DEVICE FOR THE MEASUREMENT
OF SMALL FRICTIONAL
TORQUE

By

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DEVICE FOR THE MEASUREMENT

OF SMALL FRICTIONAL

TORQUE

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FOREWORD

The development of a device for the measurement of small frictional torque represents a portion of the duties of the author while assigned to the Fluid Seal Project as a graduate research assistant. The Fluid Seal Project was conducted for the Service Engineering Division of the Oklahoma City Air Materiel Command under contract number AF 34(601)-5470.

CHAPTER I

TORQUE MEASUREMENT DEVICES

One of the characteristic measurements made on rotating devices is that of torque. To measure this rotational tendency of a force requires some type of energy absorbing or deformation indicating device and a read-out arrangement. The measurement of torques produced by large machines typically requires a prony brake, water or fan type brake, or an electric dynamometer. The disadvantages coupled with each of these energy absorbing devices are the inability to compensate for varying load conditions, the somewhat inconvenient loading adjustments, and high cost, respectively (1)[1].

An example of a direct reading torque indicator for the measurement of small torques is the Waters Torque Watch Gauge (2). It requires, as do all of the above mentioned torque measurement devices, access to the output shaft of the device whose output torque is being determined. In summary, a more ideal torque determination device should possess the following characteristics:

1. Capability of compensating for varying load conditions,
2. Simple loading adjustments--automatic compensation is preferred,
3. Capability of being placed adjacent to output shaft, so that the shaft can be used for a secondary function,
4. Direct reading,

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[1]Parentheses refer to Selected Bibliography.

5. Simple in construction,

6. Inexpensive,

7. Small,

8. Rugged.

For use on the Fluid Seal Test Facility at Oklahoma State University, a device for the measurement of small frictional torque has been developed which utilizes a number of these desirable characteristics (3), (4). The frictional torque to be measured was that which was developed between a rotating carbon face seal mated with a stationary steel face. A typical face seal installation is shown in Figure 1. In their usual surroundings these parts formed the shaft seal of a pump used in the fuel transfer system of various military aircraft. Thus, to duplicate operating conditions in the laboratory required driving the carbon seal against the mating face mounted in a housing which would rotate in response to the frictional torque produced and which could be supplied with the fuel

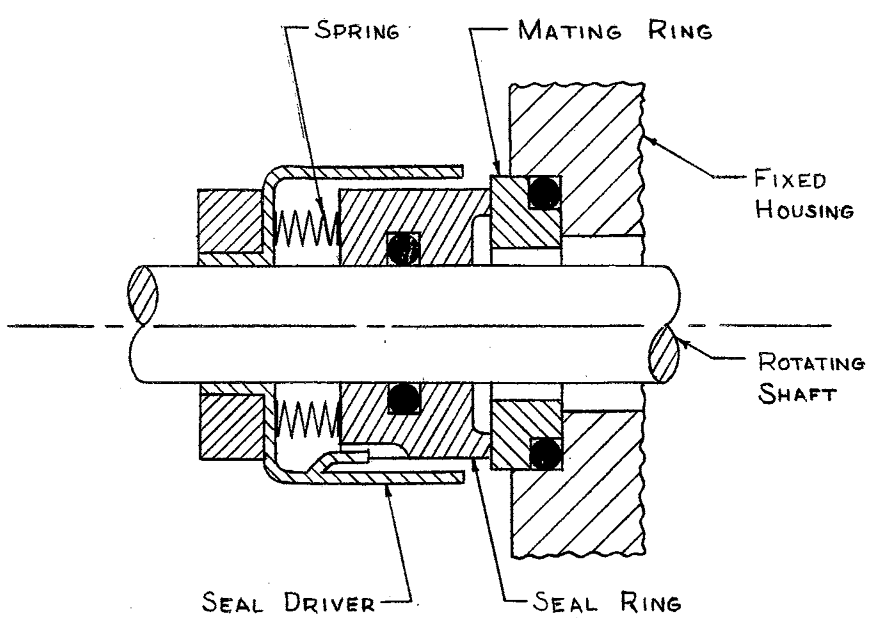


Figure 1. Typical Face Seal Installation

at the temperature and pressure of actual operation. Pressurized fluid in the housing provides face seal cooling and a visual check of seal leakage.

The frictional torque measurement device consists of a thin aluminum beam, 1/2" x 9-3/4" x 1/32", supported at the stationary seal housing in a clamp arrangement to transfer the frictional torque from the housing to the aluminum beam. The other end of the beam is supported on a fixed knife edge. Strain gages, attached to the beam at the point of greatest moment, are used to sense the strain in the surface fibers. Through instrumentation this strain is correlated with the applied frictional torque, and a direct read-out arrangement in oz-in is provided.

This thesis presents a discussion of the frictional torque measurement device based on the theory of beam loading and strain gage instrumentation. It also includes the design of the device, the techniques used during calibration and operation and the results of a series of preliminary tests.

CHAPTER II

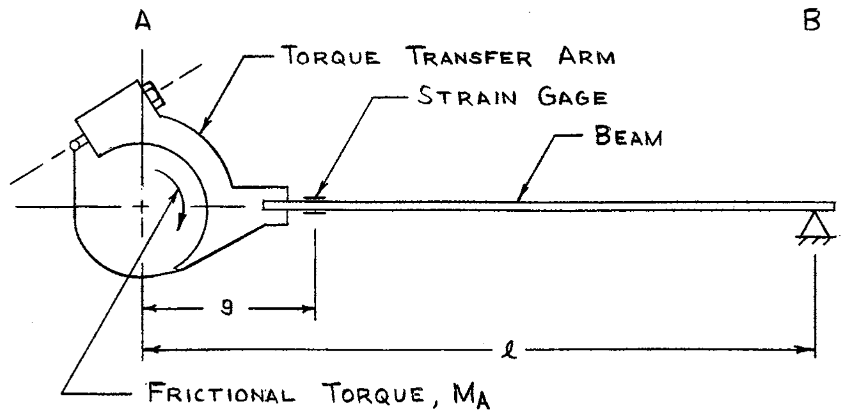
TORQUE MEASUREMENT BY STRAIN MEASUREMENT

Instrumentation for the frictional torque device is based on the moment loading on the beam being related to change of resistance of the strain gages by a constant of proportionality for small deflections of the beam. The change of resistance of the strain gages is in turn linearly related to the voltage change across a circuit composed of four gages. Thus, the equations which govern the actuation of the torque measurement device encompass mechanics of materials and basic strain gage instrumentation.

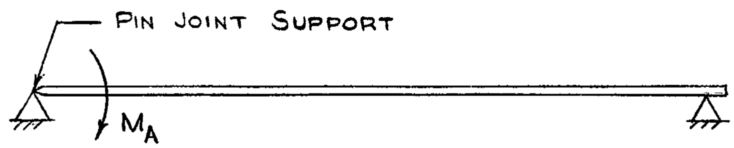
Torque to Strain Equation

The beam loading conditions of the torque measurement device are presented in Figure 2(a) and are generalized in Figure 2(b). To say that the loading in both figures is identical is based on the concept that beam loading is a function of only the applied and reaction forces and is independent of the shape of the beam on which these forces act.

Replacing the pin joint support by the equivalent forces, the loading, shear and moment diagrams of Figure 3 result.



(a) Actual Loading



(b) Generalized Loading

Figure 2. Beam Loading

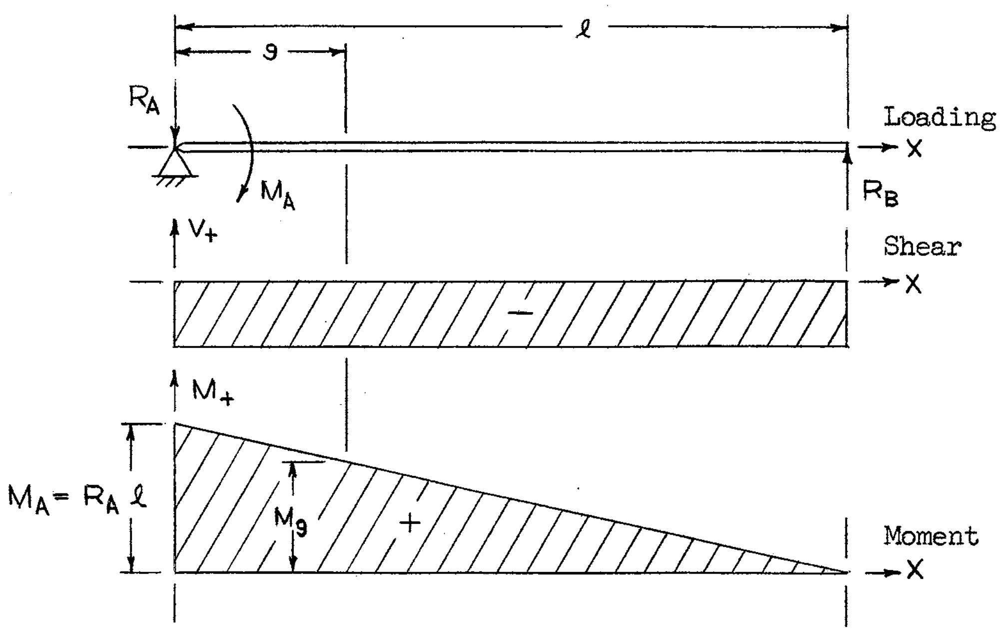


Figure 3. Loading, Shear, and Moment Diagrams

Applying equations of statics, the loading forces and end moment result.

$$\Sigma F_{VERTICAL} = 0 \;(\uparrow +): \qquad R_B - R_A = 0 \quad \text{OR} \quad R_B = R_A \tag{1}$$

$$\Sigma F_{HORIZONTAL} = 0 \;(\rightarrow +): \qquad 0 = 0 \tag{2}$$

$$\Sigma M_{ABOUT\ A} = 0 \;(\curvearrowright +): \qquad M_A - R_B \ell = 0, \quad \text{OR} \quad M_A = R_B \ell = R_A \ell \tag{3}$$

Using the method of successive integration, the shear and moment diagrams for the beam loading have the following equations:

$$V = \int_0^x w \, dx + X_0 \quad \text{BUT} \quad w = 0, \; X_0 = -R_A, \quad \text{OR} \quad V_x = -R_A \tag{4}$$

$$M_x = \int_0^x V \, dx + M_A \quad \text{OR} \quad M_x = \int_0^x (-R_A) \, dx + M_A$$

$$\text{THUS} \quad M_x = (-R_A) x + M_A \tag{5}$$

where x is the distance from the center of rotation to the moment M_x.

From equations 1 and 3, the moment at any position along the beam is given by

$$M_x = R_B (\ell - x) \tag{6}$$

The moment at the location of the strain gages is

$$M_g = R_B (\ell - g) \tag{7}$$

where g is the distance to the strain gages as noted in Figure 2(a). The ratio of the moment at the strain gage position to that at the pin joint support on the beam is given by

$$\frac{M_g}{M_A} = \frac{R_B (\ell - g)}{R_B \ell} \tag{8}$$

Rearranging, the moment acting on the beam at the position of the strain gages is

$$M_g = M_A \frac{(\ell - g)}{\ell} \tag{9}$$

The flexure formula, which relates the stress in a beam to the loading moment, is presented in summary form (5). Figure 4 shows a beam of thickness 2c and width b experiencing the moment M_g which produces the linear stress distribution shown. The distance y from the

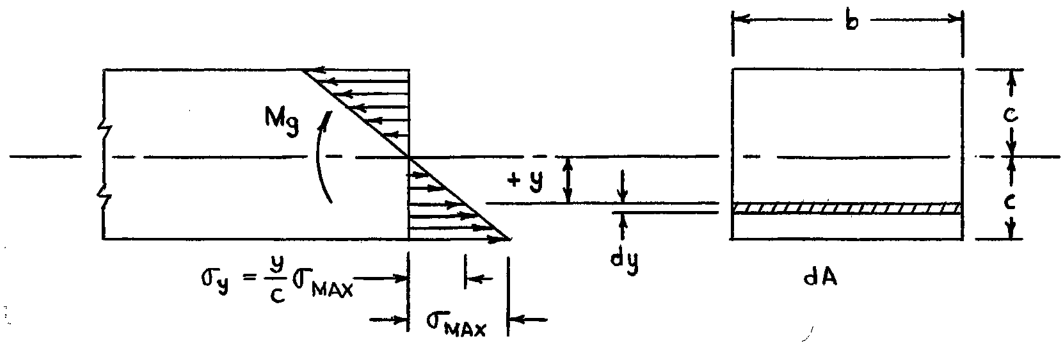


Figure 4. A Beam in Pure Flexure

neutral axis to the elemental area is taken positive downward to agree with the positive sign convention for a tensile stress.

From elementary mechanics, the maximum bending stress in the beam is found in the surface fibers and is given by

$$\sigma_{MAX_g} = \frac{M_g c}{I} \qquad (10)$$

where σ_{max_g} = Stress in the material, lb / in^2,

M_g = External moment applied at the section, lb-in,

c = Distance measured from the neutral axis, in,

I = Area moment of inertia for the beam cross-section about a horizontal axis through the centroid of the section, in^4.

Expressing the moment M_g in terms of the applied moment M_A by equation 9, the maximum stress in the beam at the strain gage position is

$$\sigma_{MAX_g} = \frac{c(\ell - g)}{I\ell} M_A \qquad (11)$$

It should be mentioned that the above derivation assumes that the stress varies linearly about the centroidal axis of the cross-section and that the magnitude of stress is within the elastic range of the material.

By Hooke's Law the constant of proportionality which relates stress and the resulting strain is the modulus of elasticity, E. Mathematically this statement is

$$E \epsilon = \sigma \tag{12}$$

where E = Modulus of elasticity of the material, lb / in^2,

ϵ = Deformation of the body in a given direction divided by the original length in that direction, inches/inch, and

σ = Stress in the material, lb / in^2.

For x = g, the position of the strain gages, the stress at the surface of the beam will be given by

$$E \epsilon_g = \sigma_{MAX_g} \tag{13}$$

Equating equation 13 to equation 11 and rearranging results in

$$\epsilon_g = \frac{c(\ell - g)}{E I \ell} M_A \tag{14}$$

Equation 14 relates the applied moment at x = 0 to the strain in the beam at the strain gage position (x = g). In future discussions it will be designated as the torque to strain equation.

Torque to Bridge Output Equation

To derive the relationship of the strain gage bridge output voltage to applied frictional torque, the physical gage arrangement on the beam, the Wheatstone-bridge circuit and the concept of strain gage factor must be noted. Figure 5 presents the arrangement of the four strain gages used to form the bridge circuit. Because of the moment loading, gages R_2 and R_4 will be in compression, while R_1 and R_3 which are located on the bottom side of the beam will be in tension.

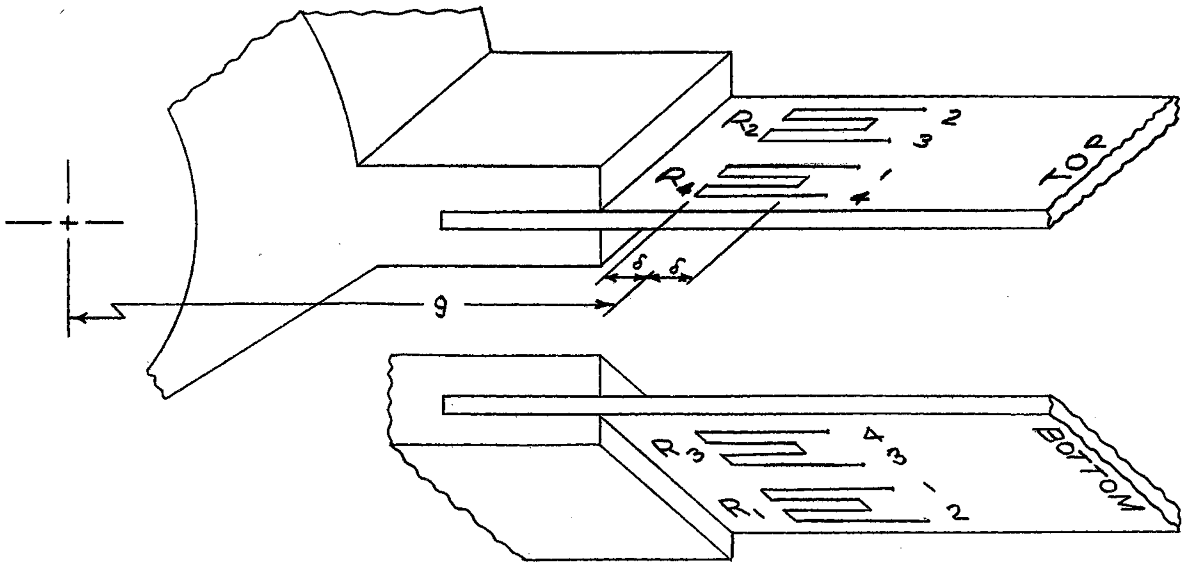


Figure 5. Strain Gage Arrangement

The Wheatstone-bridge formed by the four strain gages is noted in Figure 6. Arrangement is such that the strain gages which measure like strains are diagonally positioned across the bridge. The mathematical

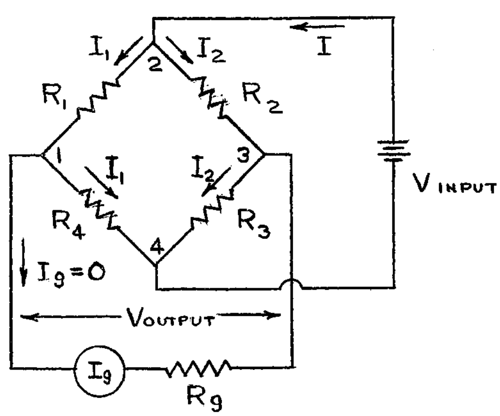


Figure 6. The Balanced Wheatstone-Bridge Circuit

analyses of the bridge are based on its two conditions of stress (6). They are the unstressed or balanced condition of the bridge and the stressed or unbalanced condition. For the balanced condition, the current I_g in the output branch is, by definition, zero; and the voltage drops across the resistors are expressed as

$$I_1 R_1 = I_2 R_2 \quad \text{and} \quad I_1 R_4 = I_2 R_3 \qquad \text{or} \qquad \frac{R_1}{R_4} = \frac{R_2}{R_3} \tag{15}$$

Thus, for a balanced bridge consisting of four resistances or strain gages, the ratio of resistances R_1 to R_4 is equal to the ratio of resistances R_2 to R_3.

Figure 7 presents the unbalanced Wheatstone-bridge circuit. Since a current I_g does exist, equation 15 which was derived for the resistances in a balanced bridge circuit will not be valid.

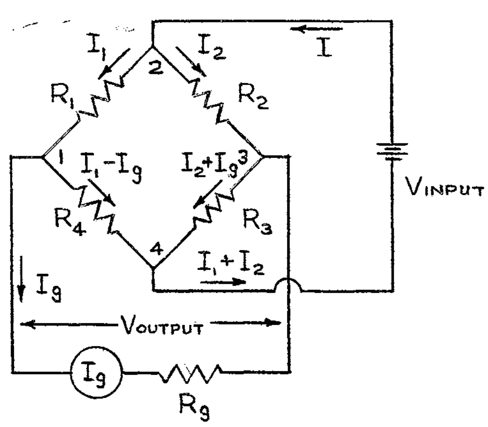


Figure 7. The Unbalanced Wheatstone-Bridge Circuit

By Kirchoff's Law, which notes that the summation of the voltages around a closed circuit loop is zero, the three loop equations can be written.

Loop 2-1-4-2: $-(I_1 R_1) - (I_1 - I_g)R_4 + V_i = 0$ (16)

Loop 1-2-3-1: $I_1 R_1 - I_2 R_2 + I_g R_g = 0$ (17)

Loop 1-3-4-1: $-(I_g R_g) - (I_2 + I_g)R_3 + (I_1 - I_g)R_4 = 0$ (18)

Solving for I_g by eliminating I_1 and I_2 from equations 16, 17, and 18 results in

$$I_g = \frac{V_i (R_2 R_4 - R_1 R_3)}{R_2(R_1 + R_4)(R_g + R_3 + R_4) + R_1 R_3 R_4 - R_2 R_4^2 + R_g R_3 (R_1 + R_4)} \qquad (19)$$

Equation 19 defines the current I_g for the unbalanced case of the Wheatstone-bridge circuit. Since R_g, the resistance in the output circuit, is fixed, by Ohm's Law, the voltage across the output bridge terminals is provided as

$$V_{OUTPUT} = I_g R_g \qquad (20)$$

where I_g is defined by equation 19.

Unit strain, which was previously defined as the total deformation of a body in a direction divided by the original length in the same direction, is related to strain gage resistance change by the gage factor. The gage factor is the dimensionless relationship defined by the following equation, (6),

$$F = \frac{(R - R_i)/R_i}{(L - L_i)/L_i} \qquad (21)$$

where R_i is the initial gage resistance,

$R-R_i$ is the change in resistance,

L_i is the initial length and

$L-L_i$ is the change in length.

Since by definition strain, $\epsilon = \frac{L - L_i}{L_i}$, equation 21 may be rearranged and written as

$$\frac{L - L_i}{L_i} = \epsilon = \frac{R - R_i}{R_i F} \tag{22}$$

Equating equations 14 and 22, the change in resistance of a strain gage, R', is seen to be directly proportional to the applied moment M_A.

$$R - R_i = R' = \frac{c\, R_i\, F\,(\ell - g)}{E I \ell}\, M_A \tag{23}$$

or

$$R' = K_1\, M_A \tag{24}$$

where

$$K_1 = \frac{c\, R_i\, F\,(\ell - g)}{E I \ell}$$

Thus, the change in resistance of a strain gage is linearly related to the applied external moment for the gage arrangement and loading developed previously.

By the gage arrangement on the beam, a moment M_A will cause R_1 and R_3 to increase in resistance by R' and R_2 and R_4 to decrease in resistance by R'. Since the gage factor, F, and the initial resistance, R_i, of each of the gages can be made equal, the resistances in the unbalanced Wheatstone-bridge circuit can be presented in a simplified form.

$$\begin{aligned} R_1 &= R_i + R' \\ R_2 &= R_i - R' \\ R_3 &= R_i + R' \\ R_4 &= R_i - R' \end{aligned} \tag{25}$$

By substituting these equalities into equation 19 and rearranging, the current in the output loop of the unbalanced bridge circuit becomes

$$I_g = \frac{-V_i R'}{R_i^2 + R_i R_g - R'^2} \tag{26}$$

Since a study of the numerical values of the terms in equation 26 might reveal those which are insignificant, the magnitude of the change of resistance, R', is investigated by applying equation 14 with the values of the physical constants of the torque device as presented below:

$c = 0.016$ in	$I = 1.36\ (10)^{-6}$ in^4
$M_A = 1.3$ lb - in	$\ell = 12$ in
$E = 10.0\ (10)^6$ lb / in^2	$g = 3.125$ in

Thus the maximum strain developed within the beam at the location of the strain gages is

$$\epsilon_g = \frac{c(\ell - g)}{EI\ell} M_A = \frac{L - L_i}{L_i} = 1.13\ (10)^{-3} \frac{\text{INCHES}}{\text{INCH}} \tag{27}$$

Since 120 ohm strain gages are used and since the gage factor for each gage is 2.09, equation 22 becomes

$$\epsilon_g F = \frac{R - R_i}{R_i} = \frac{R'}{R_i}$$

or

$$R' = \epsilon_g F R_i = 0.284 \text{ ohm} \tag{28}$$

Examination of equation 26 for $(R')^2$ in the denominator shows that 0.0806 ohm^2 is insignificant when added to the other terms. Since R_g is approximately 12,500 ohms for the read-out instruments, then

$$R_i(R_i + R_g) = 120\ (120 + 12{,}500)$$

$$= 15.16\ (10)^5\ \text{ohm}^2 \qquad (29)$$

Omitting the insignificant $(R')^2$ from the denominator of the equation, the current I_g may be written as

$$I_g = \frac{-V_i R'}{R_i(R_i + R_g)} \qquad (30)$$

Substituting R' of equation 24 into equation 30 results in

$$I_g = \frac{-V_i K_1}{R_i(R_i + R_g)} M_A \qquad (31)$$

where

$$K_1 = \frac{c\ R_i\ F\ (\ell - g)}{E\ I\ \ell}$$

Canceling R_i from the numerator and denominator gives

$$I_g = \frac{-V_i\ c\ F\ (\ell - g)}{E\ I\ \ell\ (R_i + R_g)} M_A \qquad (32)$$

and by equation 20

$$V_{OUTPUT} = \frac{-V_i\ c\ R_g\ F\ (\ell - g)}{E\ I\ \ell\ (R_i + R_g)} M_A \qquad (33)$$

where V_i = Applied circuit voltage, volts,

c = Distance measured from the centroidal axis to the most remote fiber of beam, in,

F = Gage factor,

ℓ = Distance from the center of rotation to the simply supported beam end, in,

g = Distance from the center of rotation to the location of the strain gages, in,

E = Modulus of elasticity of beam material, lb / in^2,

I = Area moment of inertia of cross-sectional area of beam, in^4,

R_i = Initial resistance of the strain gages, ohm,

R_g = Resistance of instruments in the output circuit, ohm.

Equations 32 and 33 relate the output current and output voltage of the bridge circuit to be directly proportional to the applied frictional torque. It is on the basis of these equations that the frictional torque measurement device and the device instrument actuations operate.

One of the initial bases used to derive equations 32 and 33 was Hooke's Law, $E \epsilon = \sigma$. By this law the strain is said to be linearly related to stress by a constant of proportionality, E, the modulus of elasticity. Since, however, Hooke's Law is applicable only to the proportional limit on the stress-strain diagram, then equations 32 and 33 are limited to those applied moments M_A which produce a maximum stress in the material which is less than the proportional limit.

Temperature Compensation

The need for a temperature compensated strain gage and strain gage bridge arises from two physical considerations. First, the resistance of most wire changes with temperature and second, the thermal coefficient of expansion of strain gage wire is different from that of the material to which it is bonded (6). Temperature caused changes in gage resistance can produce apparent changes in the level of strain of a gage and in turn can affect the accuracy of strain measurements.

From the analysis of the balanced bridge ($I_g = 0$) developed in this chapter, the equation relating the resistances was found to be

$$\frac{R_1}{R_4} = \frac{R_2}{R_3} \qquad (15)$$

Thus if because of temperature effects when the active strain gage R_1 is bonded to a piece of material, its resistance is increased by ΔR_t then the equation will appear as

$$\frac{R_1 + \Delta R_t}{R_4} \neq \frac{R_2}{R_3}$$

and the unbalanced bridge would produce a current I_g in the output circuit. To overcome the apparent strain produced by the temperature effect, gage R_2 is mounted on an unstrained piece of the same material. Then ambient temperature changes during the test will affect both gages identically and the bridge circuit will be temperature compensated.

$$\frac{R_1 + \Delta R_t}{R_4} = \frac{R_2 + \Delta R_t}{R_3} \qquad (34)$$

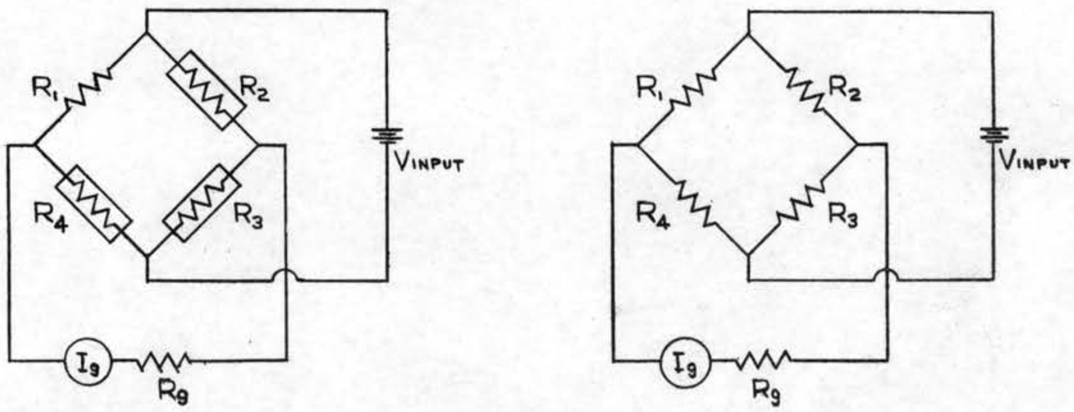
The same principle of temperature compensation would be achieved if all the gages were mounted on the same piece of test material. For temperature changes producing changes in resistance, equation 15 would become

$$\frac{R_1 + \Delta R_t}{R_4 + \Delta R_t} = \frac{R_2 + \Delta R_t}{R_3 + \Delta R_t} \qquad (35)$$

and the bridge circuit consisting of four active strain gages (Figures 5 and 6) would be completely compensated for temperature.

Bridge Sensitivity

Wheatstone-bridge sensitivity is the ratio of the output current I_g to a unit change in strain gage resistance. The greater I_g, for a unit change in resistance, the greater the bridge sensitivity will be. Figure 8 shows two Wheatstone-bridge circuits each experiencing a loading which causes the active gage members to change in resistance by R'. In Figure 8(a) only gage R_1 is utilized to sense strain, while in Figure 8(b) all four gages are active and the physical gage arrangement is presented in Figure 5.



(a) Single Active Gage (b) Four Active Gages

Figure 8. Bridge Sensitivity

For any Wheatstone-bridge circuit the current I_g is expressed by equation 19. In Figure 8, by letting the initial resistances of the gages be R_i, the equations for I_g can be written and compared for the two bridges. Thus the resistances will be expressed as

$R_1 = R_i + R'$ (active gage in tension)

$R_2 = R_3 = R_4 = R_i$ (inactive gages) for Figure 8(a),

and

$R_1 = R_i + R'$

$R_3 = R_i + R'$ (active gages in tension)

$R_2 = R_i - R'$ (active gages in compression)

$R_4 = R_i - R'$ for Figure 8(b).

By substituting the resistances of Figure 8(a) into equation 19, the output current $I_{g(a)}$ (one active gage) becomes

$$I_{g(a)} = \frac{-V_i R'}{4R_i(R_i + R_g) + R'(3R_i + 2R_g)} \tag{36}$$

Again, using the physical constants of the torque device to obtain a representative change of resistance, R', equations 27 and 28 result in

$$R' = 0.284 \text{ ohm}$$

Examination of the denominator of equation 36 shows that

$$R'(3R_i + 2R_g) = 0.284 [(3)(120) + (2)(12,500)]$$
$$= 7.202 (10)^3 \text{ ohm}^2$$

$$4R_i(R_i + R_g) = 4(120)(120 + 12,500)$$
$$= 6.057 (10)^6 \text{ ohm}^2$$

The ratio of the two parts of the denominator is

$$\frac{R'(3R_i + 2R_g)}{4R_i(R_i + R_g)} = \frac{1}{841}$$

Since the above calculation is based on the maximum values of the parameters for the frictional torque device, the negation of the negligible term in the denominator of the equation for the current $I_{g(a)}$ for a bridge consisting of only one active gage is valid and results in

$$I_{g(a)} = \frac{-V_i R'}{4R_i(R_i + R_g)} \quad \text{[For one active gage]} \tag{37}$$

As previously developed in equation 30, the current I_g for a bridge consisting of four active gages may be written as

$$I_{g(b)} = \frac{-V_{\ell} R'}{R_{\ell}(R_{\ell} + R_g)} \quad \text{[For four active gages]} \qquad (30)$$

By comparing equations 30 and 37, the effect of straining four gages simultaneously to the same degree, two in tension and two in compression, results in a bridge output current which is four times as great as the output of a bridge which possesses only one active gage. For identical loading conditions, the bridge consisting of four active gages will have a sensitivity and an output current four times that of the single active gage bridge circuit.

CHAPTER III

TORQUE MEASUREMENT DEVICE

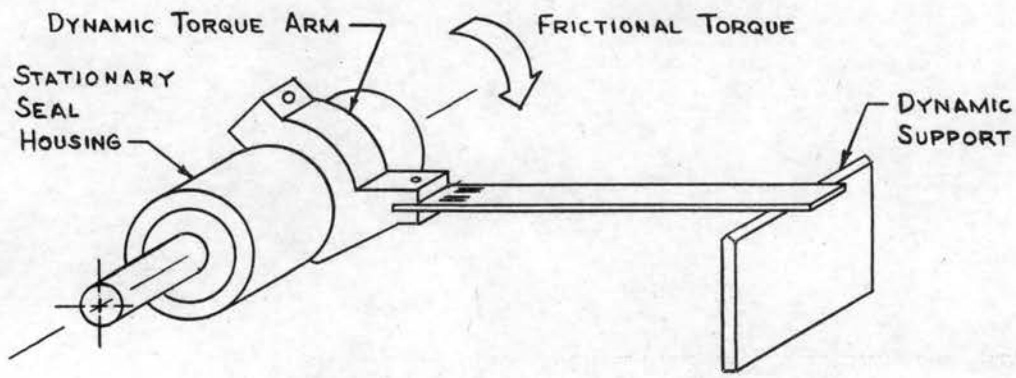
The torque measurement device is an integral part of the Fluid Seal Test Facility at Oklahoma State University. The device is composed of a strain gage assembly, a beam loading assembly, and a read-out assembly. The read-out arrangement includes facilities for both direct and indirect determination of applied frictional torque.

Strain Gage Assembly

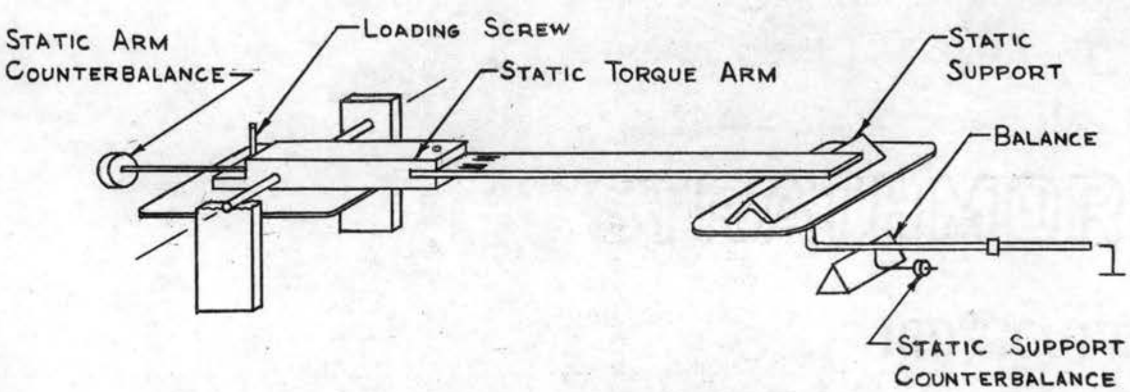
The strain gage arrangement on the beam and the Wheatstone-bridge circuit discussed in Chapter II are utilized in the torque measurement device.

Beam Loading Assembly

The beam loading assembly is composed of dynamic and static beam loading devices and is shown in Figure 9. For the measurement of face seal frictional torque the dynamic loading device, which is attached to the stationary seal housing, is utilized. For beam calibration purposes, the static beam loading device is provided. In order to calibrate the beam-strain gage combination, it is necessary to duplicate the unloaded and loaded conditions of the dynamic device in the static loading device. Thus the distance of the static arm counterbalance from the axis is varied until the apparent weight of the beam at the static support is identical to that apparent weight experienced by the dynamic support for the no frictional torque condition. In order to read the true reaction on the beam at the static support, when a torque is applied, a static support counterbalance is utilized. Thus the weight of the static support on the unequal arm balance is nullified. The loading of the beam-strain gage combination on the static device is accomplished by a 1 x 64 NC loading screw threaded into the static torque arm. Advancing the screw against the plate below the static arm causes the static torque arm to rotate downward applying a torque to the aluminum beam and, in turn, a force, R_B, to the static support on the balance.



(a) Dynamic Beam Device



(b) Static Beam Device

Figure 9. Beam Loading Assembly

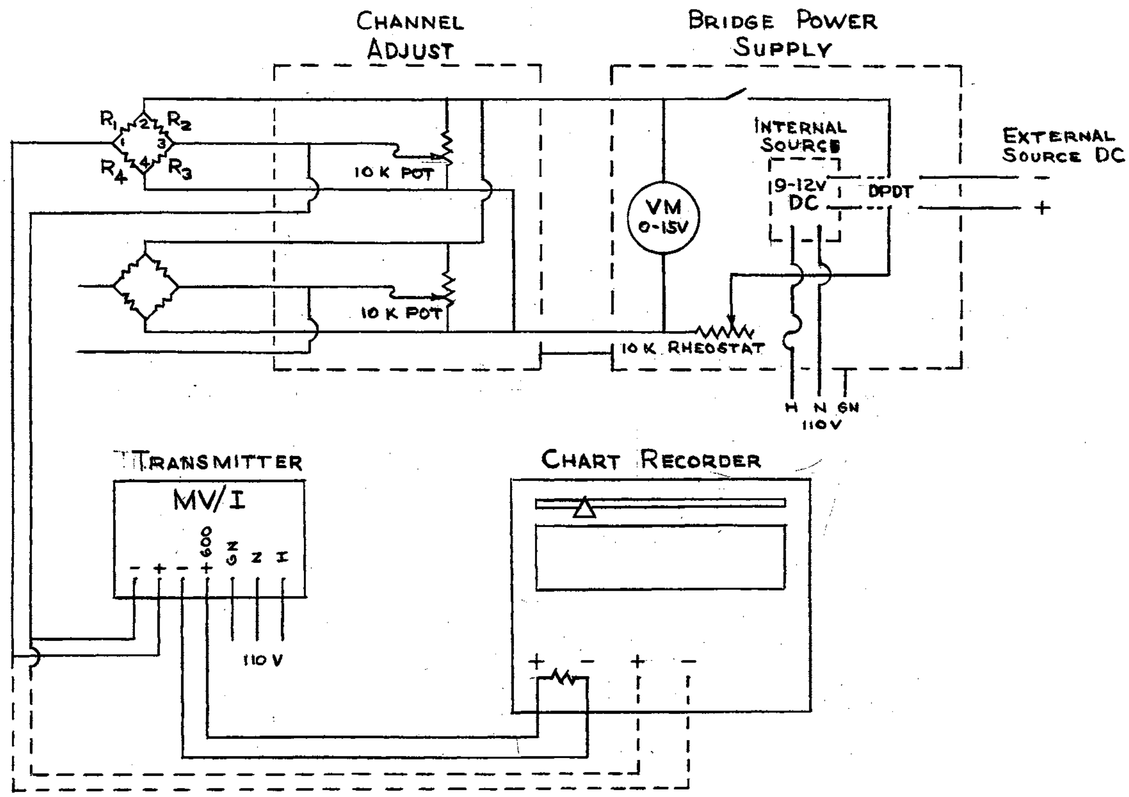
Read-Out Assembly

The read-out instrumentation for the torque measurement device as shown in Figure 10 offers two methods of frictional torque determination. By tracing a current signal from an electrically unbalanced Wheatstone-bridge circuit, the operation of the direct reading instrumentation can be noted.

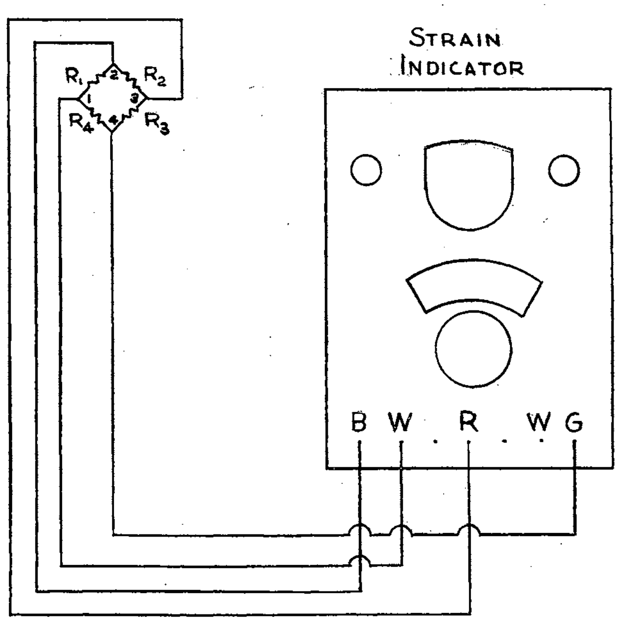
A current I_g from the bridge circuit produces a voltage potential across the input terminals of the transmitter. Through calibration of the transmitter, the input voltage can be adjusted from a zero to 2.5 millivolt range to a zero to 100 millivolt actuation range, while the output will be a constant range of 4 to 20 milliamperes. Thus, for a given range of torques, the current output of the unbalanced strain gage circuit, I_g, can be calculated by equation 32, and the maximum voltage potential across the transmitter terminals can be found by equation 33. Calibration of the transmitter for this voltage range will result in a 4 to 20 milliampere output from the transmitter.

The output current of the transmitter produces a voltage potential across a 2.5 ohm precision resistor which is placed at the input terminals of the multipoint chart recorder. The recorder is then actuated by this input to print the symbol of the variable torque on the moving chart at the position which corresponds to the value of the frictional torque. Proper calibration will allow the use of the entire zero to 100 unit range of the recorder chart. A linear scale of torque in oz-in determined for each beam and placed above the recorder chart provides a means of determining the frictional torque directly.

An alternate method of determining the applied frictional torque is provided by attaching the strain gage bridge circuit to a strain



(a) Direct Reading Instrumentation



(b) Indirect Reading Instrumentation

Figure 10. Read-Out Instrumentation

indicator. Since four active gages are employed, the strain determined is four times the actual strain experienced by the beam. Then by equa-14 the applied frictional moment can be computed as

$$M_A = \frac{EI\ell}{c(\ell - g)}(\epsilon_g) \tag{38}$$

where $\epsilon_g = \frac{\epsilon_f - \epsilon_i}{4}$ the change in strain (final minus initial) in microinches per inch as determined by the strain indicator divided by four.

To insure an absolute minimum of noise and of alternating current stray pick up, the shielded lead wires were commonly grounded.

Limitations of the Torque Measurement Device

The limitations of the torque device are those items, inherent in the system, which limit its performance. Since the actuation of the device depends upon a small rotation of the stationary seal housing to produce a moment in the aluminum beam, one might suspect that the primary source of system limitations is contained in the housing. Figure 11 presents the design of the stationary seal housing. In order to provide, simultaneously, a method of rotation for the stationary housing and a method of fluid delivery to the cavity, Tygon flexible tubing is utilized. The figure notes that this tubing is constrained only at the rear of the loading block and at the base of the cavity, a distance of 18 inches. This was done to reduce the displacement of the tubing as a result of the applied frictional torque rotating the stationary housing. To keep this residual torque caused by the tubes to a small magnitude, the tube size has been limited to 3/8 inch outside diameter.

A second limitation in the stationary housing is presented by the

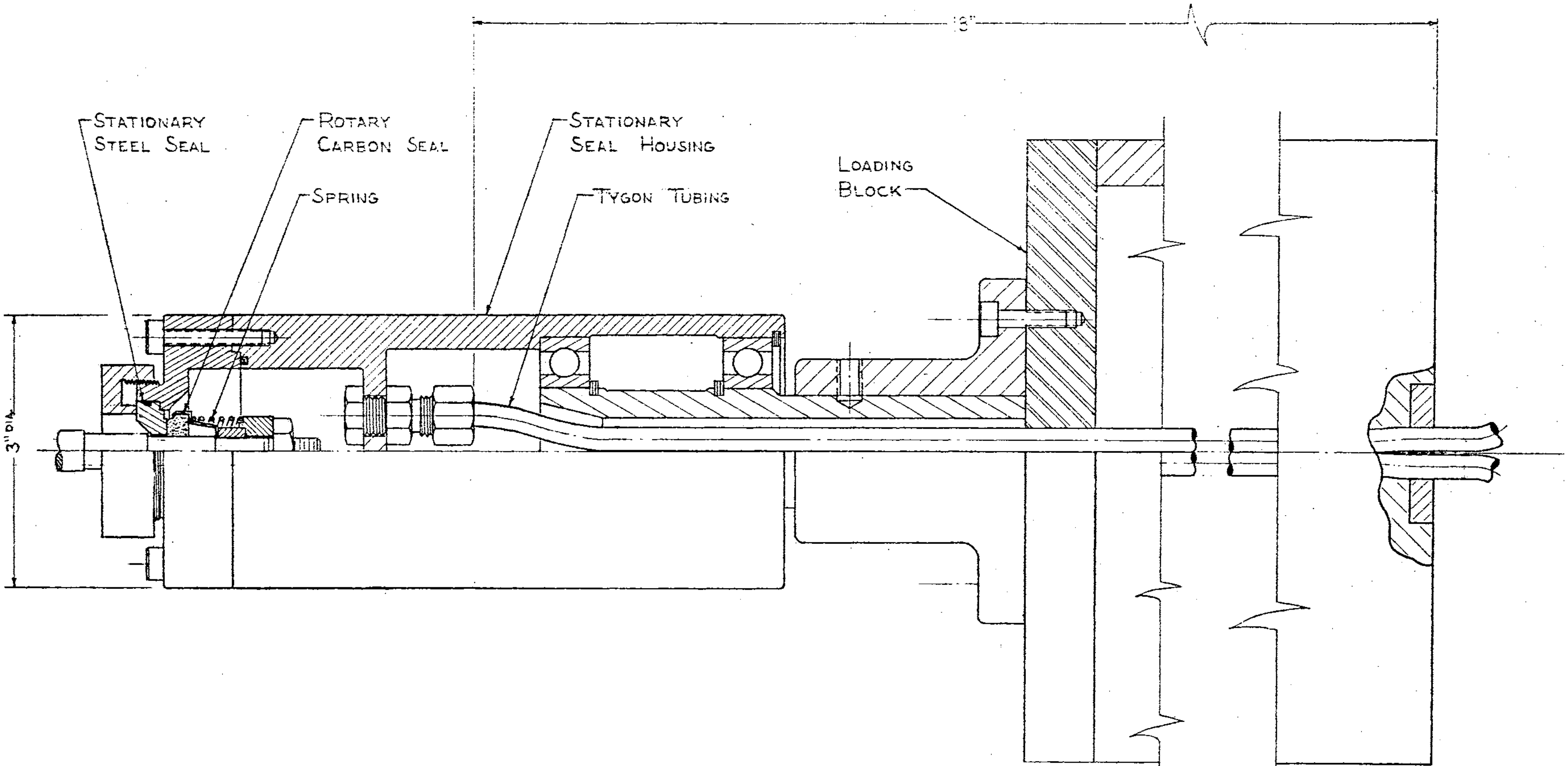


Figure 11. Stationary Seal Housing Assembly

bearings. By initially selecting super-precision bearings made to ABEC-7 tolerances, the desirable bearing characteristic of low starting torque was obtained. Further, by flushing the bearings with carbon-tetrachloride prior to the torque tests, the possibility of dust particles being in the curvilinear grooves in the races was reduced. After cleaning, a very light coat of instrument oil on the bearings was used to prevent rust.

CHAPTER IV

PROCEDURES OF OPERATION

The determination of the value of the frictional torque detected by the strain gage bridge is dependent on the calibration of the transmitter and of the beam-strain gage combination. For the indirect reading method, the calibration of the device is based upon finding the constant of proportionality which relates change in strain and the applied frictional moment through equation 38.

Direct Reading Procedure

Since the millivolt to current (MV/I) transmitter can be adjusted for a number of input voltage ranges, the basis for determining the required range is equation 33. The parameters of equation 27 along with an applied circuit voltage, $V_i = 10$ volts, when substituted into equation 33, will yield the maximum voltage, $V_{output\ (gages)}$, which will result from a maximum allowable strain in the beam for which no permanent deformation results. Since the direct reading instrumentation does not possess a method of showing bridge balance by null indication, it is desirable to select an arbitrary voltage level which will provide recorder actuation to a scale reading which will correspond to the no load condition on the beam. This bridge voltage, then, during a later test can be reproduced by varying the channel adjust potentiometer until the recorder reading is a duplication of that for prior tests. Thus the maximum voltage to be sensed by the transmitter is the summation of the zero adjust voltage, V_{min}, and the change in voltage arising from the resistance change of the gages, $V_{output\ (gages)}$. The circuit arrangement for transmitter calibration is shown in Figure 12.

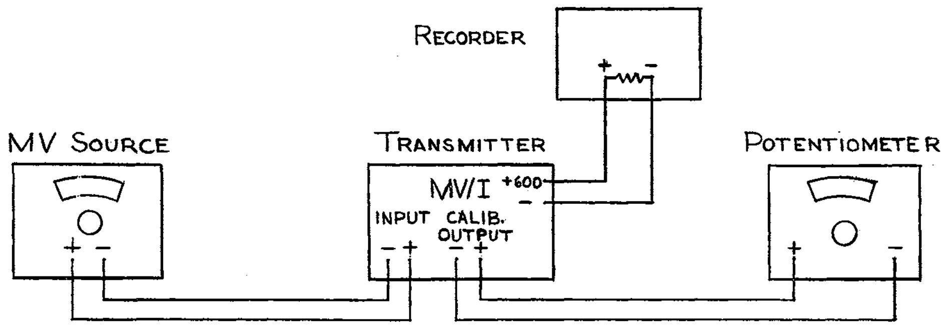


Figure 12. Transmitter Calibration Set-Up

The 2.5 ohm resistor within the transmitter at the calibration output terminals enables the potentiometer to sense a millivoltage output. During calibration the recorder remains in the circuit since without it the transmitter output would be open circuited. The Minneapolis-Honeywell Instruction Manual (7) for the MV/I transmitter model 1FB35-641 was utilized for the calibration procedures. Appendix B presents the calculations involving the transmitter calibration procedure.

The calibration of a strain gage bridge-aluminum beam assembly is one of determining the reading on the chart recorder which corresponds to a known applied torque. The calibration is performed utilizing the static beam loading device of Figure 9(b). Since for any moment loading, the moment arm, ℓ, and the reaction, R_B, are known, then the moment applied by the loading screw is given by equation 3.

$$M_A = R_B\ (\ell)$$

Thus, using the applied moment as the independent variable, a plot of the recorder reading versus the applied moment can be determined. The recorder reading is plotted since it is proportional to the voltage drop across the recorder terminals; in turn, this voltage drop is proportional to that potential across the transmitter caused by I_g. During actual seal tests to determine the frictional torque, the beam, whose calibration curve is known, is removed from the static loading device and is placed in the dynamic loading device of Figure 9(a). Reading the recorder will allow the frictional torque to be determined by the calibration curve. For added convenience, a torque calibration scale for the particular gage-beam assembly being used is placed above the chart on the recorder to provide the direct reading feature.

Indirect Reading Procedure

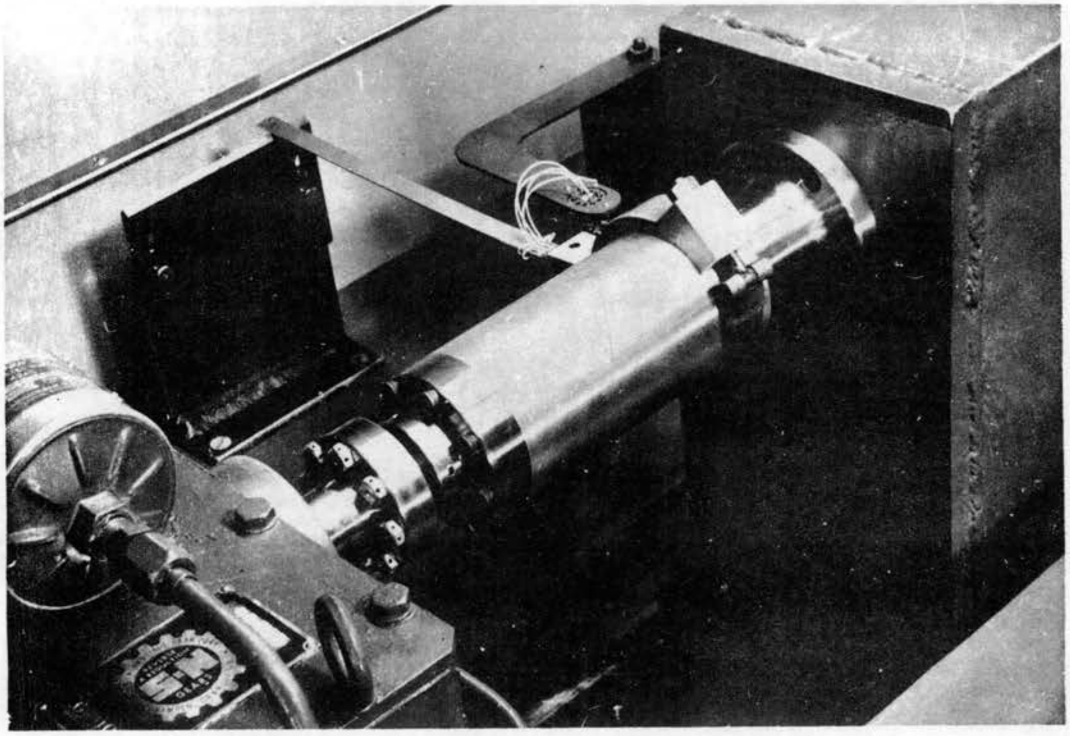
Equation 38, which relates change in strain of the gages and the applied frictional moment, can be rewritten as

$$M_A = K_2 (\epsilon_g) \tag{39}$$

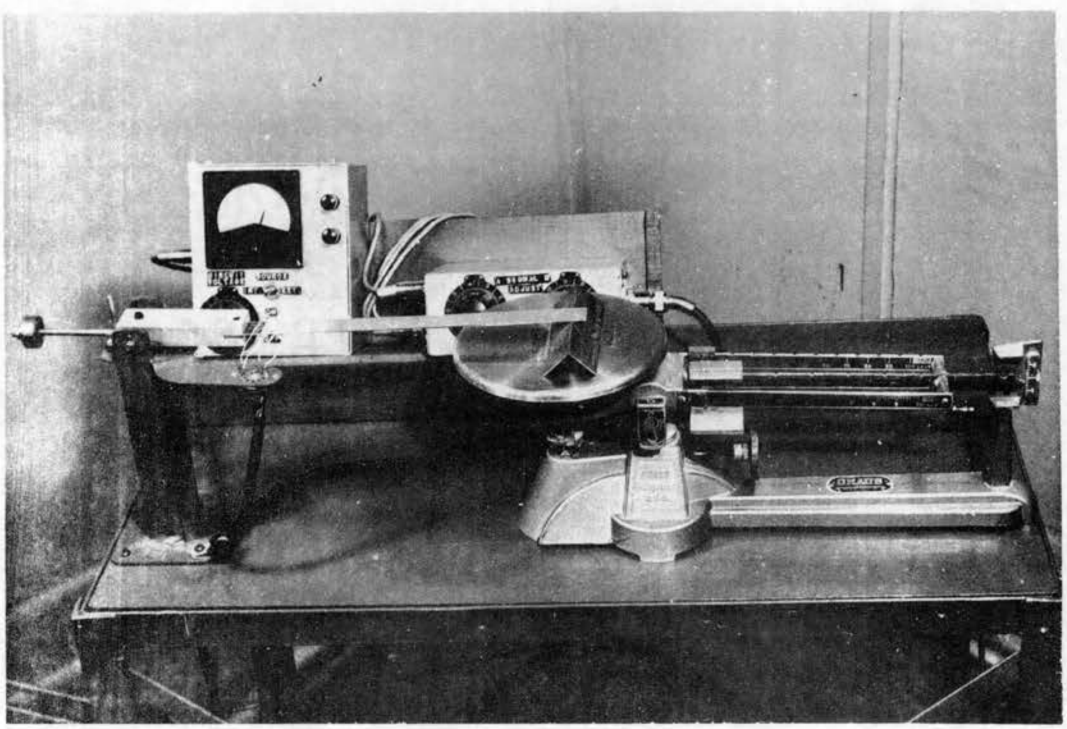
where
$$K_2 = \frac{E I \ell}{c(\ell - g)}$$

By using the static loading device and the indirect reading instrumentation of Figure 10(b), a plot of the independent variable M_A against the relative gage strain, ϵ_g, can be found. Hence, during tests in which the beam is placed in the dynamic loading device, a given ϵ_g will determine the corresponding applied frictional torque, M_A.

Figure 13 presents the dynamic and static loading arrangements. Adjacent to each beam is a modified miniature tube socket which enables the electrical connections of the strain gage bridge circuit to be made rapidly. Figure 14 shows the Fluid Seal Test Facility and recorder scale.



(a) Dynamic Beam Device



(b) Static Beam Device

Figure 13. Beam Loading Arrangements

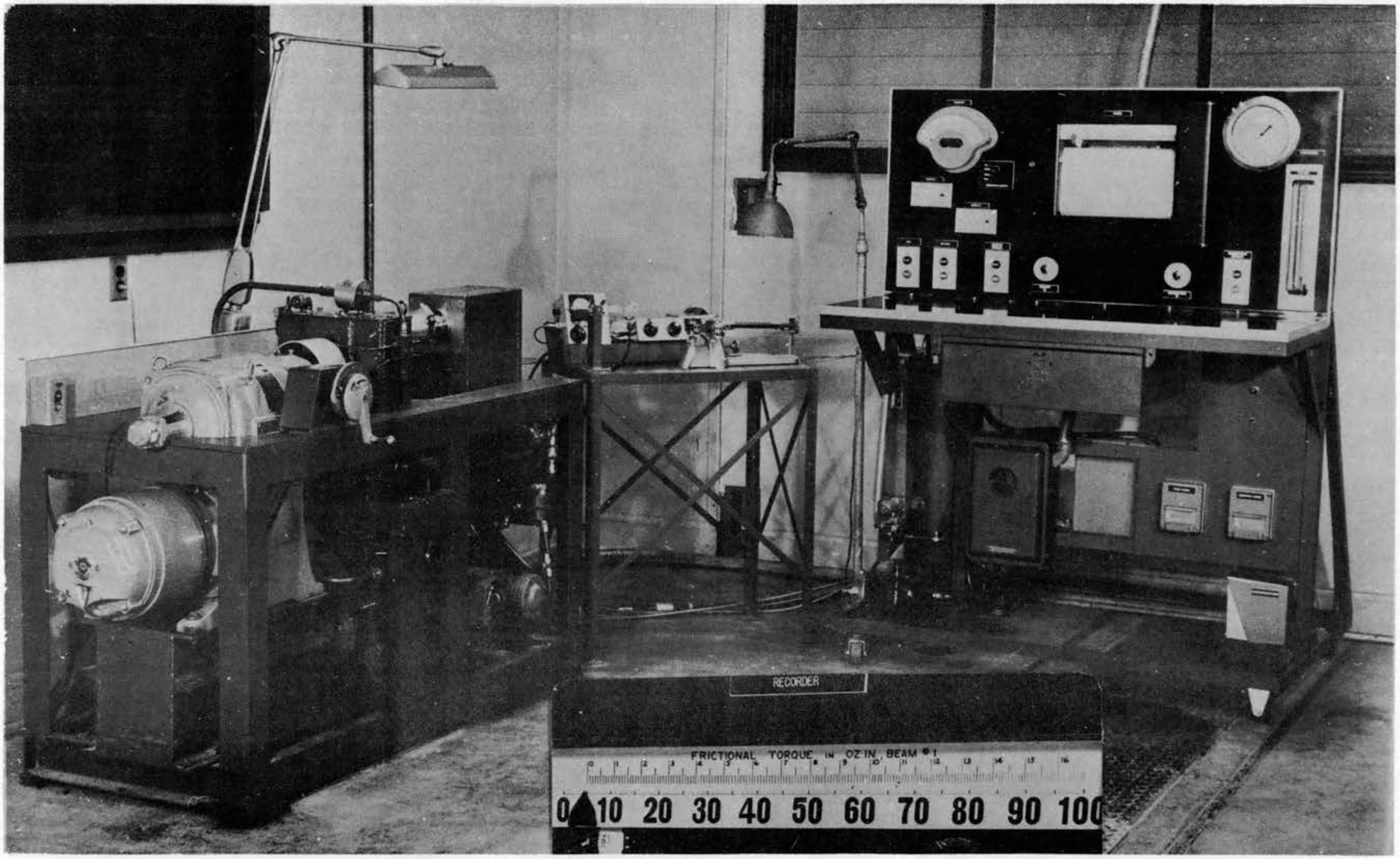


Figure 14. Fluid Seals Test Facility

CHAPTER V

RESULTS OF TESTS

The experiments performed in connection with the frictional torque device are designed to evaluate its performance as a method of measuring seal torque. Thus, a direct reading and an indirect reading procedure of torque measurement have been outlined in order that comparison of test results by the two methods might reveal discrepancies, if any, in the instrumentation and calibration techniques. Also, since mathematical analysis of the torque measurement device has revealed a linear relationship between the applied frictional moment and change in strain of the strain gages, experiments designed to calibrate a given beam-strain gage combination will show discrepancies, if present, between the theoretical and the actual torque measurement device.

Calibration Tests

Figure 15 presents the calibration curve for beam #1 and #2 by the indirect reading procedure, based on the data of Appendix A. A second beam-strain gage combination was constructed since results of the beam #1 test showed a deviation from the linear relationship between loading and strain above the 40 gram loading level because of slight permanent deformation. The calibration curve for beam #2 shows a linearity of load and strain to the required 50 gram loading which corresponds to

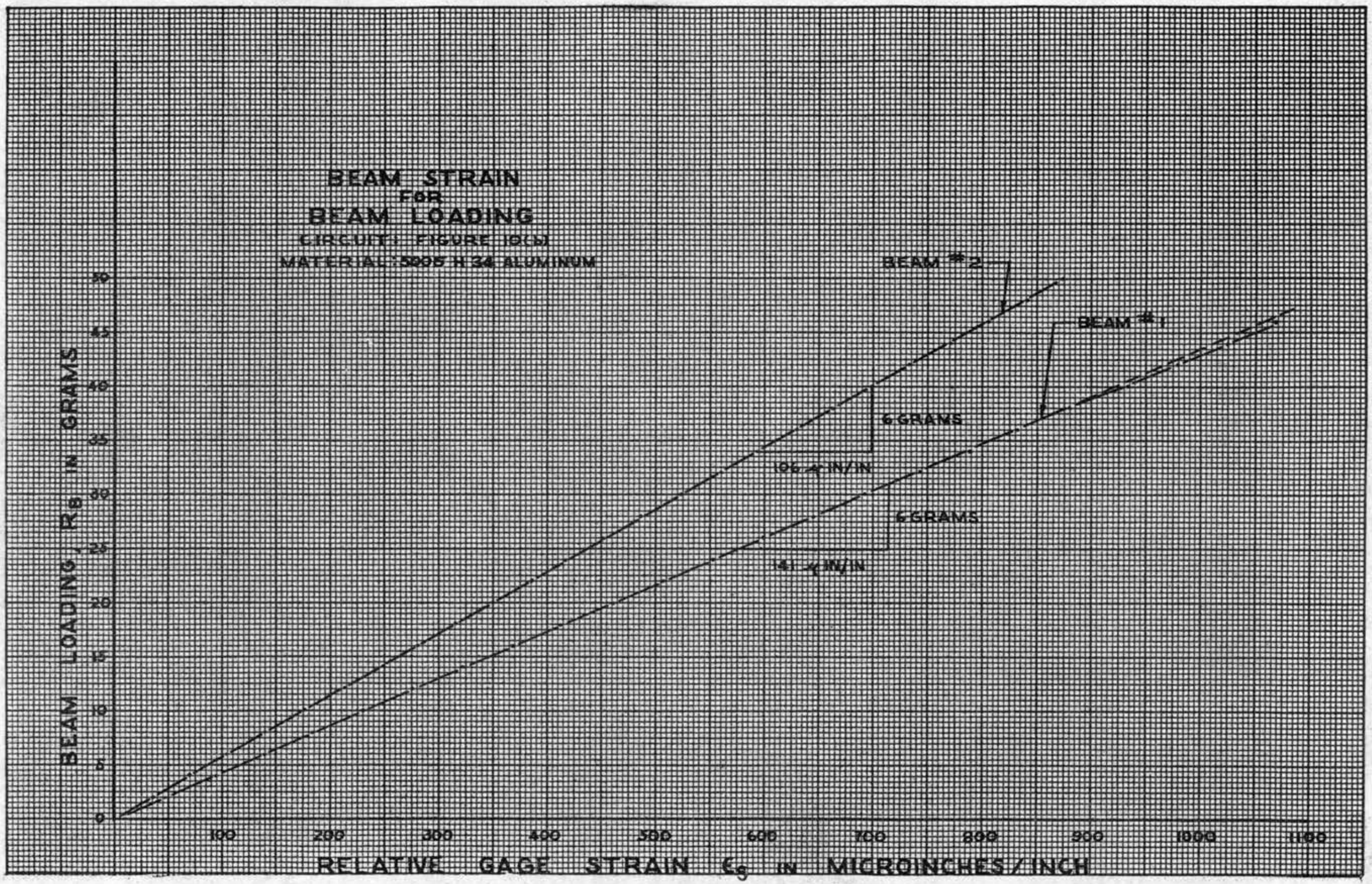


Figure 15. Indirect Reading Calibration Curve.

an applied torque of 1.3 lb - in (21 oz-in).

Before the direct reading instrumentation could be utilized, it was necessary to determine the voltage output of the bridge which corresponds to the maximum beam loading for which permanent deformation of the part would not occur. With this voltage, the transmitter was calibrated to provide complete use of the recorder range for the corresponding linear torque range of beam #2. The various calculations for the transmitter calibration are presented in Appendix B. Following the Minneapolis-Honeywell Instruction Manual, the equivalent minimum and equivalent span voltages were determined for the calibration.

The direct reading calibration curve for each of the beams was found by two circuit arrangements. Figure 10(a) presents these circuit variations. The solid lines denote a circuit which contains the transmitter; the dashed lines present the modified circuit which bypasses the transmitter. Since the strain gage bridge provides an output voltage and since the recorder is voltage actuated, no resistor is necessary across the recorder terminals for the dashed circuit configuration. The data obtained by subjecting each beam to the two variations of the direct reading instrumentation is presented in Appendix A and is summarized in Figures 16 and 17. Again, the deviation of the linear relationship of loading and bridge output in terms of recorder reading is noted for beam #1 in Figure 17. The linear deviation of beam #1 is not found in Figure 16 since the load was limited to 39 grams because of the recorder scale limitation.

Frictional Torque Tests

To demonstrate the torque measurement device, the Fluid Seal Test

Facility was utilized. While holding the test conditions noted in Appendix C constant, the frictional torque developed by the carbon face seal and the mating stationary face was transmitted to the dynamic loading device and was measured using both beams and both methods of instrumentation. Because the accuracy of each torque determination should be as great as is possible for comparison purposes, the torques were calculated by using the recorder and strain indicator readings and the various beam calibration data rather than using the torque scale on the recorder. The resulting torque measurements are shown below.

	Beam #1	Beam #2
Direct Reading Instrumentation		
With transmitter	1.61 oz-in	1.82 oz-in
Without transmitter	1.76 oz-in	1.69 oz-in
Indirect Reading Instrumentation	1.85 oz-in	1.71 oz-in

The average of the torques is 1.74 oz-in, and the maximum deviation from this average is -0.13 oz-in from the 1.61 oz-in reading. The percent deviation from the average value is 7.47%.

A design difficulty became apparent as a result of the frictional torque tests. The effect of the Tygon flexible tubing upon the rotation of the stationary seal housing was appreciable, although the design precautions of small tube size and careful choice of tubing restraints had been used. The cause of the resistive torque of the tubing appears to be a combination of two items: the fluid being pumped and the length of service sustained by the tubes. Initially after installation, the fluid had no apparent affect on the tubing which remained pliable. The intervening months following the tubing installation and prior to the above tests resulted in the tubing losing its pliability.

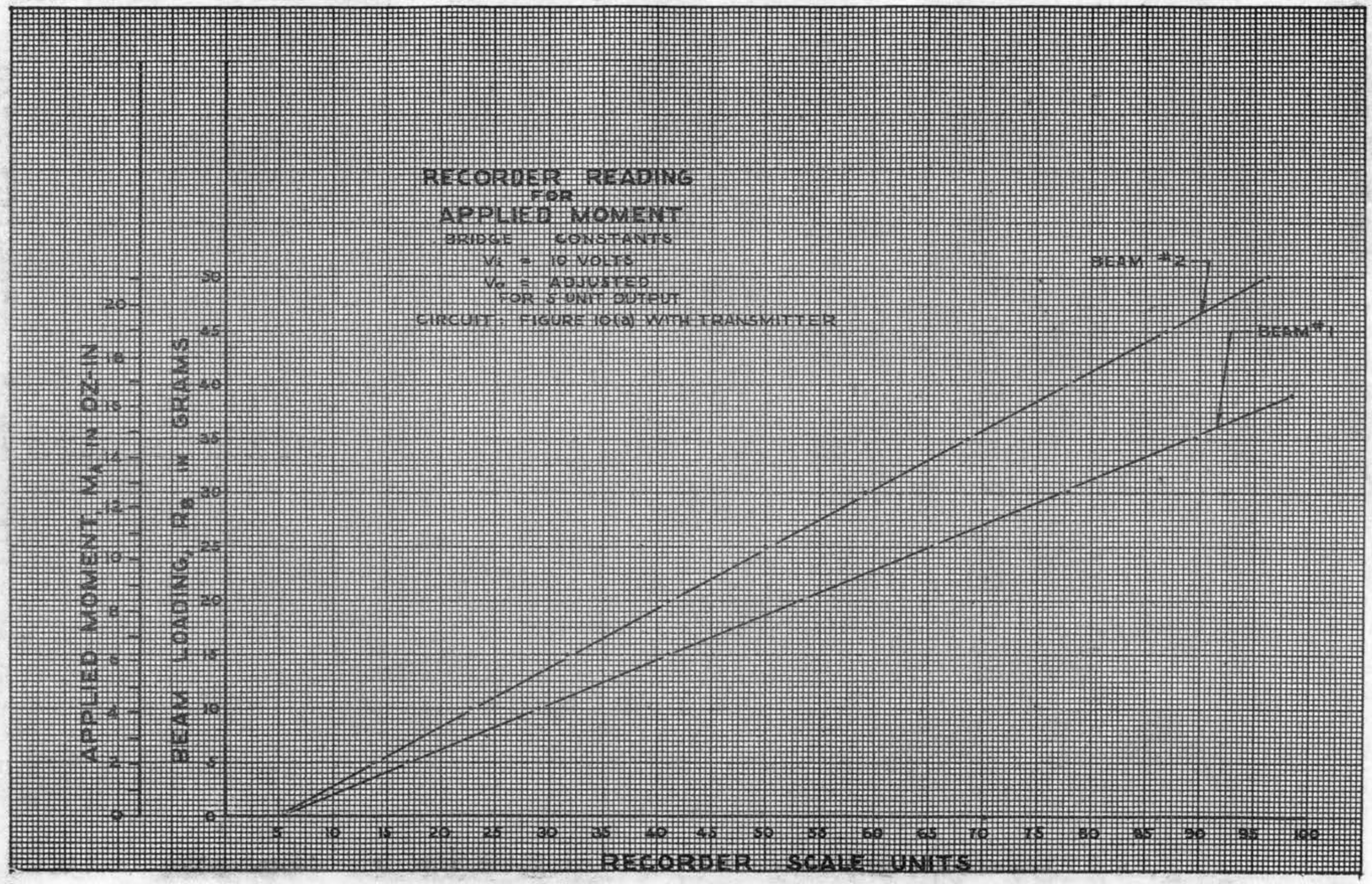


Figure 16. Direct Reading Calibration Curve With Transmitter.

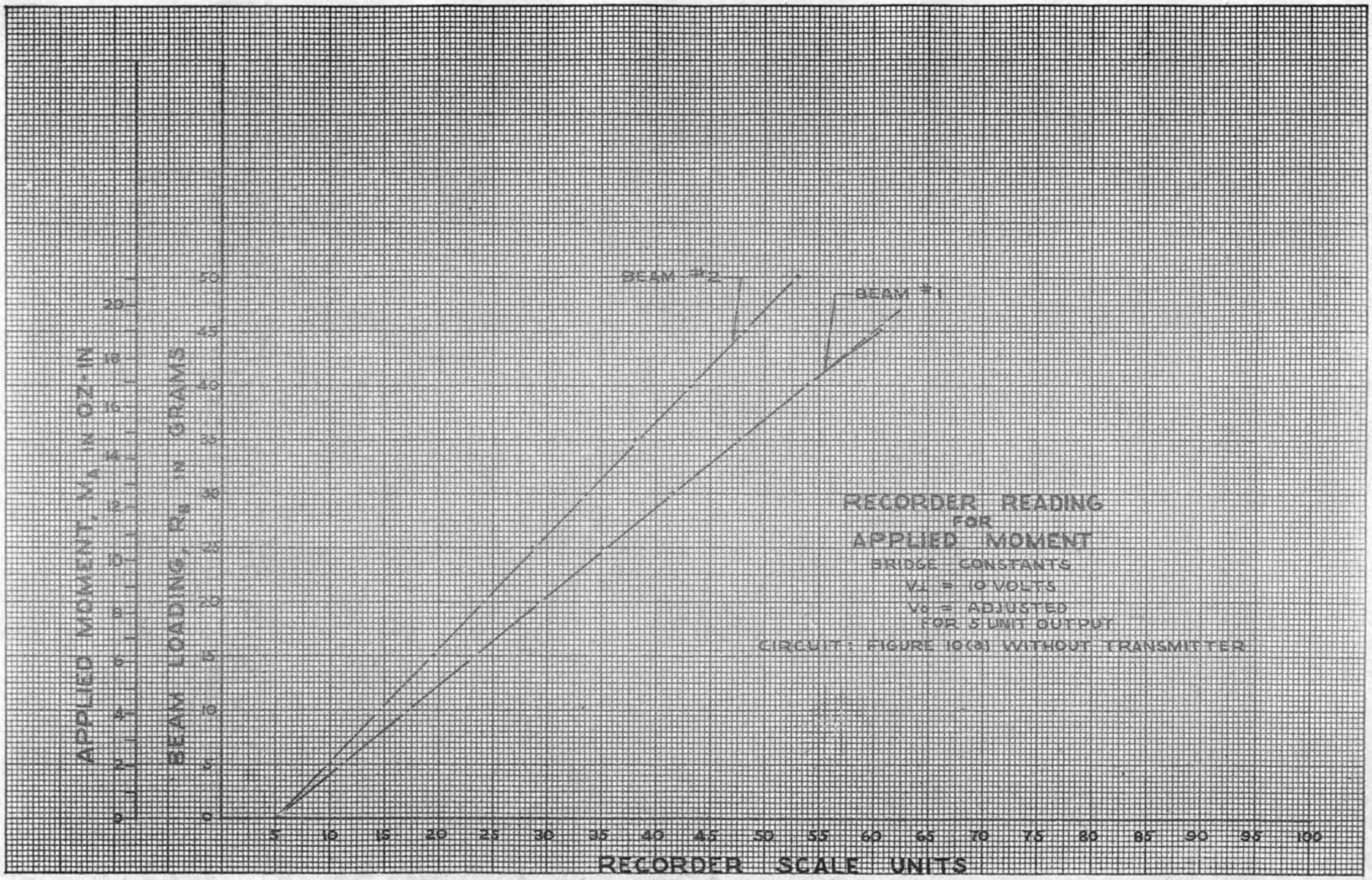


Figure 17. Direct Reading Calibration Curve Without Transmitter.

In order to run the preliminary tests to observe the functioning of the torque measurement device when integrated into the operation of the Fluid Seal Test Facility, the restraining torque of the tubes was reduced by heating the stationary seal housing and tubes to approximately 100°F. This temperature was far enough removed from the ambient condition to allow the stationary housing to function properly in response to an applied frictional torque.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The conclusions of this study and the recommendations for further activities are presented as a possible aid for those whose interests include instrumentation techniques and specifically, the measurement of small torques.

Comparison to the Ideal Measurement Device

As a torque measurement device, the strain gage-flexible beam combination possesses the following characteristics:

1. The device is capable of both compensation and automatic self-compensation for varying load conditions.

2. The device can be attached adjacent to the output shaft in order that the shaft might perform a secondary function such as fluid delivery and return.

3. Instrumentation techniques enable the device to be direct reading.

4. Although the beam-strain gage combination is simple in construction, the techniques of strain gage mounting and wiring require meticulous care.

5. The cost of the electronic equipment which is required to make the device direct reading limits the number of torque measurement applications.

6. The size and ruggedness of the device depend upon both the magnitude of the torque to be measured and the presence of over loads which could cause permanent damage to the beam-strain gage assembly.

Test Conclusions

Based upon the calibration and frictional torque tests, these conclusions are reached:

1. The linear relationship between the applied moment and the device output voltage and output reading demonstrates the agreement of the actual loading and the theoretical loading equation up to the yield point of the material. This result further shows that the device is suitable for the torque tests for which it was designed.

2. The transmitter functions as a linear amplifier of the bridge output potential and provides versatility in the torque span which is read on the recorder.

3. The torque determination by the indirect reading instrumentation is somewhat time consuming; the direct reading procedure offers an equally accurate yet faster method of torque determination.

Recommendations for Future Activities

Evaluation of the present frictional torque device suggests possible future activities:

1. The modification of the stationary seal housing to allow a slip fit assembly with the bearings would eliminate the temperature extremes to which the parts are presently subjected during the shrink fit assembly.

2. The frequent replacement of the flexible tubing would reduce,

if not eliminate, the resistive torque present in aged tubing.

3. In order to observe the instantaneous torque fluctuations of the rotating seal assembly, a cathode ray oscilloscope could be added to the direct reading instrumentation circuit. The addition of a camera to the oscilloscope would allow study of the instantaneous fluctuations in torque.

4. The utilization of the second strain gage circuit in the channel adjust assembly could allow two sets of four strain gages each to be mounted on the same beam for the summation of the two bridge outputs, thus providing amplification of very low bridge output potentials to levels which could be further amplified by the transmitter for full scale recorder actuation.

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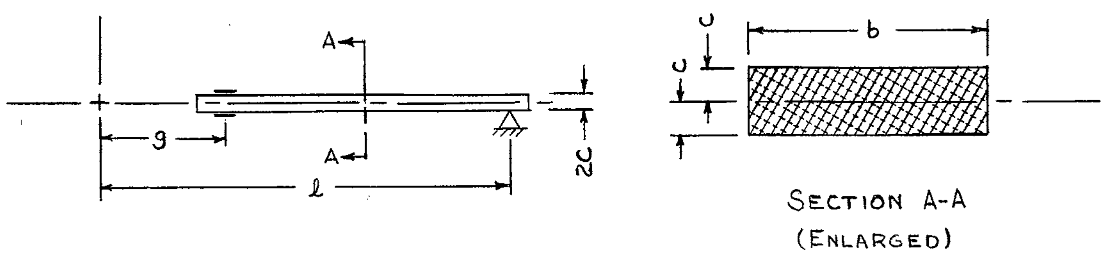
APPENDIX A

BEAM CALIBRATION DATA

Beam Composition: 5005 H 34 aluminum sheet
Thickness: 0.032 in, $E = 10.0\ (10)^6$ psi
Yield Strength: 20,000 psi, tension and compression

System Dimensions:



$g = 3\ 1/16$ in.
$\ell = 12$ in.

b = As noted
$c = 0.016$ in.

Strain Gages: Budd Metalfilm Strain Gages
type: C12-121
resistance: 120 ± .2 ohm
gage factor: 2.09 ± 1/2%
lot no.: A5 S-FAE - 4

Strain Gage Mounting: The four active gage Wheatstone-bridge circuit of Chapter II was utilized.

Beam Loading: Calibration loading was accomplished by the static loading device of Chapter III, Figure 9(b).

Indirect Reading Instrumentation
Figure 10(b)

Data: Beam #1: b = 0.507 in. Beam #2: b = 0.706 in.

Loading, grams	Beam #1 Bridge Strain μ in/in	Beam #1 Relative Gage Strain $\frac{\epsilon_f - \epsilon_i}{4} = \epsilon_g$, μ in/in	Beam #2 Bridge Strain μ in/in	Beam #2 Relative Gage Strain $\frac{\epsilon_f - \epsilon_i}{4} = \epsilon_g$, μ in/in
0	7083	0	9182	0
2	7271	47	9320	35
4	7460	94	9462	70
6	7640	139	9598	104

	Beam #1: b = 0.507 in.		Beam #2: b = 0.706 in.	
Loading, grams	Bridge Strain μ IN/IN	Relative Gage Strain $\frac{\epsilon_f - \epsilon_i}{4} = \epsilon_g$, μ IN/IN	Bridge Strain μ IN/IN	Relative Gage Strain $\frac{\epsilon_f - \epsilon_i}{4} = \epsilon_g$, μ IN/IN
8	7816	183	9741	140
10	7993	228	9881	175
12	8184	275	10029	212
14	8370	322	10169	247
16	8552	367	10303	280
18	8731	412	10444	316
20	8926	461	10583	350
22	9107	506	10720	385
24	9290	552	10851	417
26	9477	599	10989	452
28	9667	646	11123	485
30	9852	692	11272	523
32	10053	743	11420	560
34	10235	788	11555	593
36	10411	832	11700	630
38	10602	880	11830	662
40	10816	934	11977	699
42	10991	977	12111	732
44	11179	1024	12265	771
46	11352	1067	12400	805
48	-----	----	12546	841
50	-----	----	12671	872
Descending				
44	-----	---	12271	772
40	10845	941	-----	---
38	-----	---	11832	662
35	10380	824	-----	---
32	-----	---	11438	564
30	9906	706	-----	---
26	----	---	11011	457
25	9423	585	-----	---
20	8972	472	10600	355
15	8505	356	-----	---
14	----	---	10172	248
10	8053	243	-----	---
8	-----	---	9758	144
5	7592	127	----	---
2	----	---	9340	40
0	7150	17	9208	7

By equation 14 and the results of the respective calibration curve, the moment strain relation for each of the beams is found by the following:

$$\frac{M_A}{\epsilon_g} = \frac{E I \ell}{c(\ell - g)} = \frac{R_B \ell}{\epsilon_g}$$

Beam #1: $\frac{M_A}{\epsilon_g} = \frac{R_B \ell}{\epsilon_g} = \frac{6 \text{ GRAMS}}{141 \mu \text{ IN/IN}} \cdot \frac{1 \text{ OZ}}{28.35 \text{ GRAMS (EQUIV. "FORCE")}} \cdot \frac{12 \text{ IN}}{1}$

$$M_A = 0.01801 \frac{\text{OZ-IN}}{\mu \text{ IN/IN}} \cdot \epsilon_g \qquad \text{(A-1)}$$

Beam #2: $\frac{M_A}{\epsilon_g} = \frac{R_B \ell}{\epsilon_g} = \frac{6 \text{ GRAMS}}{106 \mu \text{ IN/IN}} \cdot \frac{1 \text{ OZ}}{28.35 \text{ GRAMS (EQUIV. "FORCE")}} \cdot \frac{12 \text{ IN}}{1}$

$$M_A = 0.02395 \frac{\text{OZ-IN}}{\mu \text{ IN/IN}} \cdot \epsilon_g \qquad \text{(A-2)}$$

Direct Reading Instrumentation With Transmitter

Circuit Instrumentation: The circuit diagram is presented in Figure 10(a), with the transmitter.

Transmitter calculations for the calibration of the transmitter are presented in Appendix B.

V_i, applied circuit voltage = 10 volts.

Channel Adjust Potentiometer: The potentiometer is adjusted to provide a recorder scale reading of 5 units for zero beam loading. (Note that 5 units on recorder scale correspond to 9.03 mv across the strain gage bridge output terminals for the zero loading condition.)

Data: Beam #1: b = 0.507 in. Beam #2: b = 0.706 in.

Loading, grams	Beam #1 Recorder Reading Arbitrary Units	Beam #2 Recorder Reading Arbitrary Units
0	5.0	5.0
5	16.8	13.6
10	29.0	22.7
15	41.0	31.6
20	53.2	41.0
25	65.3	50.0
30	77.7	59.2
35	89.5	68.6
39	98.2	----
40	Limit	77.6
45	of	86.8
50	Recorder	96.0
Descending		
45	----	86.5
40	----	77.6
39	98.2	----

Loading, grams	Beam #1: b = 0.507 in. Recorder Reading Arbitrary Units	Beam #2: b = 0.706 in. Recorder Reading Arbitrary Units
35	89.5	68.5
30	77.5	59.6
25	65.1	50.2
20	53.2	40.8
15	41.0	31.8
10	29.0	22.8
5	16.6	13.8
0	5.2	5.0

Direct Reading Instrumentation
Without Transmitter

Circuit Instrumentation: The circuit diagram is presented in Figure 10(a), with the dashed connections showing the transmitter omission.

V_i, applied circuit voltage = 10 volts.

Channel Adjust Potentiometer: Adjusted to provide a recorder scale reading of 5 units for zero beam loading. (Five units on recorder correspond to 12.0 mv across the strain gage bridge for the zero loading condition since the transmitter is not being used.)

Data:

Loading, grams	Beam #1: b = 0.507 in. Recorder Reading Arbitrary Units	Beam #2: b = 0.706 in. Recorder Reading Arbitrary Units
0	5.0	5.0
5	11.0	10.0
10	17.0	14.5
15	22.9	19.5
20	29.0	24.0
25	35.0	28.5
30	41.5	33.5
35	47.6	38.0
40	53.9	43.0
45	60.6	48.0
50	----	53.0
Descending		
40	55.1	43.5
30	42.5	34.0
20	30.0	24.0
10	17.5	14.5
5	11.0	10.0
0	5.0	5.0

APPENDIX B

TRANSMITTER CALIBRATION

Material Limitation: Yield strength = 20,000 psi, tension and compression. Yield strength is the stress which corresponds to a permanent set in the part, usually 0.001 or 0.002 in/in (8). To assure that no permanent deformation occurs, the maximum stress experienced by the beam is arbitrarily limited to one-half of the yield strength.

Modulus of elasticity, $E = 10.0\ (10)^6$ psi

From

$$E\,\epsilon = \sigma \tag{12}$$

$$\epsilon_{max.\ allowable} = \frac{20{,}000\ \text{PSI}}{2}\ \frac{1}{10.0\ (10)^6\ \text{PSI}} = 1000\ \mu\ \text{IN/IN}$$

For beam #2 by the calibration curve

$$M_A = 0.02395\ \frac{\text{oz-in}}{\mu\text{in/in}}\ \epsilon_g \tag{A-2}$$

For the maximum allowable strain in the part without deformation

$\epsilon_g = \epsilon_{max.\ allowable}$ and

$$M_A = 23.95\ \text{oz-in.}$$

By equation 33, the bridge circuit output voltage is expressed as

$$V_{OUTPUT_{MAX.}} = \frac{c(\ell - g)}{EI\ell} \cdot \frac{-V_i R_g F}{(R_i + R_g)} M_A$$

$R_i = 120$ ohm

$R_g = 12,500$ ohm

$F = 2.09$

$M_A = 23.95$ oz-in (max. allowable by strain consideration)

Select $V_i = 10$ volts (meaningless algebraic sign omitted)

$$V_{OUTPUT_{MAX.}} = \frac{1\,\mu\text{ IN/IN}}{0.02395\text{ OZ-IN}} \cdot \frac{10\text{ VOLTS}\;\; 12.5\,(10)^3\,\Omega\;(2.09)}{(0.120 + 12.5)(10)^3\,\Omega}\; 23.95\text{ OZ-IN}$$

$$V_{OUTPUT_{MAX.}} = 20.7\text{ MV}$$

A potential of 8 millivolts is selected as the apparent minimum strain gage bridge output and is controlled by the circuit adjust potentiometer. Thus the output voltages of the strain gage bridge are

$V_{min} = 8$ mv

$V_{max} = 8$ mv + 20.7 mv = 28.7 mv

The span voltage of 20.7 mv is the change in voltage across the bridge produced by the resistance changes in the strain gages.

For the transmitter calibration by the Minneapolis-Honeywell Instruction Manual, two equivalent voltages are used.

Minimum equivalent voltage = 8 mv (1.25) = 10 mv

Span equivalent voltage = 20.7 mv (1.25) = 25.89 mv

Since the least count of the millivoltage source used in the calibration of the transmitter is 0.05 millivolts, a span equivalent voltage of 25.90 mv is used in the interest of reading repeatability.

APPENDIX C

MEASUREMENT OF FACE SEAL FRICTIONAL TORQUE

Test Conditions:

Seal assembly: A Thompson Fuel Seal and Stationary Seal of unknown history were used for the test.

Axial seal pressure: A pressure corresponding to the force applied with the axial drive spring in Figure 11 compressed to one-half its free length was used.

Fluid: Kerosene

Fluid pressure in stationary seal housing: 10 psig.

Fluid Temperature: 75°F

Flow rate: 0.5 gpm (approx.)

Shaft speed: 7500 rpm.

Torque Measurement:

Direct Reading Instrumentation: Figure 10(a) was utilized, first with the transmitter in the circuit, then with the transmitter removed as denoted by the dashed connections.

Indirect Reading Instrumentation: Figure 10(b) and equation 38 were used.

Calculations of Frictional Torque: Since for comparison purposes the accuracy of each torque determination should be as great as possible, the torques have been calculated by using the recorder and strain indicator readings and the various beam calibration curves and data. However, during operation of the Fluid Seal Test Facility, the frictional torque is normally determined directly by the torque scale located above the recorder chart.

Data:	Beam #1	Beam #2
Direct Reading Instrumentation (transmitter in circuit)		
Recorder reading	14.0 units	12.4 units
Seal frictional torque	1.61 oz-in	1.82 oz-in
Direct Reading Instrumentation (without transmitter)		
Recorder reading	10.0 units	9.0 units
Seal frictional torque	1.76 oz-in	1.69 oz-in
Indirect Reading Instrumentation		
Bridge strain, final	10192 μin/in	10040 μin/in
Bridge strain, initial	9780 μin/in	9755 μin/in
Relative gage strain	103 μin/in	71 μin/in
Seal frictional torque	1.85 oz-in (Eq. A-1)	1.71 oz-in (Eq. A-2)

Calculations:

Average of torques: 1.74 oz-in

Maximum deviation from this average: -0.13 oz-in (1.61 reading)

Percent deviation from the average: 7.47%

By the analysis of a frictional-contact axial clutch experiencing uniform pressure loading (8), the coefficient of sliding friction of the carbon seal and mating steel face can be found from

$$M_A = \frac{F\,f}{3} \cdot \frac{D^3 - d^3}{D^2 - d^2}$$

where M_A = Applied frictional moment, oz-in,

F = Axial force, oz,

D = Outside diameter of friction disk, in,

d = Inside diameter of friction disk, in, and

f = Coefficient of friction.

The dimensions of the mating seal surfaces required for the above calculation are

$D = 0.625$ in

$d = 0.375$ in.

The axial force is the summation of the pressure force exerted by the fluid and the spring force.

$$F = (10\ \tfrac{lb}{IN^2})\ \frac{\pi}{4}(0.625^2 - 0.375^2)\ IN^2 + 2.25\ lb = 4.21\ lb = 67.36\ oz$$

Thus

$$f = \frac{3\ M_A}{F} \cdot \frac{D^2 - d^2}{D^3 - d^3} = \frac{3\ (1.74)}{67.36} \cdot \frac{0.25}{0.1914} = 0.101$$

A comparison of this coefficient of friction can be made with the static friction of hard steel on graphite under greasy conditions (9). The static frictional coefficient is reported as 0.09. Since the coefficient of static friction is normally greater than the coefficient of sliding friction, the sliding coefficient although not reported in the reference would probably be lower than the 0.09 quantity. Also since dissimilar lubrication conditions are present, the comparison becomes even more qualitative.

APPENDIX D

INSTRUMENTS AND EQUIPMENT

Instruments

1. Millivolt Potentiometer: Thwing-Albert Instrument Co., Range 101 mv, Least Count .05 mv, Type PM-1, Serial No. 9029.

2. Millivolt Potentiometer: Leeds and Northrup Co., Range -10.1 mv to +100.1 mv, Least Count 0.005 mv, Cat. No. 8686, Serial No. 1583769.

3. SR-4 Strain Indicator: Type N, Baldwin Lima Hamilton, Serial No. 784746.

4. Millivolt to Current Transmitter: Minneapolis-Honeywell Regulator Co., Brown Instrument Division, Input adjustable span 0 - 2.5 to 0 - 100 mv d-c, Output 4 to 20 ma d-c, Model 1FB35-641, Serial No. 17239.

5. Millivolt Recorder: Minneapolis-Honeywell Regulator Co., Brown Instrument Division, 24 Point (With kit 919H10 for 3 point recording), Input 10 to 50 mv, Model Y153X87-(C)-II-III-101, Serial No. A1166632001.

6. Direct Current Vacuum Tube Voltmeter: Hewlett Packard Co., Model 412 A, Serial No. 004-03250.

7. Power Supply Components: 1. Helipot Potentiometer, 10,000 ohm, 3 turns, Model C; 2. Direct Current Voltmeter, Weston, Range 0 - 15 volts, Least Count 0.2 volts; 3. Internal Power Supply, Elcor, Inc., Output 9 - 11 volts, 150 ma, Model AT10 - 150, Serial No. 124-361; Power supply assembled by the author.

8. Circuit Adjust Components: Two Helipot Potentiometers, 10,000 ohm, 10 turns, Model A; Circuit adjust assembled by the author.

Equipment

Unequal Arm Balance: Ohaus Co., Range 610 grams, Least Count 0.1 grams.

VITA

Fred Morris Welsh

Candidate for the Degree of

Master of Science

THESIS: DEVICE FOR THE MEASUREMENT OF SMALL FRICTIONAL TORQUE

MAJOR FIELD: Mechanical Engineering

BIOGRAPHICAL:

Personal Data: Born in Tulsa, Oklahoma, November 6, 1938, the son of Fred Morris and Clara Etta Welsh.

Education: Attended grade school in Tulsa, Oklahoma; graduated from Tulsa Central High School in 1956; received the Bachelor of Science degree from Oklahoma State University, with a major in Mechanical Engineering, in May, 1961; completed the requirements for the Master of Science degree in May, 1962.

Experience: Employed as a Detail and Design Draftsman and as a Heat Transfer Research Technician during summer months of the undergraduate study; served as a Research Assistant in the School of Mechanical Engineering, Oklahoma State University, from June, 1960, to August, 1961; employed as a Graduate Teaching Assistant from September, 1961 to January, 1962; served as an Instructor in the Mechanical Engineering Department from January, 1962 to June, 1962.

Professional Organizations: Member of the American Society of Mechanical Engineers; Engineer-In-Training, State of Oklahoma, State Board of Registration for Professional Engineers.

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Honors and Awards: Who's Who Among Students in American Universities and Colleges, 1959-1960.