuitry to Measure The Torque and Speed

1-1 To Light Sensors
2-2 To Voltmeter to Measure the Torque
3 To Power Supply (25 Volts)

4 To Micro Ameter To Measure the Speed
5 To Power Supply (25 Volts)
6 Potentiometer To Balance the Differential Ampli.
Fig. 4.20

Picture Showing the Relative Size of Mechanical Components, Photographic Plate and Mounting for Light Source and Light Sensors.
A. General

The results discussed are those from data acquired in the laboratory by the author. Theoretical results have been compared with the experimental results. Sources of error are discussed. During the experiment, the following assumptions were made:

(1) When the 253 x lamps are operated at constant voltage, light output falls with time, rapidly during the first 50 hours, more slowly thereafter. While when lamps are operated at constant current, light output rises with time, slowly at first, then accelerating to catastrophic destruction. In this experiment the lamps were operated at a constant 2.5 volts, 60 c.p.s., and light output was assumed to be constant.

(2) The two light sensors and the two light sources are identical.

(3) Transistors used in the differential amplifier are matched.

(4) Power supply gives constant output voltage.

B. Experimental Results Of The Differential Amplifier, The High Input Impedance Amplifier, And the Monostable Multivibrator.

1. Differential Amplifier.
Experimental results were observed on the oscilloscope and R.C.A. V.T.V.M.

<table>
<thead>
<tr>
<th></th>
<th>Theoretical Results</th>
<th>Experimental Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage between base to ground</td>
<td>6V</td>
<td>6.2V</td>
</tr>
<tr>
<td>Differential gain</td>
<td>13</td>
<td>13.7</td>
</tr>
<tr>
<td>Voltage Between Collector to emitter</td>
<td>10V</td>
<td>9.5V</td>
</tr>
<tr>
<td>Quiescent Collector Current</td>
<td>2.1 m.a.</td>
<td>2.122 m.a.</td>
</tr>
</tbody>
</table>

The experimental results are very close to the theoretical results. Slight deviation is largely due to the resistance and capacitance are used with 10 percentage tolerance. Assumptions were made in the design of differential amplifier that $I_B$ and $I_{CBO}$ are very small in comparison with collector current, because $h$ of the 2N3391 transistor is very high.

2. **High Input Impedance Amplifier.**

Input impedance of the amplifier is measured using the Z-angle meter at 400 c.p.s. The block diagram is shown in Fig. 5.1.
Capacitor $C_A$ is used for d-c isolation. Input impedance ($R'_i$) and phase angle were observed on the Z angle meter:

$$R'_i = 55 \, K$$

Phase angle = 0.31°

Since the impedance of the capacitor $C_A$ is very small at 400 c.p.s., the input impedance ($R'_i$) of the amplifier can be calculated by treating circuit as a parallel combination of 100K and input impedance of the amplifier, $R_i = 122.2K$.

The theoretical value, obtained by equation 4.22, was $132.1 \times 10^3 \, \Omega$. Experimental results and theoretical results are fairly close. Error is due to tolerance of the transistor parameters and resistances.

Gain of the amplifier was checked by a calibrated oscilloscope. It was 3.28, while the theoretical value was 3.84. Again deviation in the gain is due to transistor parameters, and tolerance of resistances.


Experimental results were observed on the oscilloscope.

Duration of the pulses was observed on the oscilloscope was .13 msec. while theoretical result for the duration of the pulse was .173 msec.

There is quite a difference between theoretical and
experimental results. This is due to the following reasons:

a. The transistor model is considered as ideal model in the analysis.
b. There is another discharging path for capacitor C in the circuit, i.e., through input circuit.
c. Resistances and capacitors used had 10% tolerance. This is main source of error.

C. Experimental Results Of Photoelectric Transient Torque Meter And Speed Meter.

A D.C. motor and D-C dynamometer were connected through the torquemeter as shown in Fig. 5.2. Speed of the motor was controlled by changing the field rehostat and the armature rehostat of the D-C motor. The torque was controlled by loading the D-C generator. Speed of the motor-generator set and torque transmitted by the D-C motor were known by the attached tachometer and dynamometer scale, respectively.

The photoelectric torquemeter and speed meter were calibrated by knowing the speed and torque transmitted, on the tachometer and dynamometer respectively. The torque output of the torquemeter was measured in terms of voltage, and the speed output in terms of micro-amps. The graphs are shown in Figure 5.3 and Figure 5.4.
Fig. 5.2 Calibration Of a Photoelectric Transient Torque and Speed Meter
Torque:

Observation Table 5.1

<table>
<thead>
<tr>
<th>Voltage Output of Differential Amplifier</th>
<th>Torque in lbs/ft. from Dynamometer Reading</th>
</tr>
</thead>
<tbody>
<tr>
<td>.28</td>
<td>.92</td>
</tr>
<tr>
<td>.68</td>
<td>3.68</td>
</tr>
<tr>
<td>1.06</td>
<td>6.31</td>
</tr>
<tr>
<td>1.33</td>
<td>8.21</td>
</tr>
<tr>
<td>1.66</td>
<td>10.45</td>
</tr>
<tr>
<td>1.96</td>
<td>12.5</td>
</tr>
<tr>
<td>2.25</td>
<td>14.4</td>
</tr>
<tr>
<td>2.49</td>
<td>16.05</td>
</tr>
<tr>
<td>2.71</td>
<td>17.6</td>
</tr>
<tr>
<td>2.85</td>
<td>18.05</td>
</tr>
</tbody>
</table>

Speed:

Observation Table 5.2

<table>
<thead>
<tr>
<th>Tachometer Readings</th>
<th>Output of Monostable Multivibrator in micro amps.</th>
</tr>
</thead>
<tbody>
<tr>
<td>340</td>
<td>160</td>
</tr>
<tr>
<td>390</td>
<td>175</td>
</tr>
<tr>
<td>650</td>
<td>250</td>
</tr>
<tr>
<td>890</td>
<td>320</td>
</tr>
<tr>
<td>1120</td>
<td>390</td>
</tr>
<tr>
<td>1150</td>
<td>399</td>
</tr>
<tr>
<td>1200</td>
<td>410</td>
</tr>
<tr>
<td>1300</td>
<td>440</td>
</tr>
<tr>
<td>1400</td>
<td>470</td>
</tr>
<tr>
<td>1500</td>
<td>495</td>
</tr>
<tr>
<td>1600</td>
<td>525</td>
</tr>
</tbody>
</table>
Fig. 5.3 Relationship Between The Collector To Collector Voltage Of The Differential Amplifier and Torque Transmitted
Fig. 5.4 Graph Between Output of a Multivibrator and Speed of D-C Motor
The deviations between the theoretical and experimental results of the photoelectric transient torquemeter and speedmeter were due to following reasons:

1. Light source and light sensor were considered as being point-size in theoretical calculations. Since the gain of the differential amplifier was very high, small amount of input to the differential amplifier, will cause both transistors to operate in cut-off and saturation regions. So the output will be approximately square waves. Error introduced due to this assumption is very small.

2. It was assumed that the light sources produce parallel beams of light and that the beams of light are parallel to the horizontal axis of the torque tube. This assumption will introduce zero error in all readings of torque results.

3. The main source of the error in the torque results is the tolerance in the torque tube parameters, which may be as high as 30%.

4a. The main source of the error in the speed results is the difference between design values and experimental values of the duration of output pulse of the monostable multivibrator. Reasons for this deviation were discussed before in this chapter.

b. Internal resistance of microammeter was assumed zero ohms. Internal resistance of the microammeter was very
small in comparison with resistance $R_6$ so it will not introduce considerable amount of error.
CHAPTER VI
CONCLUSIONS

A literature survey revealed that no commercial torque-meter was available that could be appropriate to use at high speed. Present rocket-pump and turbine research and development require a remote-reading torque-meter usable to 50,000 RPM. An optical torque-meter for high rotational speeds, developed by Alois Krsek, Jr. and Marvin Tiefermann, requires much space and has a response time measured in seconds.

The photoelectric transient torque-meter and speed-meter discussed in this thesis is compact, precise, and economical. Outputs of the differential amplifier and monostable multivibrator are linear functions of the torque and speed respectively. The dynamic tests were made over a limited speed and torque range. However, the range of the speed and the torque can be increased by the design of the suitable differential amplifier, monostable multivibrator, differentiator circuit, torque tube, and the photographic plate using the same light sensors and light source.

Small shaft displacements (radial or axial) due to floating bearing or thermal expansion or end play did not effect the accuracy of torque indication. By suitable design of the photographic plates, and adjusting distance between light sources and light sensors, one can allow for any required axial and radial displacement of the torque
tube, without adding any error in reading of the torque and the speed.

Since the output of the light sensor is very high, it would have been desirable to use a vacuum-tube differential amplifier, rather than one employing transistors. A vacuum-tube amplifier would have a large output for the same torque, and would be easier to balance.

For greater relative transparency of the apertures it would be desirable to use metal plates instead of photographic plates. This would avoid flopping of the plates at high speed.
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VITA

The author was born on February 8, 1942, in Sisva Gujrat-State, India. He received his primary and secondary education in Sisva, Bhadaran, and Anand in Gujrat-State. He has received his college education from V. P. College in Anand, Gujrat-State; B. and B. Polytechnic, in Anand, Gujrat-State; and the University of Missouri at Rolla, Rolla, Missouri. He received a Bachelor of Science Degree in Electrical Engineering from the latter institution in January, 1964.

He has been enrolled as a graduate student at the University of Missouri at Rolla since February, 1964.
APPENDIX

GAIN OF THE DIFFERENTIAL AMPLIFIER

CONSIDERING LOW COLLECTOR RESISTANCE OF TRANSISTOR

When collector resistance of transistor is very small, it is necessary to consider it in the derivation of the gain. Consider a-c equivalent circuit of the differential amplifier, which is shown in Fig. 1:

![Diagram of A-C Equivalent Circuit of Differential Amplifier]

Fig. 1 A-C Equivalent Circuit of Differential Amplifier

The transistor parameter $r_p$ is lumped with generator resistance $R_g$ to form a composite, which is termed $R_s$. Similarly the transistor parameter $r_e$ is lumped with potentiometer resistance $\frac{R_p}{2}$ to form a composite, which is termed $V_E$. Above circuit can be simplified by using "Norton's Theorem". Simplified circuit is shown in Fig. 2. It can be seen that $i_{bi} = i_1$ and $i_{b2} = -i_4$.
Current loop equations from the above circuit are:

\[ e_1 = (R_s + r_c + R_L + \beta r_c) i_1 - (R_L + r_c) i_2 \]  \hspace{1cm} (A-1)

\[ 0 = -(R_L + r_c + \beta r_c) i_1 + (R_L + r_c + r_E + R_x) i_2 - i_3 R_x \]  \hspace{1cm} (A-2)

\[ 0 = -R_x i_2 + (R_x + r_E + r_c + R_L) i_3 - (r_c + R_L + \beta r_c) i_4 \]  \hspace{1cm} (A-3)

\[ -e_2 = -(r_c + R_1) i_3 + (R_L + r_c + R_S + \beta r_c) i_4 \]  \hspace{1cm} (A-4)

Solving for \( i_3 \) and \( i_4 \) from Equation A-I, Equation A-II, Equation A-III and Equation A-IV.

\[ i_3 = \frac{[X e_1 (R_L + r_c + R_S + \beta r_c) - (r_c + R_L + \beta r_c) e_2]}{y(R_L + r_c + R_S + \beta r_c) - (r_c + R_L + \beta r_c)(r_c + R_L)} \]  \hspace{1cm} (A-5)

and

\[ i_2 = \frac{[-y e_2 + X e_1 (r_c + R_L)]}{y(R_L + r_c + R_S + \beta r_c) - (r_c + R_L + \beta r_c)(r_c + R_L)} \]  \hspace{1cm} (A-6)

where

\[
x = \frac{R_x [R_L + r_c + \beta r_c R_L]}{R_s + r_c + R_L + \beta r_c} \]  \hspace{1cm} (A-7)

\[
= \frac{[-(R_L + r_c + \beta r_c)(R_L + r_c)] + R_L + r_c + r_E + R_x}{R_s + r_c + R_L + \beta r_c}
\]
\[ y = \frac{[-R_x^2]}{-(R_L + r_c + \beta r_c)(R_L + r_c)} + \frac{r_E + r_c + R_L}{R_s + r_c + R_L + \beta r_c} + R_x \]

(A-8)

Making following assumptions to perform subtraction operation by the differential amplifier

\[ R_s \ll \beta r_c \]  

(A-9)

\[ r_E \ll R_x \]

and \( r_E \ll \beta r_c \)

An output voltage of the differential amplifier will be

\[ e_o = (i_3 - i_4) R_L \]

(A-10)

\[ = \frac{R_L \beta r_c (e_1 - e_2)}{[\frac{-R_x}{r_E + R_x} + R_x + r_E + r_c + R_L][r_c + R_L + \beta r_c]} \]

Gain will be

\[ G = \frac{e_o}{(e_1 - e_2)} = \frac{R_L \beta r_c}{[\frac{-R_x}{r_E + R_x} + R_x + r_E + r_c + R_L] - (r_c + R_L)} \]

(A-11)

\[ \frac{[r_c + R_L + \beta r_c]}{[r_c + R_L + \beta r_c]} \]