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Design considerations are presented which apply to all types of electrical resistance strain gage transducers. While the concepts apply to mass produced transducers, the information should be most useful for the engineer or technician who designs one-of-a-kind or "home-made" transducers.

Errors which affect the accuracy of strain gage transducers are presented together with the usual techniques of eliminating or minimizing these errors. Procedures are detailed for temperature compensation and for modulus compensation. References are given which discuss each of the errors or problems in detail.

Nomographs are presented which calculate strain levels, maximum excitation, and output signal for torsion, axial force, beam, ring, and diaphragm type transducers. Five transducer examples illustrate the use of the nomographs.

Design Considerations for Strain Gage Transducers

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DESIGN CONSIDERATIONS FOR STRAIN GAGE TRANSDUCERS

INTRODUCTION

Electrical resistance strain gages are in common use today to determine stresses on structural members. The ease with which strain gages can be attached to metals has led to their widespread use in industry. Also, refinement of readout equipment has made oscilloscopes and strain indicators readily available.

The need to measure parameters such as acceleration, displacement, force, pressure and torque often leads to the development of special transducers. The cost of a transducer is usually much less than its readout equipment. Where strain gage signal conditioning equipment is already available, the relative low cost and versatility of strain gage transducers make them attractive.

A bonded strain gage transducer consists basically of an elastic structure which will strain linearly with the parameter being measured, and strain gages attached to the structure which convert strain to electrical signal.

The design of the elastic structure involves deflections, stiffness, forces, and natural frequency of the structure. Nomograph solutions are presented in the appendix for some common configurations.

Values computed from nomographs have limited accuracy due to the problems of printing, straight edge manipulation and drafting. To insure dimensional accuracy, these nomographs were drawn by a computer plotter. The computer program is included in the appendix.

However, extreme accuracy is not needed in most calculations. Roark (12, p. 58) states:

> No calculated value of stress, strength, or deformation can be regarded as exact. The formulas used are based on certain assumptions as to properties of materials, regularity of form, and boundary conditions that are only approximately true, and they are derived by mathematical procedures that often involve further approximations. In general, therefore, great precision in numerical work is not justified.

The following presents some of the problems which have been encountered by strain gage transducer manufacturers. Their common methods of avoiding or minimizing problems are presented. References are given which treat each of the problems in greater detail. However, the design of readout equipment is beyond the scope of this thesis.

GENERAL CONCEPTS

A strain gage transducer converts some measured parameter to a resistance change. A structure is designed to deform elastically when subjected to some physical quantity. Strain gages mounted on the elastic element are elongated (or compressed) by strain in the metal. The gages change resistance with elongation. A voltage change accompanies the resistance change. The voltage change is measured by a suitable readout device; an oscilloscope, a strain gage indicator, a galvanometer, etc. Errors can affect the transmission of information at any of these locations in a strain gage transducer system.

A good strain gage transducer must respond only to the measured parameter and not to spurious inputs such as temperature, humidity, side load, or vibration. In general, it must have low hysteresis, good linearity, good repeatability and low zero shift.[1]

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[1] See glossary of terms (p. 40) for definition of technical terms.

MEASURED PARAMETER VS. STRAIN IN ELASTIC ELEMENT

Factors affecting the relationship between measured parameter and strain in an elastic element include:

Configuration

The single, most important relationship between strain and measured parameter is the configuration of the transducer. The effects of dimensions, type of transducer, and material properties are presented in nomographs in the appendix for numerous simple transducer designs. The nomographs are illustrated by examples later in the text. For transducers not covered in the appendix, see references such as Roark's Formulas for Stress and Strain (12).

Deviations from Simple Elastic Theory

Deviations from the simple elastic theory usually cause only small non-linearity. Shortening of cantilevers as they deflect, stretching of diaphragms and other non-linearities are limited by limiting deflection. See nomographs Figures 10 and 18.

Material Selection

Material properties such as Young's modulus, modulus of rigidity and Poisson's ratio vary with heat treatment, alloying proportions, and cold work to name just a few factors. Stein says that handbook values will vary 5% (13, p. 447).

Stein discusses the metallurgical problems associated with transducers. Unless a transducer must have precise zero return or meet other special requirements, one of the metals in Table 2 will be adequate (13, p. 410).

Temperature Problems

Two additional problems with most materials are the variation of the modulus of elasticity with temperature and the expansion of metals with increasing temperature. These problems will be discussed under Temperature Changes, Gage Heating.

Machining

Machining tolerances and dimensional uncertainties will affect sensitivity of a transducer. For instance, machining a 1/8 inch by 1/8 inch cross section to 0.124 by 0.124 inch will increase strain 2-1/2% when the transducer is used in bending as a load cell.

Residual stresses caused by rolling, drawing, stretching or very large overloads will cause hysteresis (noncoincidence of loading and unloading curves). Stein says:

> Exercise works out these localized stresses, whereas a stress relieving operation allows the stresses to work themselves into uniformity. A hundred cycles or so are all that

need to be carried out, but the loads imposed should be 50% higher than normal (10, p. 417).

Supporting Structure

Imperfections of the supporting structure will, at best, change only the sensitivity from the calculated value. Pinned bearings, clamped beams or bolted joints cause mechanical hysteresis or friction. For precision transducers, Stein recommends welding, brazing, the use of flexures and "fancy, 3-dimensional machining from a solid piece. . ." (13, p. 419).

Alignment

Additional problems arise in the application of transducers. Misalignment of transducers with the direction of load usually causes only small errors since transducer load varies with the cosine of the misalignment. However, large errors can result from cross axis sensitivity, especially if forces are to be resolved into components and the smaller of the components is to be measured (as in the case of wind tunnel balances).

Natural Frequency

Undamped transducers such as diaphragm pressure gages and accelerometers exhibit inaccuracies of 10% when subjected to sinusoidal excitation of about 0.3 times their natural frequency (16, p. 76). When excited at 0.1 times their natural frequency, the error is down to 1%. The useful range can be extended to 0.4 times the natural frequency if a suitable damping oil or electrical damping is added. However, the addition of oil can decrease the natural frequency (16, p. 34). Dove and Adams discuss mounting techniques and their effect on natural frequencies of accelerometers (6, p. 482). Natural frequencies are given in the appendix for the more common transducers.

Transient Measurements

Transient motion measurements such as wave propagation and mechanical shock increase dynamic requirements of transducers. An undamped transducer overshoots a square wave input by 100%. If the natural frequency can be made high enough so that five or more cycles of the transducer correspond to the rise time of the input (all "square" waves have a finite rise time), the transient motion will be measured fairly accurately. The addition of damping improves the transient response of most transducers by removing transducer natural frequencies from the output (8).

Modification of Measured Parameter

Any measuring system will affect the phenomenon being measured. Every measuring system transfers energy in order that information can be passed.

> The amount of energy drawn from the source system in the process of measurement must be small compared to the total amount of energy available in the source system at the point of disturbance (13, p. 47).

A pressure transducer requires a volume change; a force transducer requires displacement; a displacement transducer exerts a force on the "source system." An accelerometer must have a much smaller mass than the object to which it is attached; volume change of a pressure transducer must be small compared to the combustion chamber of an engine; the force required to deflect a cantilever which measures displacement of a concrete structure must be small compared to the forces deflecting the structure.

STRAIN IN ELASTIC ELEMENT VS. STRAIN IN GAGES

Elongation in the strain gage is considered representative of the calculated strain in the metal. Factors affecting this relationship include:

Stiffening Effect

On thin sections, especially in bending, the gages, their cement and waterproof covering tend to carry an appreciable portion of the load, stiffen the section, and give a low reading. For metal sections larger than 1/8 by 1/8 inch the effect is usually small (6, p. 217-221).

Gage Misalignment

Gage misalignment is a serious problem only in the torsion transducer where gages are applied at 45 degrees to the axis of a shaft. A small error in gage orientation will result in rather large sensitivity to bending or tension. Failure to mount gages on the centerline of axial force or bending transducers results in cross axis sensitivity, especially in narrow, deep sections.

Gage Thickness

Gages have a finite thickness and are located above the surface of the metal. In bending of thin sections, the strain in the gages will therefore be larger than the strain in the metal. This effect tends to cancel the stiffening effect and is small for metal thickness larger than 1/8 inch.

Gage Size

All strain gages have a finite size. As a result, they average strain over their length and cannot always be placed on the area of maximum strain. The resulting loss in sensitivity can be as much as 30%.

Adhesives

Cement creep gives the strain gage an apparent strain. Factors affecting cement creep include temperature, moisture, curing cycle, type of cement, and thickness of glue line. Manufacturers' recommendations should be relied upon for limitations of cements, curing method and technique (9, p. A129-131, A137). The temperature of a precision transducer should be kept well below the curing temperature of the adhesive.

STRAIN IN GAGES VS. RESISTANCE CHANGES

Gage resistance change versus elongation is the gage factor:

$$GF = \frac{\Delta R/R}{\Delta L/L}$$

Strain gage manufacturers vary the cold work, the alloy composition, etc. to arrive at a gage factor. Gages are mounted on a specimen and the gage factor is determined experimentally. Some factors affecting resistance versus elongation are:

Gage Factor Tolerance

Manufacturers depend upon similarity and quality control to limit gage factor variations. As a result, gage factor tolerance is usually specified about 1%. Therefore, use identical gages, from the same package and lot number.

Temperature Changes, Gage Heating

Temperature changes will cause spurious zero shift resistance changes due to differential expansion between gage and specimen and due to thermal coefficient of resistivity. "Zero shift" due to temperature can usually be reduced to less than 1% of full output between 50 and 80°F by the following:

Use strain gages temperature-compensated to match the metal used for the elastic element. For transducers used at temperatures near room temperature, the normal gage compensation should be used. It should be emphasized that over a wide temperature range, any "temperature compensated" strain gage will show temperature sensitivity. Manufacturers publish families of "apparent strain" curves--readout versus temperature for zero mechanical strain. For transducers operating at other temperature ranges (say from -80 to -150°F), a compensation should be selected for the elastic element which gives the lowest apparent strain change over the desired temperature span. Thus a gage which is "compensated for steel" at room temperature may be the best gage to use on an aluminum transducer used near 250°F.

Use a four-arm bridge with all four gages mounted on the elastic element.

Subject electrically adjacent pairs of gages (i.e., gages C and T, Figure 1) to similar temperature conditions. Maintain symmetry of heat transfer; be sure that protective coatings are the same thickness on all gages; eliminate thermal gradients where possible; shield a bending transducer from thermal radiation.

Design the transducer with a high output (use high strength elastic element). While this does nothing to reduce temperature effects, it will make the temperature sensitivity a smaller percent of the measured parameter (6, p. 106).

Because strain gages are resistors, the transducer must dissipate heat. Maximum voltage which can be applied to a transducer is limited by the heat dissipation capability to the mounting surface. Excessive temperature differences between the strain gage grid and the elastic element cause loss of temperature compensation, hysteresis and cement creep. Bubbles and voids in the cement cause local "hot spots" which degrade transducer performance (9, p. TN-127). Figure 15 shows recommended excitation levels for gages mounted on various surfaces (9, p. TN-127). Stein discusses a pulsed excitation method in which a high voltage bridge supply does not cause high gage heating. The system also has other advantages (14).

The maximum voltage which can be supplied to a strain gage transducer can be determined experimentally. At zero load, slowly increase excitation voltage until a zero shift occurs. The last stable voltage is the maximum which can be supplied (9, p. TN-127).

The problems of drift and temperature compensation are greatly minimized if the transducer can be dynamically tested or used in a rapid manner.

Pressure Sensitivity

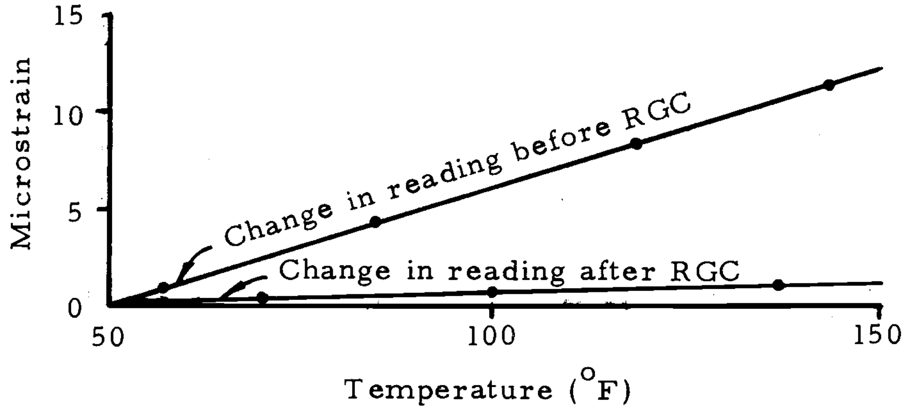
Strain gages subjected to large pressures can exhibit large errors (the basis of the Bridgman pressure gage (7, p. 166)). Pressure applied to the grid of a strain gage compresses the gage and increases its resistance. A pressure of 100 pounds per square inch applied to one gage of a transducer will cause a change of about 10 microstrain (10^{-5} inch/inch).

Compensation for Temperature Induced Zero Shift

Wider temperature variations or requirements for better accuracy require consideration of additional problems.

After following the recommendations under Temperature Changes, Gage Heating, the transducer will still have some temperature sensitivity; the bridge balance point will still vary somewhat with temperature. The following procedures usually involve a large amount of trial and error work. They should be used only where high accuracy is needed. They must be done before final waterproofing.

Hook up the transducer to a strain indicator and balance it. Increase the temperature of the transducer 100 degrees (say from 40 to 140°F); record the balance point shift. For each microstrain the balance point increases (120 ohm gages), add 0.05 inch of No. 34 copper wire to a compressive arm of the bridge. (For 350 ohm gages, add 0.14 inch per microstrain.) If the balance point decreases, put the temperature sensitive copper "resistor" in the tension arm (see Figure 1). Then repeat the temperature test. If the balance shift is sufficiently minimized, add a constantan resistor (RBAL) in an arm



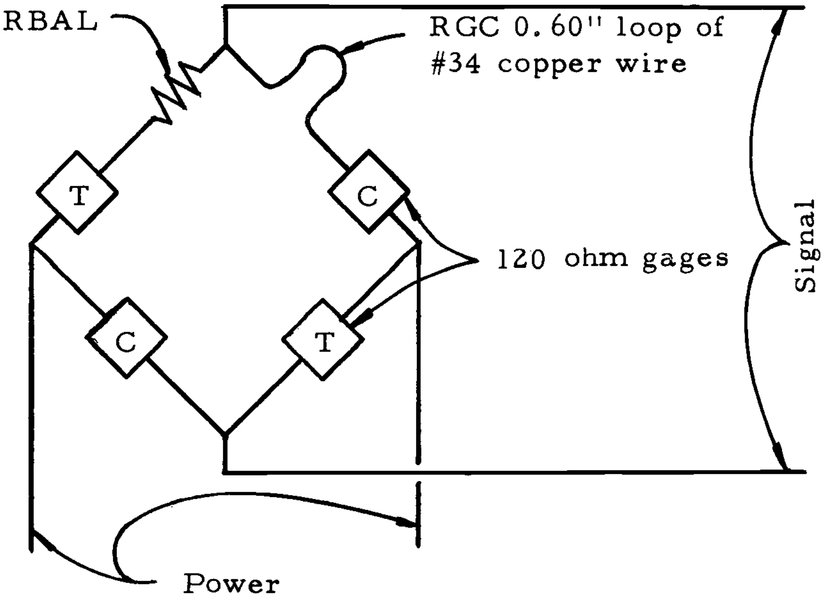


Figure 1. Temperature compensation.

adjacent to the copper wire to bring the bridge back into balance (3).

Modulus Compensation

Gage factor, elastic constants, and dimensions change with temperature. To compensate for the usual increase in sensitivity with temperature due to these factors, a resistor is placed in the power leads to decrease current to the Wheatstone bridge. Average values of the compensating resistor have been tabulated by strain gage manufacturers and range from 2 to 50 ohms.

To determine the value needed for the compensating resistor, it is first necessary to calibrate the transducer at various temperatures. The transducer must be calibrated in the same manner as it will be loaded in use. In calibration for modulus compensation, the spring constant of the loading structure is just as important as the spring constant of the transducer. Stein says, "System responses to force governed and displacement governed loading systems are entirely different!" (15, p. 465). Opposite extremes in spring constant of the loading structure are dead weights with almost zero spring constant and gage blocks with almost infinite spring constant.

Load the transducer at various temperatures to obtain the curve in Figure 2. (If the procedure in Compensation for Temperature Induced Zero Shift were followed, the readout should not change for zero load.) Place a nickel resistor in the power supply diagonal of the

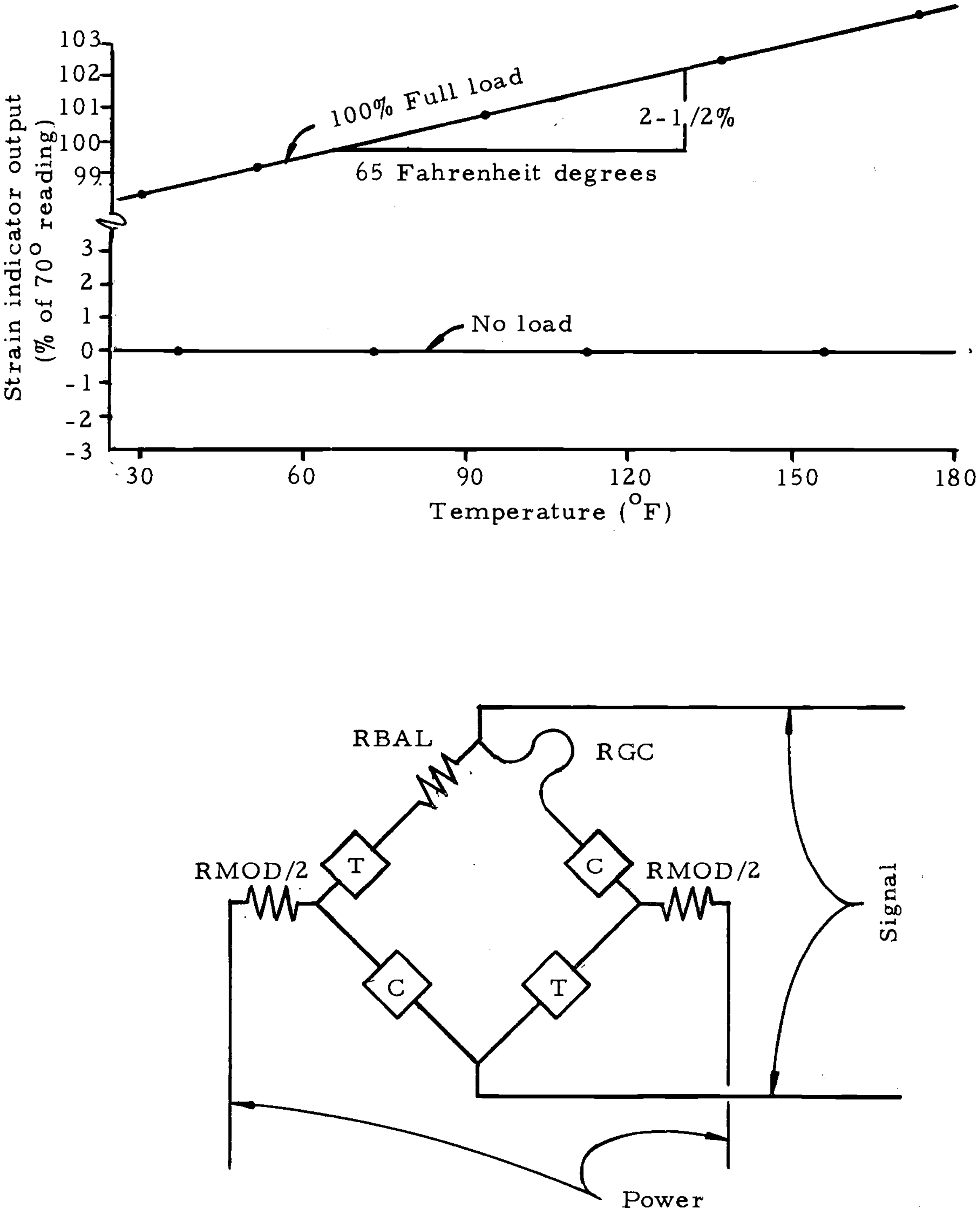


Figure 2. Modulus compensation.

bridge circuit. To find its resistance value, find the sensitivity change over a 65°F span. Multiply the sensitivity change by four times the bridge resistance. Thus in Figure 2, the bridge resistance is 350 ohms, add 35 ohms or each RMOD/2 equals 17.5 ohms. After adding the resistors, repeat the procedure to check remaining temperature sensitivity.[1] (The sensitivity of this transducer will be lowered 10% as a result of the resistor.)

The purpose of using two identical resistors (RMOD/2) is to maintain symmetry and to simplify electrical calibration (see Calibration, Nature of Errors). Once the RMOD/2 resistors have been added to a transducer, it is imperative that the proper leads always be attached to the power supply.

Two additional resistors which are not temperature sensitive are sometimes put in transducers to standardize the sensitivity and the input resistance. RSEN in Figure 3 reduces the sensitivity of the transducer to some standard value. To avoid changing the modulus temperature compensation, it must be very small compared to the bridge resistance. RES reduces the input resistance to a standard value, it must be very large compared to the bridge resistance.

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[1] This is a simplified procedure which assumes that the bridge resistance is large compared to the internal resistance of the power supply, and that the temperature sensitivity of nickel (26% over 65 Fahrenheit degrees) is large compared to the temperature-sensitivity of the bridge. For a more exact analysis, see (11).

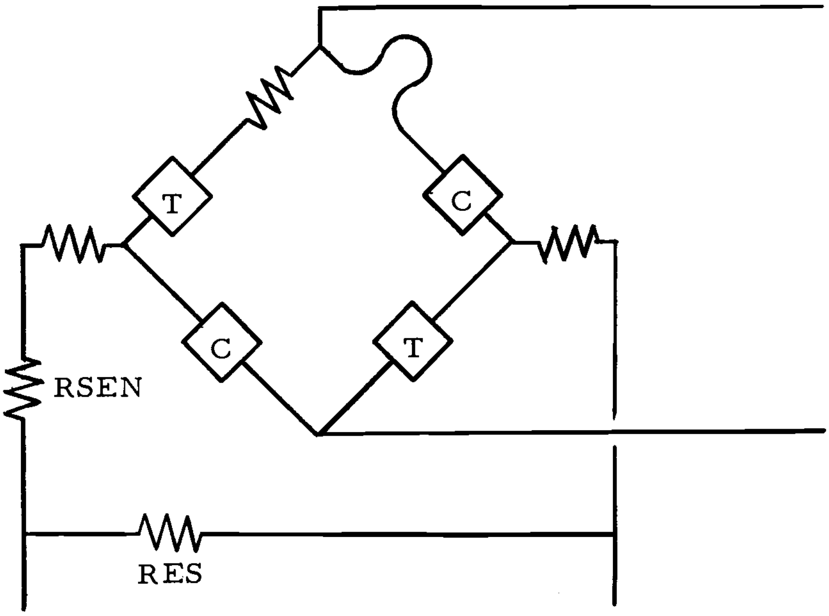


Figure 3. Standardization resistors.

These two resistors should only be used to standardize a family of transducers and are not needed in "one of a kind" transducers (15, 18).

GAGE RESISTANCE CHANGES VS. SIGNAL AT READOUT

The signal measured at the readout apparatus can be modified from the resistance signal at the compensated bridge. Several factors are:

Transducer Output

The transducer output, expressed in millivolts per volt, is proportional to strain in the metal, the gage factor, and the number of effective arms. The nomograph in Figure 16 illustrates this relationship. For an unbalance measuring system, the reading is proportional to the supply voltage. The millivolt output is the important design consideration, and applying a high voltage to the transducer is just as important as the millivolt/volt sensitivity. (For the maximum voltage which can be supplied, see Figure 15.) For null-balance measuring systems, the voltage which can be supplied is only of secondary importance; the millivolt/volt sensitivity is the design criteria (10). The supply voltage of null balance systems should be checked to prevent overheating (see Temperature Changes, Gage Heating.)

Switches and Slip Rings

Switches and slip rings in strain gage circuits are sources of randomly varying resistance. If switches or slip rings must be used, they should be placed in the leads, outside the Wheatstone bridge circuit. Other techniques are available for further minimizing slip ring and contact errors (5, p. 689; 6, p. 117).

Lead Wire

Lead wire resistances cause additional problems. Adding resistance in the form of long wires to the power leads reduces the sensitivity of a transducer. The problem can be minimized by using short, low resistance cables, high resistance gages, and by always using the same length cables. Cables subjected to unusually high pressure or mechanical strain behave as strain gages themselves and contribute errors (13, p. 170).

Lead wire resistance usually increases with temperature. While the use of high resistance gages, short cables, and full bridges minimize the problem, extreme temperature variations may require the use of special wire whose resistance changes little with temperature (such as constantan).

Large capacitance between long leads may cause capacitive balancing problems in alternating current bridges. Many strain indicators and oscilloscopes have built-in capacitance balance or capacitance compensation features (6, p. 150).

Moisture

Moisture causes erratic variations in resistances, producing changes which will be interpreted as strain. Underwater use of transducers requires special consideration of leakage paths. Strain gage manufacturers publish recommended coatings for various environments (9, p. A134).

Permeable cables which allow moisture to penetrate the outer cover should be avoided. Even though a cable may be specified waterproof for ordinary use, it may not be suitable for use with strain gage transducers. Leakage of cables can be checked by measuring open circuit resistance between leads with a Megger. If the resistance falls when several loops of cable (not the ends) are immersed in water, the cable should not be used. Special provision should be made to waterproof the ends of cables; moisture can travel down the cable and change resistance values (19).

Noise

Electrostatic and magnetic noise can interfere with strain signals. Stein discusses experimental noise hunting techniques and discusses methods of reducing or avoiding them (13, p. 220-h).

CALIBRATION; NATURE OF ERRORS

Many of the preceding errors and problems are of a constant nature. Variations in material properties, location of gages, machining inaccuracies, rigidity of supports, and gage factor variations will change the sensitivity of the transducer <u>from that which is calculated</u> by as much as 50%. Differences of 5 to 15% are common. These differences will not change the sensitivity with time. Therefore, when an overall system calibration is performed, relating readout change to primary parameter, the strain gage transducer can easily be made accurate within 1% of full scale (2).

"Electrical calibration" of transducers is a method of relating readout of an electrical device to a calibration resistor. It does nothing to insure that the measured parameter will actually cause such a resistance change. It cannot be performed in place of overall system calibration. This calibration method most often involves producing a known resistance change by means of parallel resistors, temporarily placed across one or more gages of a Wheatstone bridge (6, p. 99). In using electrical calibration with strain gage transducers, there are numerous problems, especially when the transducer has RMOD, RES and RSEN (Figure 3) resistors added (1).

TRANSDUCER EXAMPLES

Nomographs were constructed with the aid of a computer plotter for some common types of strain gage transducers. The examples which follow illustrate their use.

Table 1 (Appendix I) is a list of variables used in the nomographs. Figure 9 explains which nomographs to use for each type of transducer. For example, axial-force-transducer strain, and deflection, Y, are found from nomograph Figure 14. The natural frequency is found from Figure 13. The maximum bridge excitation and the output signal are found from Figures 15 and 16 respectively. The nomographs can be used to find any one of the unknowns in the equations they represent. The diaphragm pressure sensor nomograph, Figure 18, can be used to find STRAIN if the material and dimensions are known; if the material and STRAIN are known and thickness is given, radius can be found.

Cantilever Bending

The strain gage anemometer (Figure 4) is a roughened sphere mounted on a cantilever beam. The cantilever is made of aluminum and its width is equal to its thickness since both components of wind direction are to be measured. Determine length, L, deflection, Y, and natural frequency.

From Table 2, use 7075 T-6 aluminum with $E = 1.05 \times 10^7$ and design to only 1000 microstrain in the metal. From Figure 10 a cantilever has a strain sensitivity constant of 0.333 and a deflection constant of 3.0. Therefore, "KE" is 3.15×10^7 psi.

Enter Moment of Inertia nomograph, Figure 11, with $B = 0.4$ inch and $H = 0.4$ inch; determine $I = 2.1 \times 10^{-3}$ inches^4.

Enter Beam and Ring Bending nomograph, Figure 12, with:

KE = 3.15×10^7 psi
FORCE = 10 pounds
I = 2.1×10^{-3} inches ^{4}
STRAIN = 1000 microstrain
H = 0.4 inch
K2 = 0.333

Find Y = 0.22 in; L = 11.2 in.

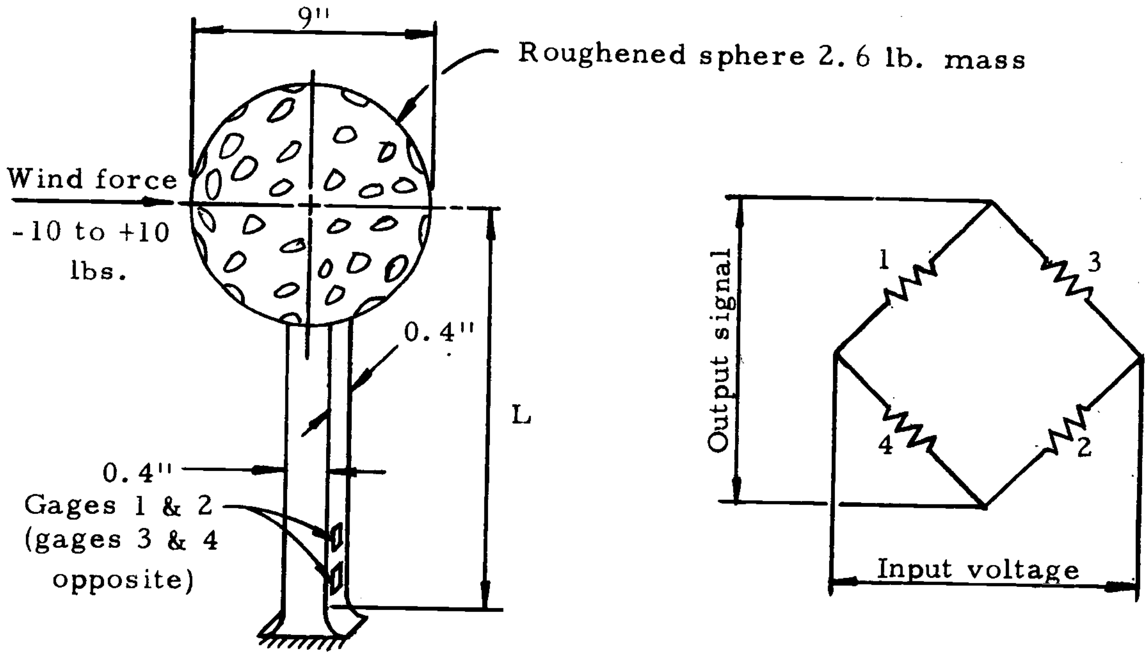


Figure 4. Strain gage anemometer.

Next, determine the natural frequency. The total mass is determined from Figure 10 as the concentrated mass plus 0.246 times the mass of the beam. The mass of the beam is 0.24 pounds. The total mass is therefore 2.66 pounds mass. (The mass of the beam was negligible compared to the sphere.) Enter Natural Frequency of Transducers, Figure 13, with Force = 10 pounds

Y = 0.22 inch

Total mass = 2.66 pounds mass

and determine frequency of 13 cycles per second.

Axial Force

An axial force or a P/A transducer is used to measure pressure fluctuations of 1000 psi. The transducer (Figure 5) is machined from one piece of Beryllium copper. The force varies from 0 to 1230 pounds.

Determine:

1. Strain in the metal
2. Deflection of the transducer
3. Natural frequency
4. Maximum voltage which can be applied to the bridge
5. Output signal when this voltage is applied to the bridge

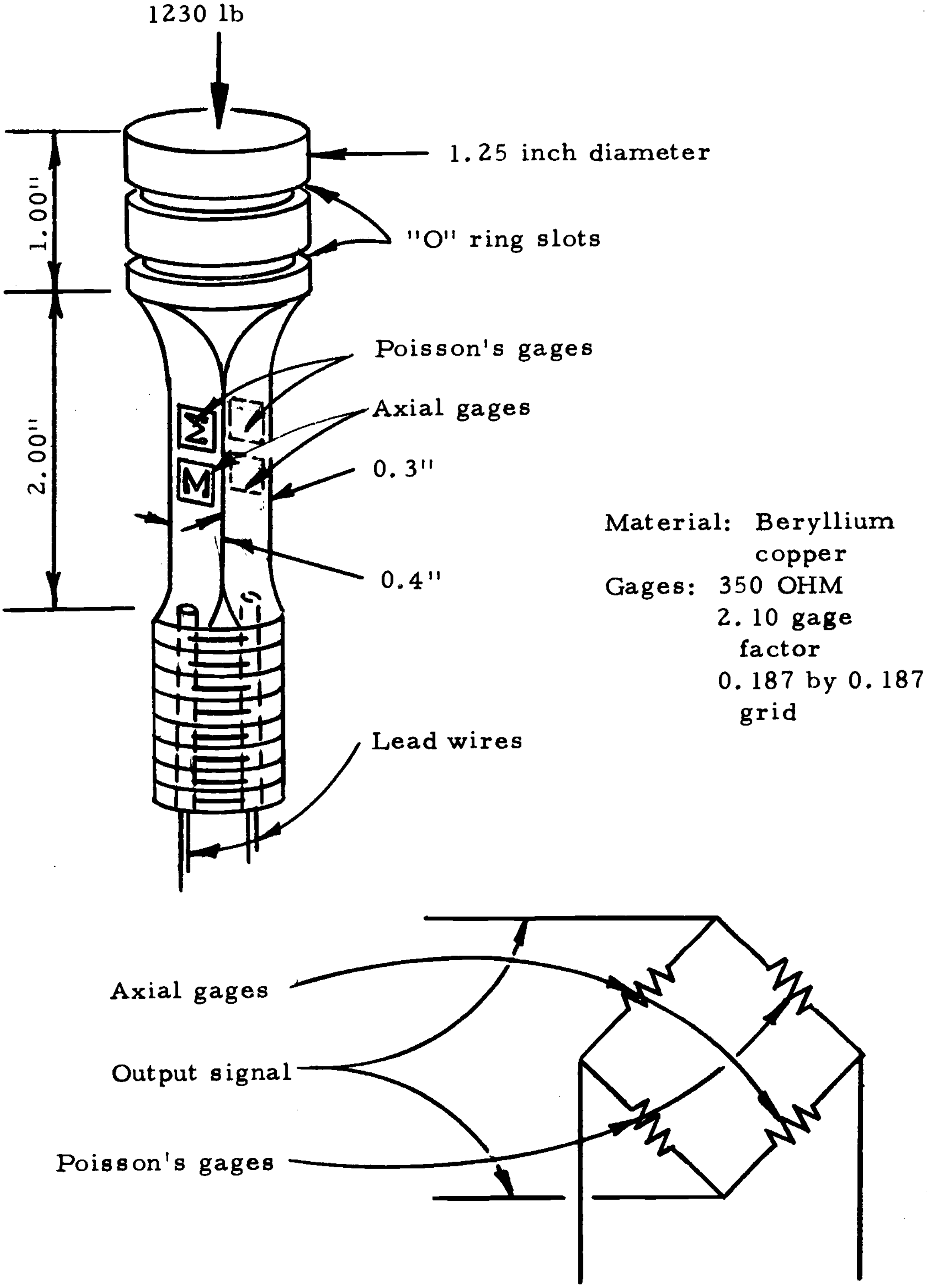
Enter Axial Force nomograph, Figure 14, with:

A = 0.12 square inches

FORCE = 1230 pounds

E = 18.5 x 10^6 psi (from Table 2)

L = 2.0 inches



Material: Beryllium copper
Gages: 350 OHM
2.10 gage factor
0.187 by 0.187 grid

Figure 5. Axial force pressure gage.

Determine strain of 550 microstrain (note that this is smaller than the allowable 2150 microstrain from Table 2 since all dimensions and loads were fixed). Also, find deflection of 0.0011 inch.

The "head" or the upper portion of the transducer has a mass of 0.37 pounds. The necked portion or the elastic element has a mass of 0.074 pounds. From Figure 10, the total mass is W + 0.333 M or 0.395 pounds.

Enter Natural Frequency of Transducers (Figure 13) and find a natural frequency of 6000 cycles per second (the example is not shown on the nomograph to avoid confusion. Also, the "PIVOT" must be extended).

The maximum voltage which can be applied to the bridge is determined from Figure 15. Use a value of 10 watts per square inch and 350 ohm gages and determine bridge excitation voltage of 21 volts.

The Poisson's ratio of Beryllium-Copper is 0.24 (Table 2). Therefore, the number of active arms is 2.48.[1] Enter Output Signal nomograph, Figure 16, with 2.48 active arms, 550 microstrain, and gage factor of 2.10 and find 0.73 millivolts per volt. Thus the output signal is 0.73 millivolts/volt x 21 volts or 15.3 millivolts.

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[1] A Wheatstone bridge with four gages arranged to measure both tension and compression as in the bending transducers will have four active arms. In this example, each Poisson's gage lengthens 0.24 times the calculated strain, each axial gage shortens according to the calculated strain. Thus the number of active arms is 2 + 2 (Poisson's Ratio).

Square Ring

The section of square tubing is used (Figure 6) to weigh loads lifted by a shop crane. Determine the maximum load which can be lifted and the relative deflection of the two shackles. Assume that the square tube is low strength steel, not one of the steels in Table 2, with a maximum allowable strain of only 600 microstrain.

From Figure 10, K = 24 and K2 = 0.236. The Elastic modulus of steel is approximately 30×10^6 psi, so KE is 7.2×10^8 psi. From the Moment of Inertia nomograph, Figure 11, the moment of inertia is 9×10^{-3}. Enter Beam and Ring Bending nomograph, Figure 12, with

KE = 7.2×10^8 psi
L = 5.6 inches (approximately)
K2 = 0.236
I = 9×10^{-3} inches ^{4}
H = 0.375 inch
STRAIN = 600 microstrain

And find FORCE = 900 pounds
Y = 0.025 inch

Diaphragm Pressure Transducer

A diaphragm type pressure gage is made of phosphor-bronze (Figure 7) (6, p. 388). Determine the strain at 10 psi and the natural frequency. Check the deflection to insure linearity.

Enter Pressure Transducer nomographs (Figures 17 and 18) with

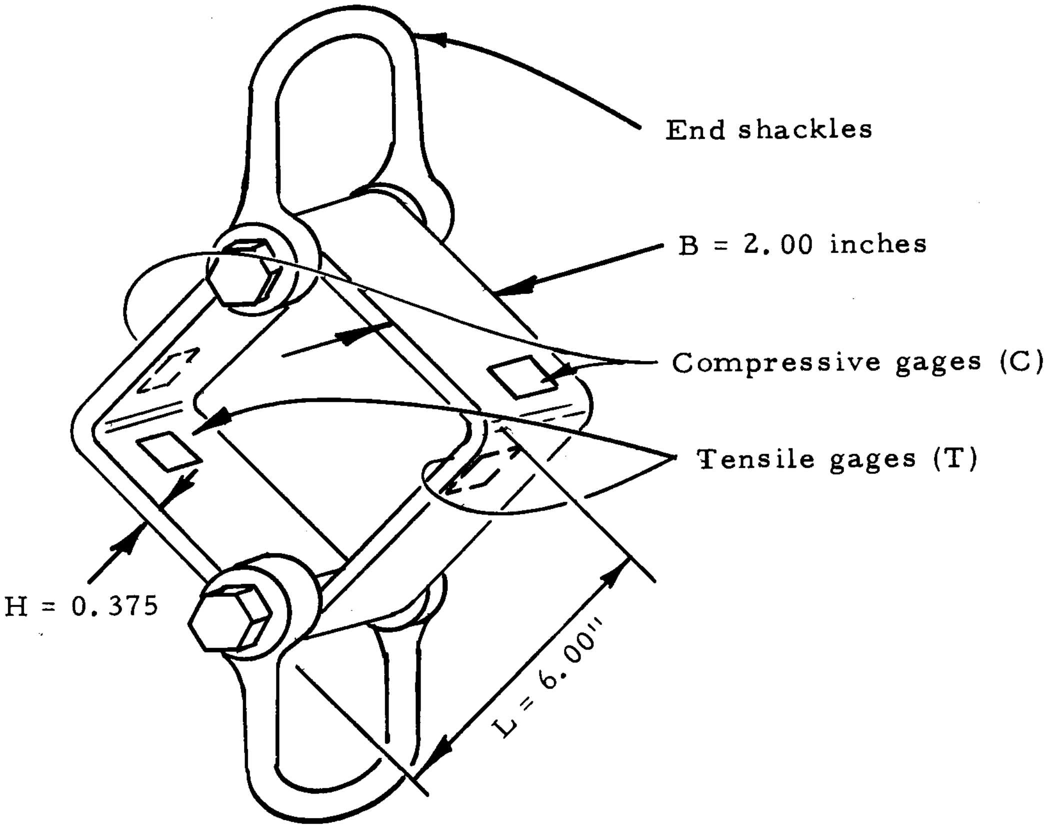

Figure 6. Square ring.

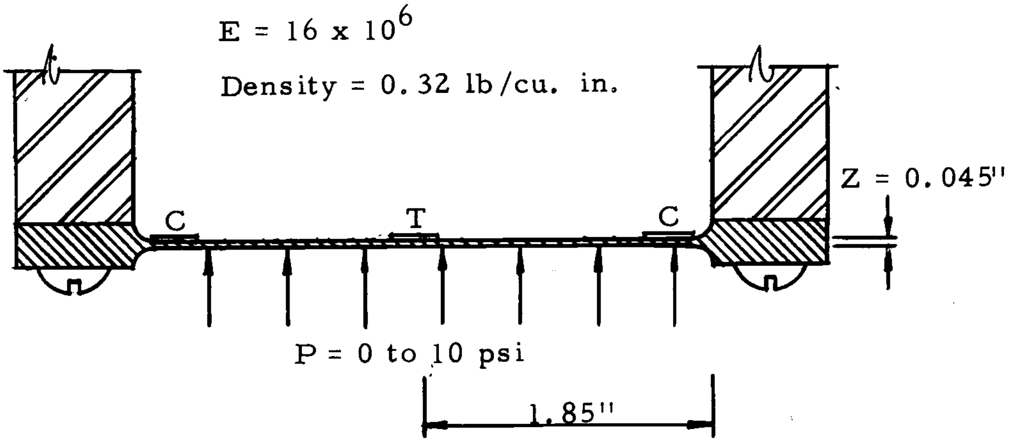

Figure 7. Diaphragm pressure transducer.

$E = 16 \times 10^6$ psi
$P = 10.0$ pounds
$R = 1.85$ inches
$Z = 0.045$ inch
DENSITY = 0.32 pounds/cu. in.

Find frequency of 930 cps, strain of 400 microstrain and deflection of 0.014 inches. (The deflection of 0.3 times the thickness causes a non-linearity of about 0.7 percent.)

Torsion

A square steel shaft is used to measure torque between a motor armature and a large flywheel (Figure 8). The motor develops 500 inch pounds upon starting. Determine shaft size if strain in the steel is to be limited to 1000 microstrain. Also determine the torsional deflection and the natural frequency.

In Figure 19, connect G of 1.06×10^7 with TORQUE of 500 to determine a point on pivot. Connect STRAIN and pivot to determine Q of 0.026 inches cubed.

To find the size of the shaft, in Figure 20, connect "square" and Q to find D of 0.5 inches. J is then 0.01 inches ^{4}.

Then re-entering Figure 19 with $J = 0.01$ inches^4 and $L = 6$ inches, determine THETA = 1.7 degrees or 0.030 radians.

To find the natural frequency of the armature-shaft, enter Torsional Frequency nomograph, Figure 21, with

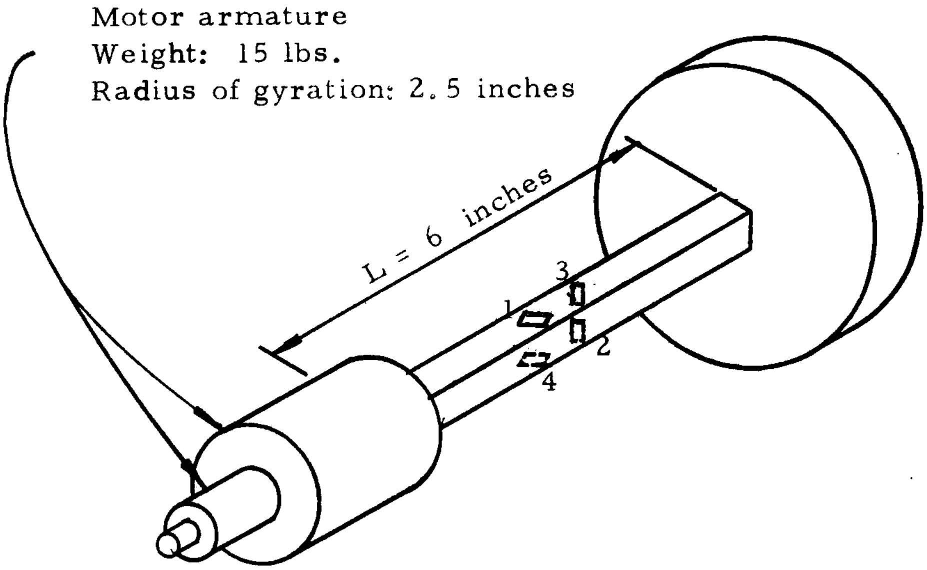

Figure 8. Torsion transducer.

THETA = 0.030 radian
TORQUE = 500 inch pounds
RADIUS OF GYRATION = 2.5 inches
MASS AT END OF SHAFT = 15 pound mass

Then determine FREQ = 40 cycles per second. (The polar moment of the armature is assumed to be much lower than that of the flywheel.)

CONCLUSION

Numerous authors have presented both experimental and theoretical work related to the measurement of strain on structures. Others have discussed one particular aspect of strain gage transducer design. Some (Stein) have presented extensive theoretical work on strain gage transducers.

The experimental work of strain measurements on structures has been modified and adapted to apply to strain gage transducers. The theoretical work pertaining to strain gage transducers has been presented in a simplified, easily understood manner. Nomographic solutions for strain, frequency, signal, and input voltage are rapid and simple.

It is hoped that this information will be useful to the technician who is familiar with gage application techniques but not with stress analysis formulae and their manipulation. It is also hoped that the engineer who designs "hurry up" transducers will benefit. For the transducer designer, the nomographs should help pick preliminary configurations and dimensions.

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APPENDICES

APPENDIX I

Table of Symbols

Table 1. List of symbols.

A	Cross sectional area, square inches
B	Width of beam, inches
C	Compressive strain gage
D	Diameter or width of torsional cross section, inches
E	Modulus of elasticity, psi
FORCE	Load on transducer, pounds
FREQ	Natural frequency of transducer and load, cycles per second or cycles per minute
G	Modulus of rigidity, psi
H	Height or thickness of beam, inches
I	Moment of inertia, inches to the fourth
J	Polar moment of inertia, inches to the fourth
K	Deflection constant in the equation: $Y = \frac{(\text{FORCE})\,L^3}{K(E)(I)}$
K2	Constant in equation: $2.0\,(K2)\,L^2\,(\text{Strain}) = Y\,H$
L	Length or characteristic dimension of a transducer, inches
M	Mass of elastic element, pound mass
P	Pressure difference across a diaphragm, psi
Q	Constant relating TORQUE to shear stress: $\text{shear stress} = \frac{\text{TORQUE}}{Q}$

(Continued on next page)

Table 1. (Continued)

R	Radius of pressure transducer, inches
RBAL	Constantan resistor to bring Wheatstone bridge into balance
RES	Parallel resistor which reduces input resistance to a standard
RGC	Compensating resistor for temperature induced zero shift
RMOD	Compensating resistor which lowers sensitivity with increasing temperature
RSEN	Series resistor which reduces sensitivity of a transducer to a standard value
S	Section modulus, inches cubed
STRAIN	Strain in metal, microinches per inch $\frac{\Delta L}{L}$
T	Strain gage in tension
THETA	Angle of twist of torsional transducer, degrees or radius
TORQUE	Twisting moment on torsional transducer, inch pounds
TOTAL MASS	Total mass used to find natural frequency. The sum of W and a portion of M (see Figure 10)
W	Concentrated mass on a transducer, pound mass
Y	Deflection of transducer, inches
Z	Thickness of pressure diaphragm, thickness of thin walled tube, inches

APPENDIX II

Glossary of Terms

APPENDIX II

Glossary of Terms

Accuracy - Ratio of error to full scale output (usually expressed in percent)

Ambient Conditions - Conditions of pressure, temperature, humidity of the medium surrounding a transducer

Calibration - A test procedure in which known values of measured parameters are applied to a transducer and corresponding output readings are recorded

Compensation - Provision of a supplementary device or special material to counteract known sources of error

Drift - Inability of a transducer to hold a constant output over some interval of time

Elastic Element - The portion of a transducer which strains uniformly as the measured parameter is applied

Error - Difference between the indicated value and the true value of the measured parameter

Gage Factor - The ratio of the relative change in resistance to the relative change in length of a strain gage:

$$\frac{\Delta R/R}{\Delta L/L}$$

Hysteresis - The maximum difference in output at any value of measured parameter when approached first from increasing then from decreasing measured parameter

Linearity - The closeness of a calibration curve to a specified straight line

Measured Parameter - A physical quantity, property or condition which is measured

Modulus of Elasticity - Ratio of elastic stress to axial strain in a tensile test (Young's Modulus)

Modulus of Rigidity - Ratio of elastic shear stress to strain angle in shear (Shear Modulus)

Moment of Inertia - The second moment of area. The integral of Y^2dA where Y is the distance from the neutral axis. For a rectangle,

$$\frac{BH^3}{12}$$

Natural Frequency - Frequency of free vibration of a system. Frequency of measured parameter at which output becomes much larger than measured parameter.

Output - The electrical quantity produced by a transducer which is a function of measured parameter

Poisson's Ratio - Ratio of lateral strain to axial strain in a tensile test

Repeatability - Ability to reproduce output values when the same measured parameter is applied from the same direction

Resolution - Smallest change in measured parameter which produces a detectable change in output

Self Heating - Internal heating of a transducer due to electrical heating by strain gages

Sensitivity - Ratio of change in output to change in measured parameter

Strain - Ratio of increment in gage length to the gage length:

$$\frac{\Delta L}{L}$$

Zero Return - Difference in output at zero load, before and after application of 100 percent of measured parameter

Zero Shift - An error characterized by a parallel displacement of the entire calibration curve.

Reference: (17)

APPENDIX III

Transducer Design

TABLE II

PROPERTIES OF SOME TRANSDUCER METALS

MATERIAL	ELASTIC MODULUS E PSI	MODULUS OF RIGIDITY G PSI	POISSON'S RATIO	ELASTIC LIMIT, KSI	STATIC STRAIN DESIGN LIMIT MICROSTRAIN	FATIGUE STRAIN DESIGN LIMIT MICROSTRAIN	COEFF OF THERMAL EXPANSION PER ^{o}F
STEELS (BHN 400+) SAE 4340 410 SS RDS TOOL STEEL ARMCO 17-4 PHSS	$2.9x10^{7}$	$1.06x10^{7}$	0.30	Above 90	3,000	1,500	$6x10^{-6}$ TO $9x10^{-6}$
ALUMINUM ALLOYS (BHN 130+) 2024 T-81 2014 T-6 7075 T-6 X-2020	$1.05x10^{7}$	$4x10^{6}$	0.33	Above 40	3,800	1,900	$13x10^{-6}$
BERYLLIUM-COPPER BERYLCO 25 HT	$1.85x10^{7}$	$7.5x10^{6}$	0.24	130	7,000	2,150	$9x10^{-6}$

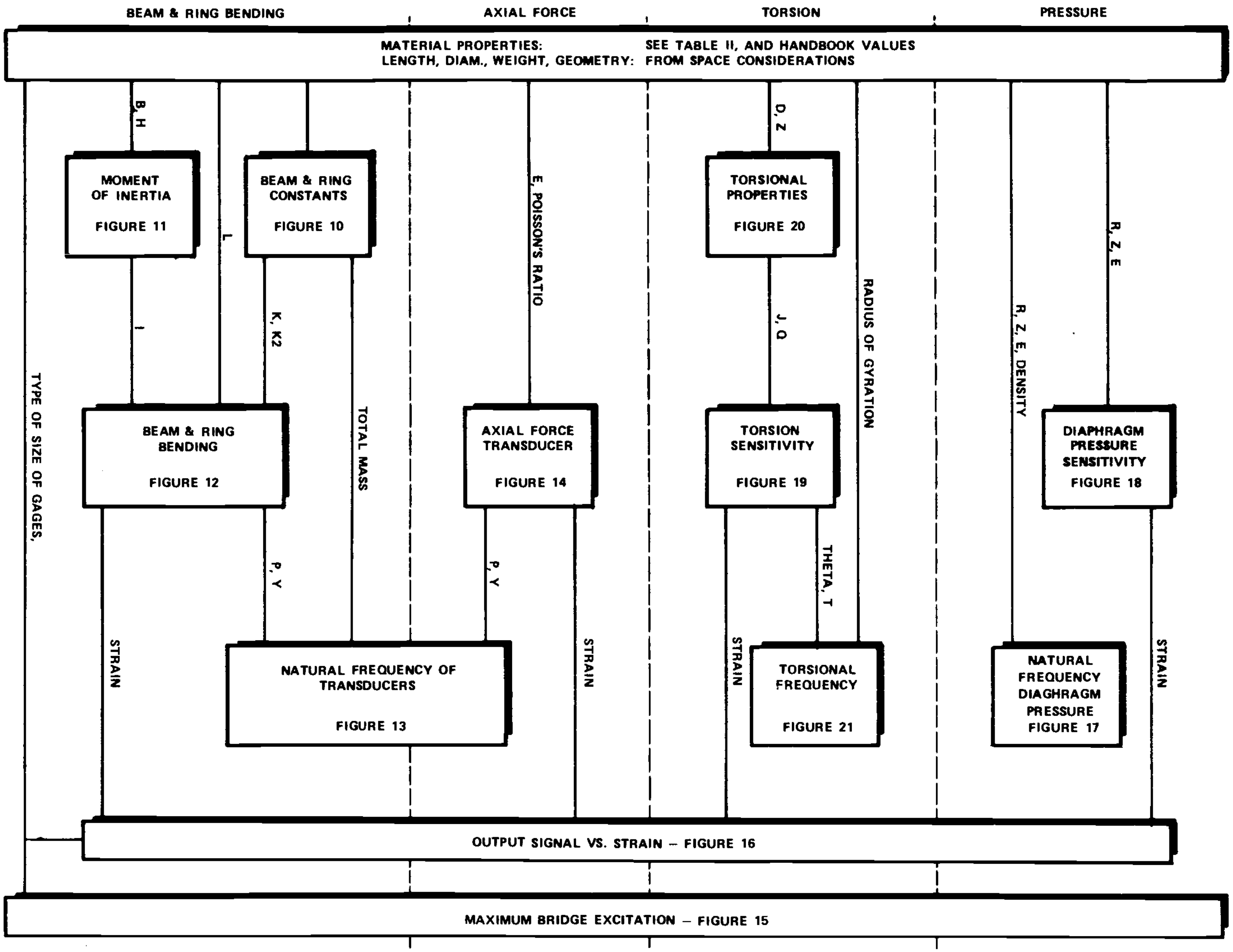
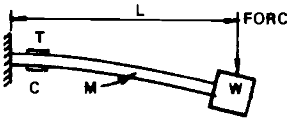
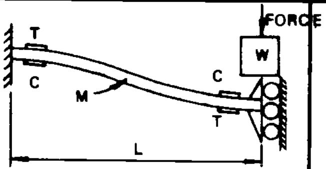
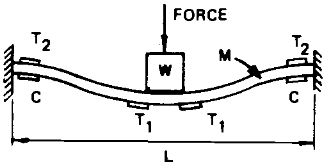
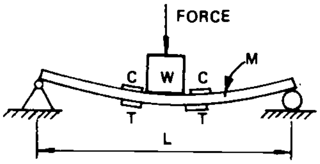
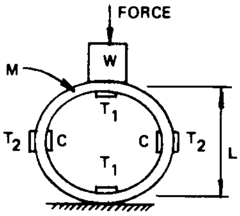
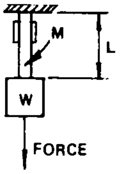
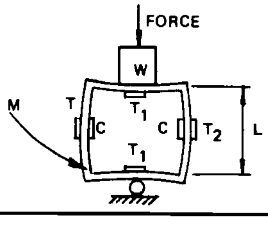
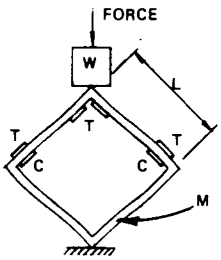


FIGURE 9 – INDEX TO NOMOGRAPHS

ITEM	TOTAL MASS	DEFL CONST., K	STRAIN SENS CONST., K2
	W+0.236M	3.0	0.333
	W+0.264M	12.0	0.167
	W+0.264M	192.0	0.0417
	W+0.486M	48.0	0.0833
	W+0.30M*	53.7	0.117 FOR T_1 0.205 FOR C & T_2
	W+0.333M	SEE NOMOGRAPH FIGURE 14	
	W+0.27M*	38.4	0.139 FOR T_1 0.417 FOR C & T_2
	W+0.33M*	24	0.236

* APPROX.

FIGURE 10

BEAM AND RING CONSTANTS

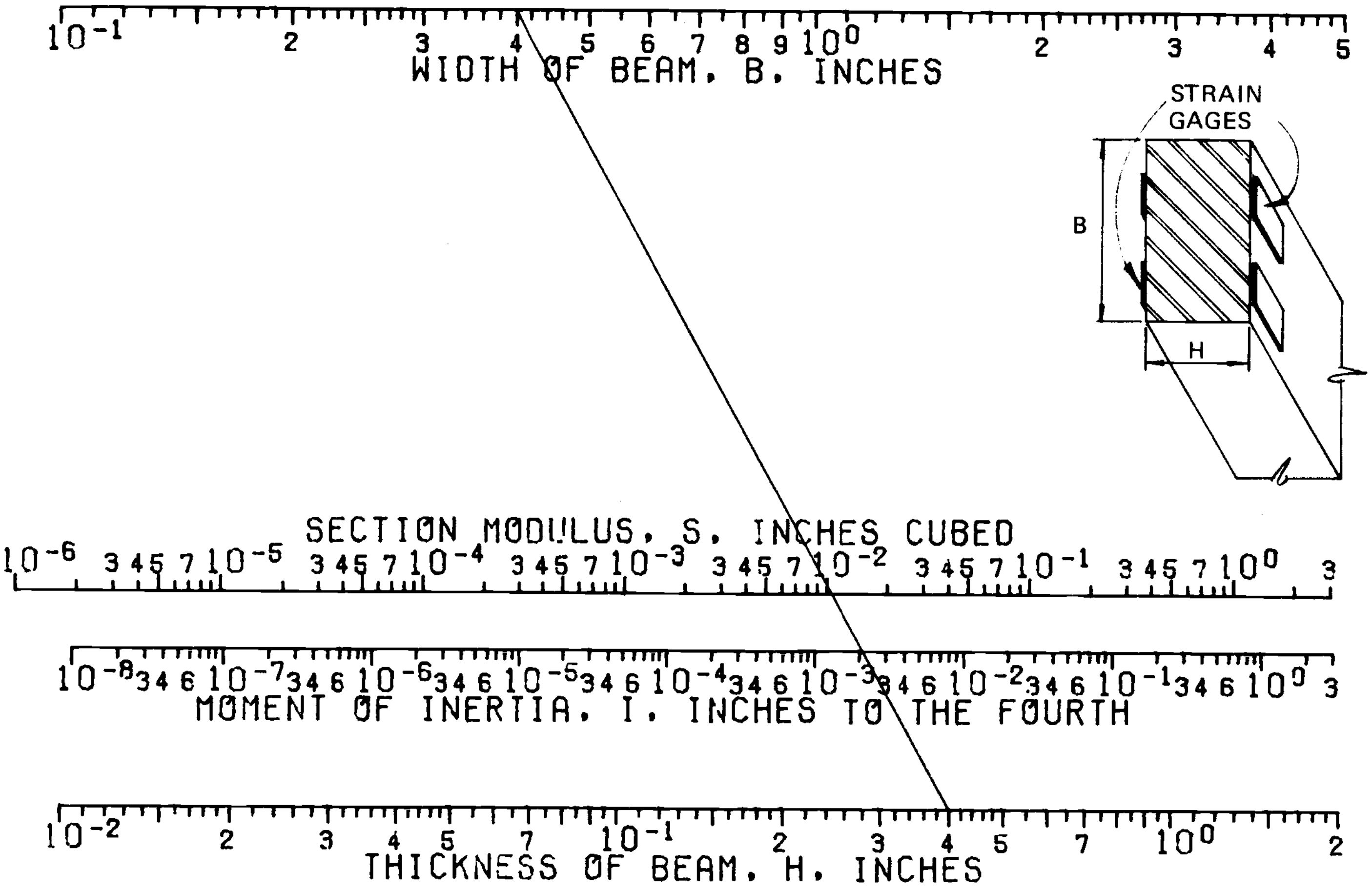


FIGURE 11

MOMENT OF INERTIA NOMOGRAPH

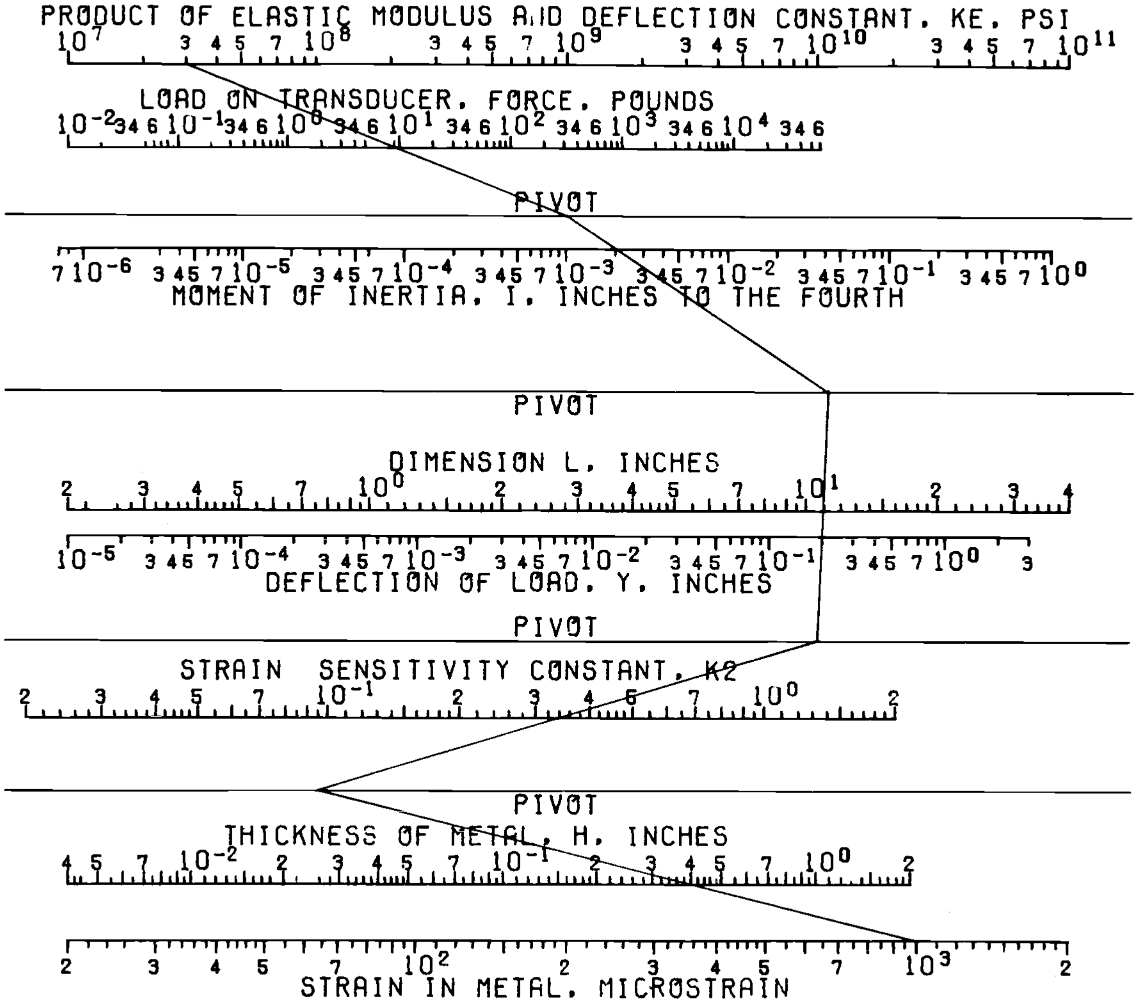


FIGURE 12

BEAM AND RING BENDING NOMOGRAPH

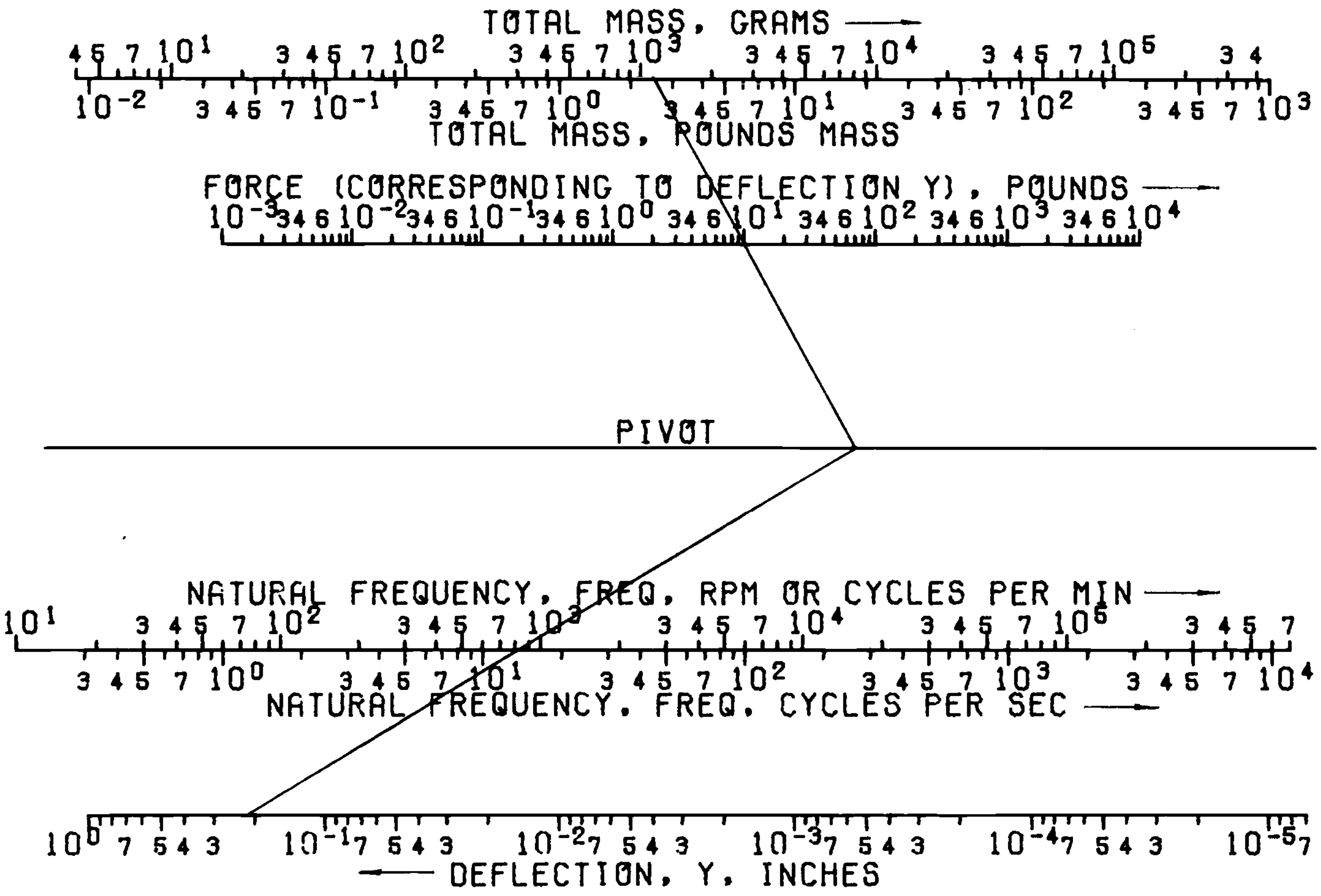


FIGURE 13

NATURAL FREQUENCY OF TRANSDUCERS

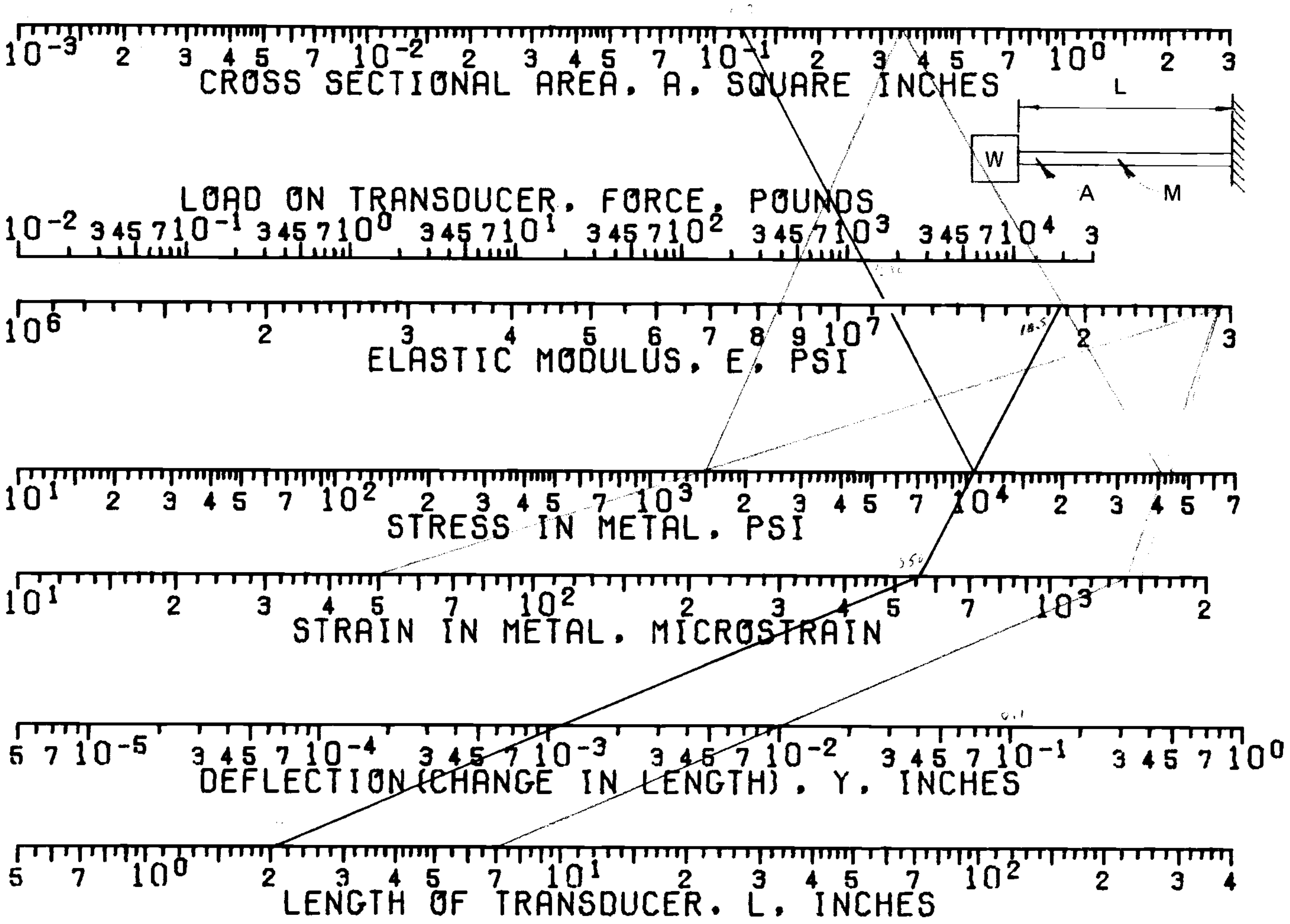


FIGURE 14

AXIAL FORCE TRANSDUCERS

TYPICAL POWER-DENSITY LEVELS IN WATTS/SW. INCH

HEAT-SINK CONDITIONS

* ACCURACY REQUIREMENTS		EXCELLENT HEAVY ALUMINUM OR COPPER SPECIMENS	GOOD THICK STEEL SPECIMENS	FAIR THIN STAINLESS-STEEL/OR TITANIUM
STATIC	HIGH	2.–5.	1.–2.	.5–1.
	MODERATE	5.–10.	2.–5.	1.–2.
	LOW	10.–20.	5.–10.	2.–5.
DYNAMIC	HIGH	5.–20.	5.–10.	2.–10.
	MODERATE	10.–20.	10.–20.	5.–10.
	LOW	20.–50.	20.–50.	10.–20.

* REFERENCE: (9, P.TN-127)

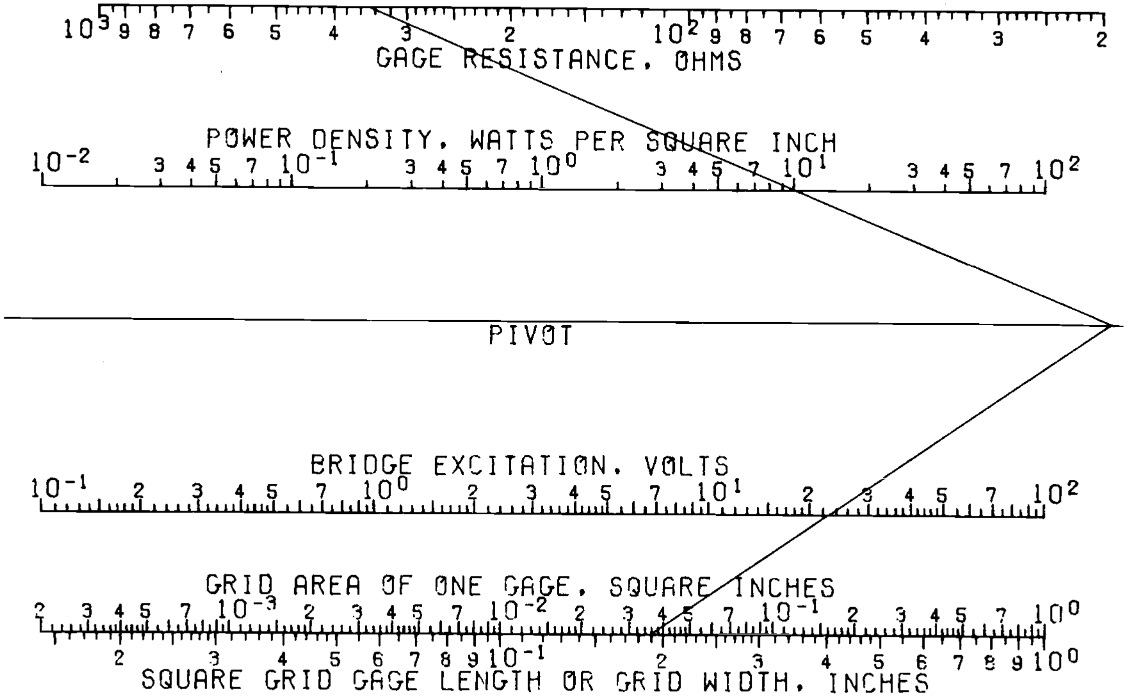


FIGURE 15

MAXIMUM BRIDGE EXCITATION

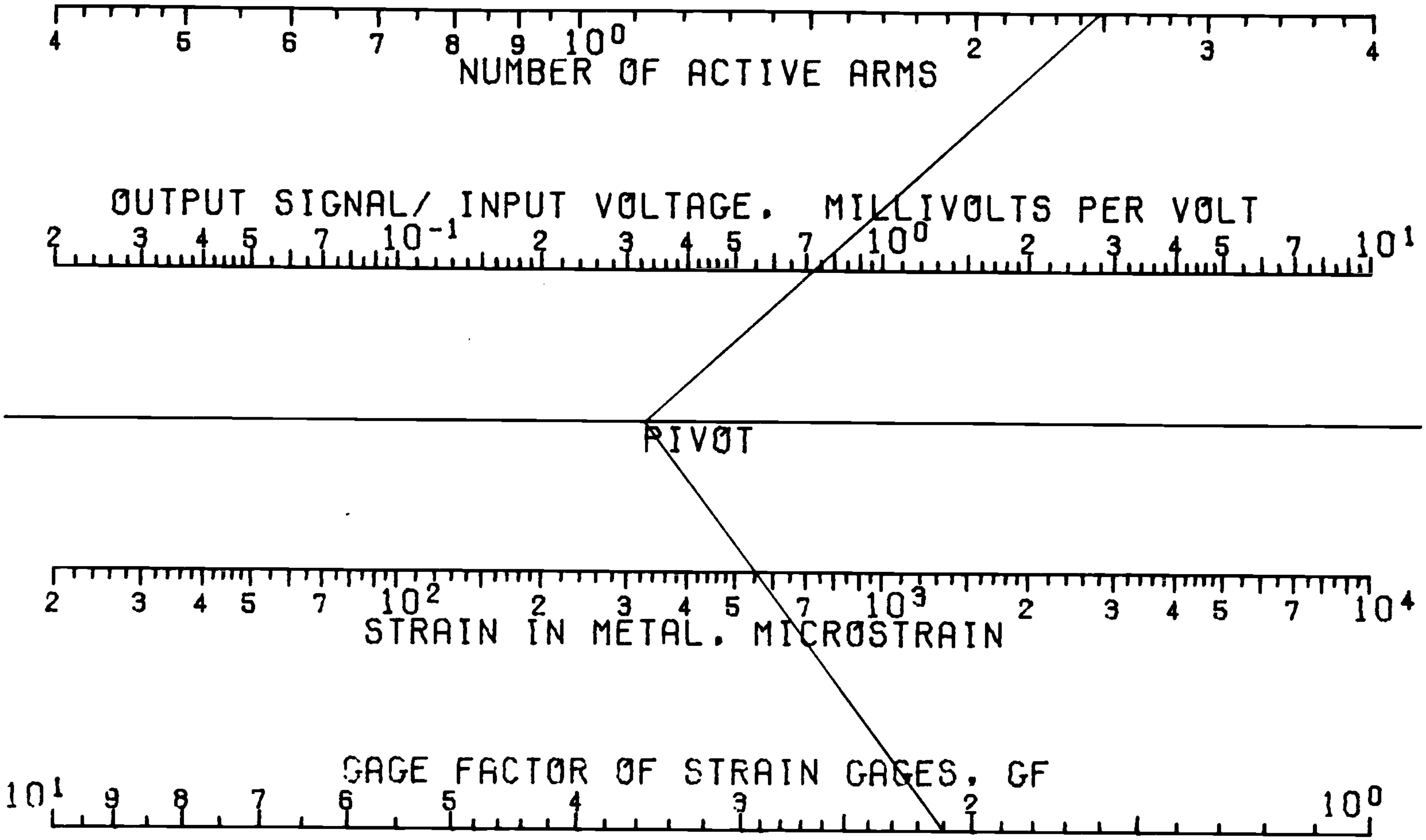


FIGURE 16

OUTPUT SIGNAL VS. STRAIN

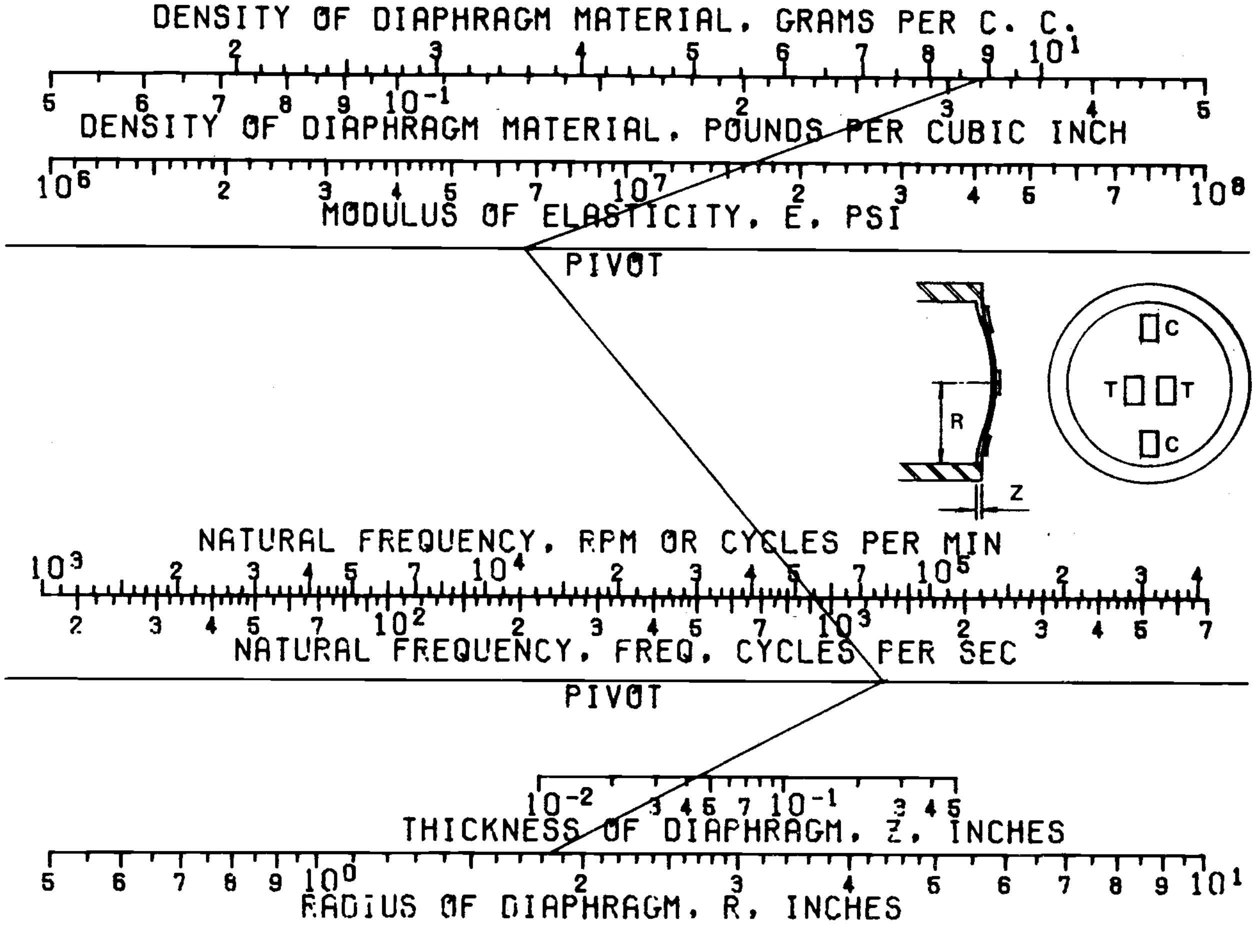
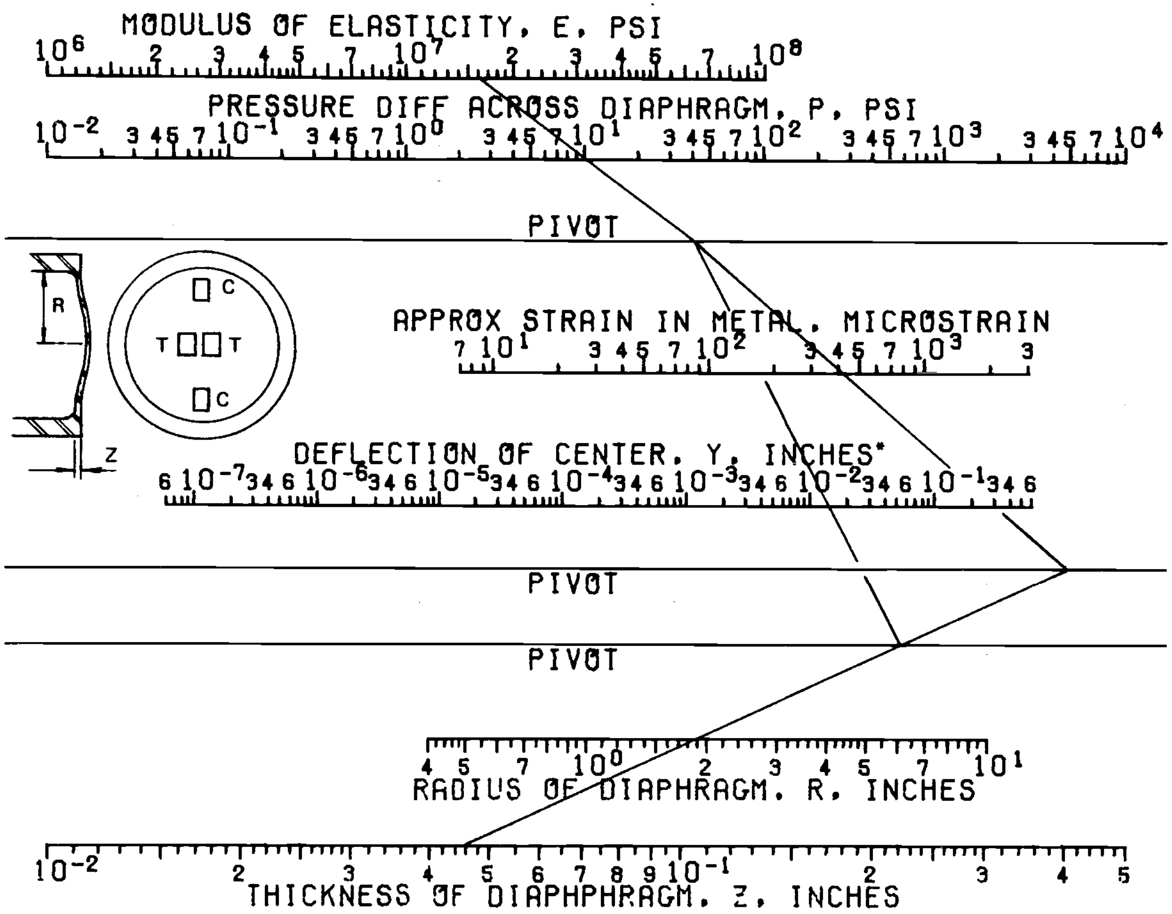


FIGURE 17

NATURAL FREQUENCY OF
DIAPHRAGM PRESSURE TRANSDUCERS
WITH FIXED EDGES



* FOR LINEARITY, DEFLECTION Y SHOULD BE LIMITED TO ABOUT 0.3 TIMES THICKNESS Z

FIGURE 18

DIAPHRAGM PRESSURE TRANSDUCER SENSITIVITY
(FIXED EDGES)

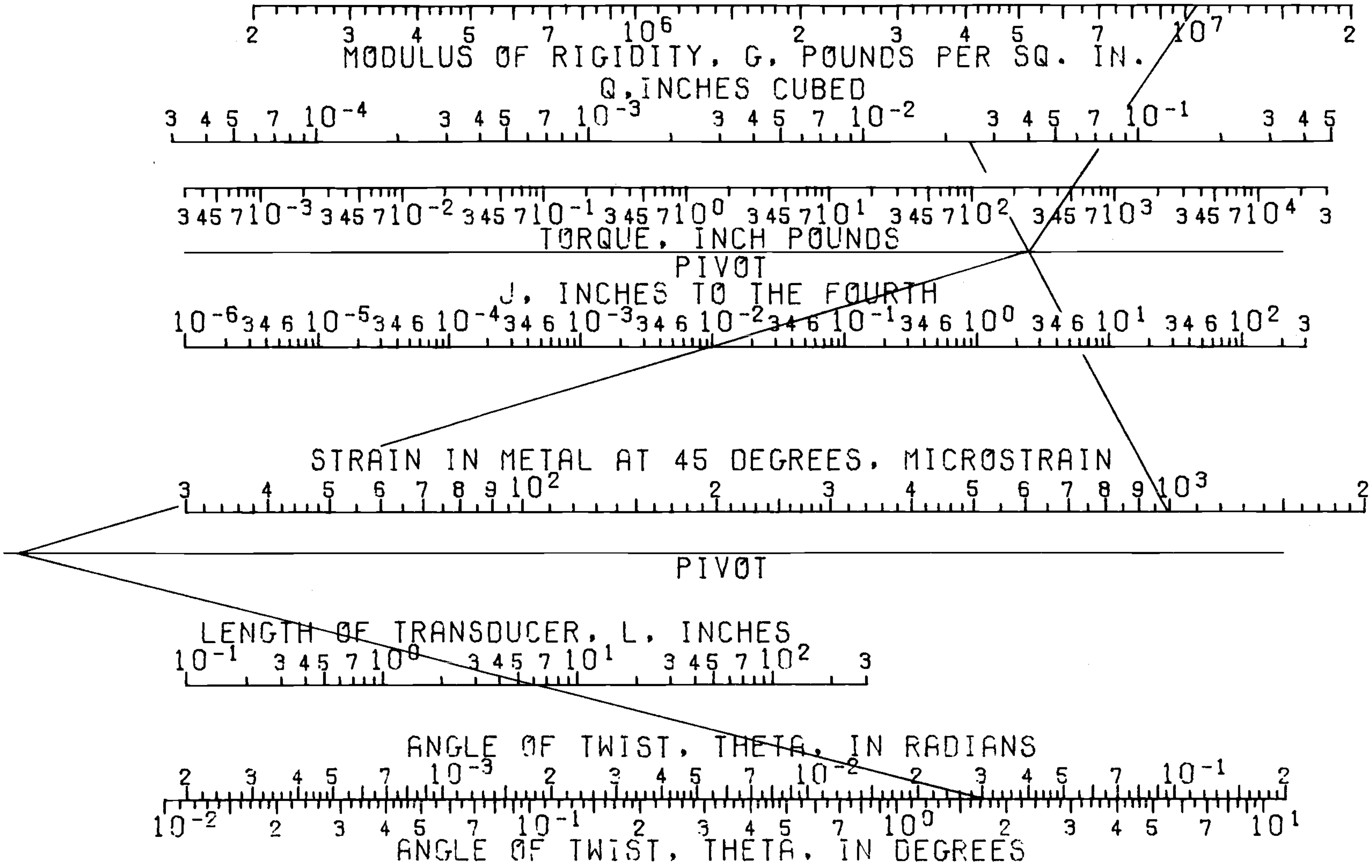


FIGURE 19

TORSION TRANSDUCER SENSITIVITY AND DEFLECTION

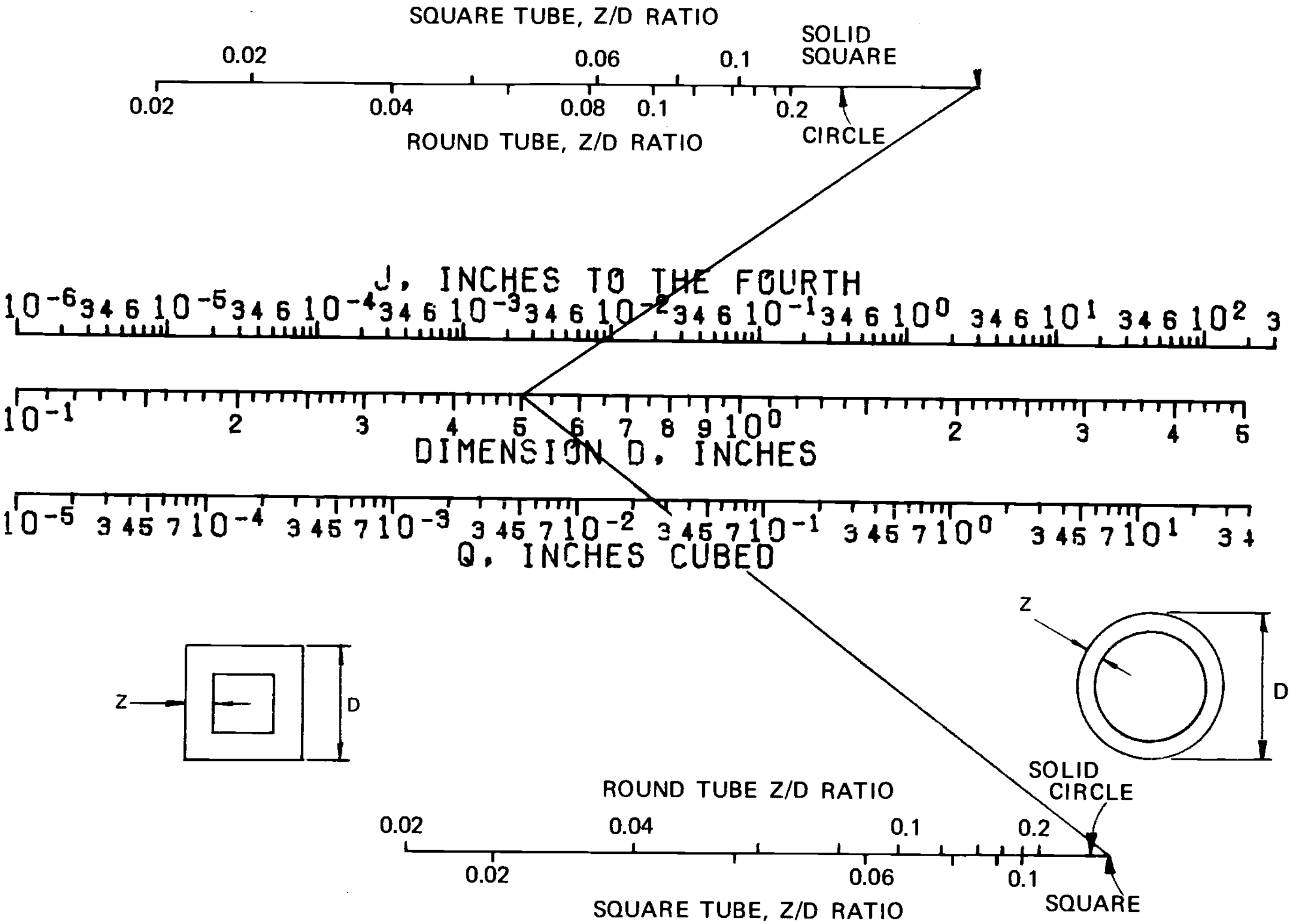


FIGURE 20

TORSIONAL PROPERTIES OF SQUARES AND CIRCLES

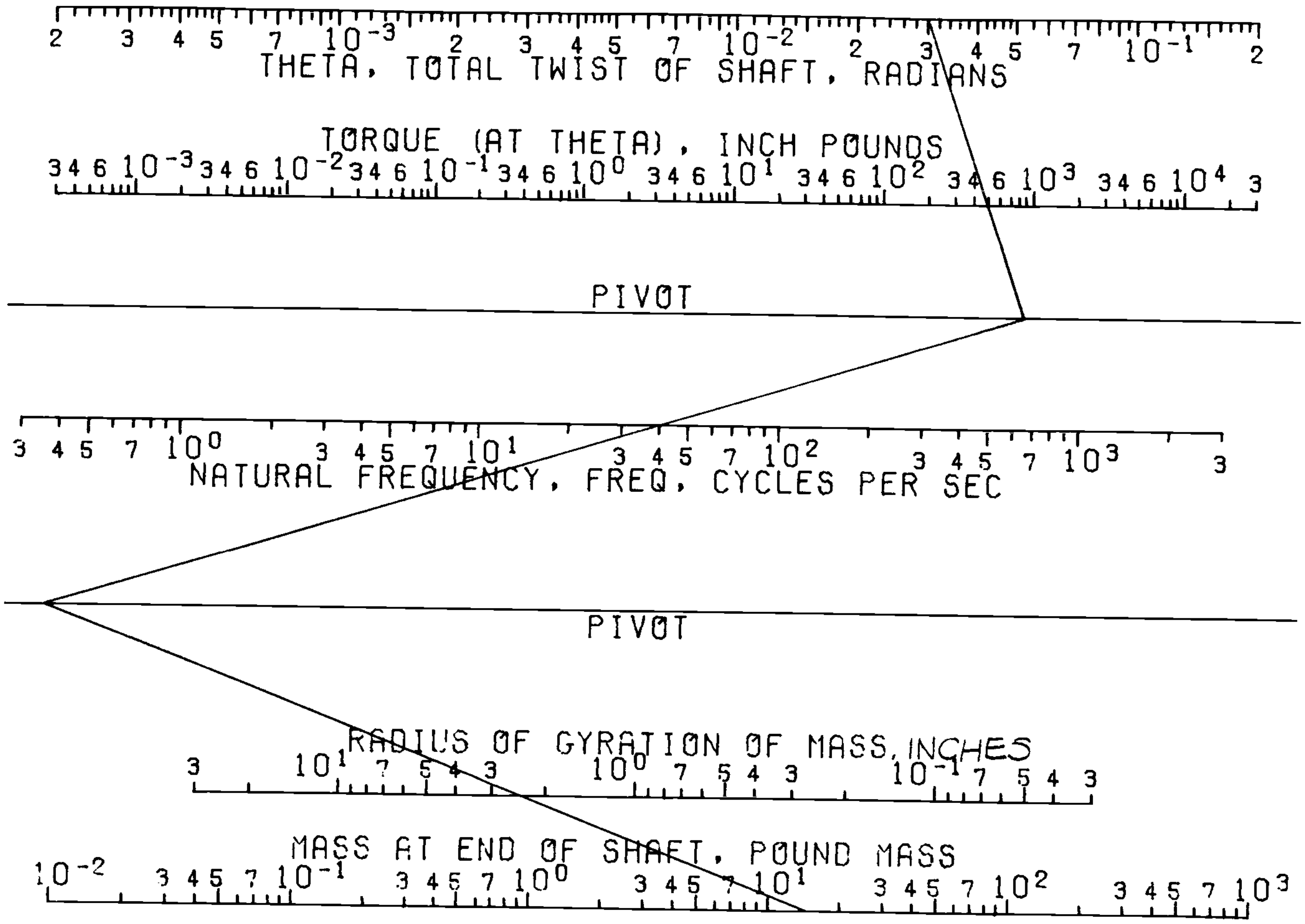


FIGURE 21

TORSIONAL FREQUENCY

APPENDIX IV

Computer Program

```
// JOB    0101 01FF                                                    1
*EQUAT(CARDZ,CRDZO)
// FOR
*IOCS(1403 PRINTER,CARD)
*ONE WORD INTEGERS
*_ISTALL
C---   X        -IS X COORDINATE OF STARTING POINT OF NOMOGRAPH
C---   Y        -IS Y COORDINATE OF STARTING POINT OF NOMOGRAPH
C---   AXLN     -LENGTH OF AXIS BETWEEN FIRS AND LAST
C---   CYLN     -LENGTH OF ONE CYCLE (THE SUBRO. LOGAX NEEDS ONE OR THE OTHER)
C---   FIRS     -NUMERICAL VALUE OF FIRST NUMBER ON SCALE.
C---   LAST     -NUMERICAL VALUE OF LAST NUMBER ON SCALE.
C---   NCR      -NEG FOR TITLE BELOW AXIS. MAGNITUDE GREATER THAN 998 ENDS
C---            -NOMOGRAPH.  VALUE GREATER THAN  9998 ENDS RUN.
      DIMENSION NLMN(40),IP(3),ICARD(80)
      DATA IP/'PI','VO','T '/
      CALL PLOT (2.,-8.,-3)
      CALL PLOT (0.,2.5,-3)
    5 NCR=+1
      READ (2,10) NCR,X,Y,AXLN,CYLN,FIRS,VLAST
   10 FORMAT (I10,4F8.3,F15.0,F23.0)
      IF (FIRS) 110,110,20
   20 CALL PREAD
      READ (2,100) ICARD
  100 FORMAT (80A1)
      N=LCHNE(ICARD,1,80,16448)
      N=N/2+1
      READ (2,101) (NLMN(I),I=1,N)
  101 FORMAT (40A2)
      NCH=3000+2*N
      INTER=ISIGN(NCH,NCR)
      CALL LOGAX (X,Y,NLMN,INTER,AXLN,0.0,FIRS,VLAST,CYLN)
      GO TO 200
  110 CALL PLOT (X,Y,3)
      XX=X+AXLN
      CALL PLOT (XX,Y,2)
      XX=X+AXLN*0.5-0.4
      YY=Y-0.07+SIGN(0.11,FLOAT(NCR))
      CALL SYMB (XX,YY,0.14,IP,0.0,3006)
  200 CONTINUE
      IF (IABS(NCR)-998) 5,210,210
  210 IF (CYLN) 215,215,217
  215 XXX=X+AXLN+9.0
      GO TO 219
  217 XXX=X+9.0+CYLN*0.43429*ABS(ALOG(VLAST/FIRS))
  219 CALL PLOT (XXX,0.0,-3)
      IF (IABS(NCR) -9998) 5,220,220
  220 CALL EXIT
      END
// DUP
*DELETE             NOMOG      01FF
*STORECI    WS  UA  NOMOG            01FF
```

```
// JOB    0101 01FF
// FOR
*ONE WORD INTEGERS
*LISTALL
      SUBROUTINE LOGAX(XPAGE.YPAGE.IBCO.NCHAR.AXISL.THETA.FIRST.VLAST.
     +CYCLN)
C---  XPAGE.YPAGE-COORDINATES OF STARTING POINT. INCHES
C---  IBCO       -AXIS TITLE
C---  NCHAR      -NO. OF CHAR IN TITLE  + TIC ON C.C.. - TIC ON C..
C---  AXISL      -AXIS LENGTH IN INCHES.
C---  CYCLN      -LENGTH OF ONE CYCLE IN INCHES. SPECIFY EITHER AXISL OR
C---             -CYCLN
C---  THETA      -ANGLE OF AXIS FROM X-DIRECTION--DEGREES COUNTER C.
C---  FIRST.VLAST-FIRST AND LAST VALUES ON LOG AXIS
C---  NOTE THAT IF VLAST IS LESS THAN FIRST. THE SCALE IS DRAWN IN THE
C---  OPPOSITE DIRECTION.
C---
      DIMENSION IBCO(2). NO(11). B(20). TL(50)
      THEN=0.0
      CYLEN=CYCLN
      AXLEN=AXISL
      IF (VLAST-FIRST) 1,2,2
    1 THEN=180.0
      FONEY=FIRST
      FIRST=VLAST
      VLAST=FONEY
    2 ANGLE=THETA+THEN
    3 IF (CYLEN) 6,4,6
    4 CYLEN= AXLEN/(0.4342944*ALOG(VLAST/FIRST))
    6 AXLEN= CYLEN*(0.4342944*ALOG(VLAST/FIRST))
C---
C---                    BRANCH TO VARIOUS DATA BASED ON CYLEN
      IF( CYLEN-4.0) 45.45.70
   45 IF( CYLEN-2.0) 50,50.65
   50 IF( CYLEN-1.0) 55,55.60
   55 NO(1)=3
      NO(2)=4
      NO(3)=6
      NO(4)=10
      N=4
      B(1)=10.
      NB=1
      TL(1)=2.
      TL(2)=3.
      TL(3)=4.
      TL(4)=5.
      TL(5)=6.
      TL(6)=7.
      TL(7)=8.
      TL(8)=9.
      NL=8
      GO TO 75
   60 NO(1)=3
      NO(2)=4
      NO(3)=5
      NO(4)=7
      NO (5)=10
      N=5
      B(1)=5.
      B(2)=10.
      NB=2
      TL(1)=2.
      TL(2)=3.
      TL(3)=4.
      TL(4)=6.
      TL(5)=7.
      TL(6)=8.
      TL(7)=9.
      NL=7
      GO TO 75
   65 NO(1)=2
      NO(2)=3
      NO(3)=4
      NO(4)=5
      NO(5)=7
      NO(6)=10
      N=6
      B(1)=1.5
      B(2)=2.
      B(3)=3.
      B(4)=4.
      B(5)=5.
      B(6)=6.
      B(7)=7.
      B(8)=8.
      B(9)=9.
      B(10)=10.
      NB=10
      TL(1)=1.1
      TL(2)=1.2
      TL(3)=1.3
      TL(4)=1.4
      TL(5)=1.6
      TL(6)=1.7
      TL(7)=1.8
      TL(8)=1.9
      TL(9)=2.2
      TL(10)=2.4
      TL(11)=2.6
      TL(12)=2.8
      TL(13)=3.2
      TL(14)=3.4
      TL(15)=3.6
      TL(16)=3.8
      TL(17)=4.2
      TL(18)=4.4
      TL(19)=4.6
      TL(20)=4.8
      TL(21)=5.5
      TL(22)=6.5
      TL(23)=7.5
      TL(24)=8.5
      TL(25)=9.5
      NL=25
      GO TO 75
   70 NO(1)=2
      NO(2)=3
      NO(3)=4
      NO(4)=5
      NO(5)=6
      NO(6)=7
      NO(7)=8
      NO(8)=9
      NO(9)=10
      N=9
      B(1)=1.5
      B(2)=2.
      B(3)=2.5
      B(4)=3.
      B(5)=4.
      B(6)=5.
      B(7)=6.
      B(8)=7.
      B(9)=8.
      B(10)=9.
      B(11)=10.
      NB=11
      TL(1)=1.1
      TL(2)=1.2
      TL(3)=1.3
      TL(4)=1.4
      TL(5)=1.5
      TL(6)=1.6
      TL(7)=1.7
      TL(8)=1.8
      TL(9)=1.9
      TL(10)=2.1
      TL(11)=2.2
      TL(12)=2.3
      TL(13)=2.4
      TL(14)=2.6
      TL(15)=2.7
      TL(16)=2.8
      TL(17)=2.9
      TL(18)=3.2
      TL(19)=3.4
      TL(20)=3.6
      TL(21)=3.8
      TL(22)=4.2
      TL(23)=4.4
      TL(24)=4.6
      TL(25)=4.8
      TL(26)=5.5
      TL(27)=6.5
      TL(28)=7.5
      TL(29)=8.5
```

```
      TL(30)=9.5
      NL=30
   75 CONTINUE
C---                                                FIND FIRS AND VLAS
C---
      DO 30 I=1,40
      IF (IFIX(1000.*( FIRST*10.**(I-20)-1.))) 30,30,31
   30 CONTINUE
   31 FIRS=FIRST*10.**(I-20)
      NFST=21-I
      IF (IFIX(1000.*( FIRS-FLOAT(NO(1))))) 32,33,33
   32 NFST=20-I
   33 CONTINUE
      DO 35 J=1,40
      IF (IFIX(1000.*( VLAST*10.**(J-20)-1.))) 35,35,36
   35 CONTINUE
   36 VLAS=VLAST*10.**(J-20)
C---
C---                                         FIND NOFT + F AND NOLT + V
      DO 80 K=1,N
      NNN=N-K+1
      IF (IFIX(1000.*(  FLOAT(NO(NNN))-FIRS)))78,78,80
   78 NOFT=NO(NNN)
      F=CYLEN*0.4343 *ALOG(FIRS/FLOAT(NOFT))
      GOTO 82
   80 CONTINUE
      NOFT=NO(N)
      F=CYLEN*0.4343 *ALOG(FIRS)
   82 CONTINUE
      DO 90 K=1,N
      IF (IFIX(1000.*( FLOAT(NO(K))-VLAS))) 90,92,92
   90 CONTINUE
   92 NOLT=NO(K)
      V=CYLEN*0.4343 *ALOG(FLOAT(NOLT)/VLAS)
      K=NCHAR/IABS(NCHAR)
      H= FLOAT(K)*(1.-THEN/90.0)
      NCHAR=IABS(NCHAR)
      STH=ANGLE*0.0174533
      CTH=COS(STH)
      STH=SIN(STH)
      XFT=XPAGE-F*CTH
      YFT=YPAGE-F*STH
      XLT=XPAGE+(AXLEN+V)*CTH
      YLT=YPAGE+(AXLEN+V)*STH
C---                                   WRITE OUT NUMBERS FOR BIG TICS
C---
      KV=1
   96 DO 100 ITIS=1,N
      IF (IFIX(1000.*( 10.**(KV-1)*FLOAT(NO(ITIS))-FLOAT(NOFT))))
     +100,98,98
   98 R=CYLEN*0.4342944*ALOG(FLOAT(NO(ITIS))/FLOAT(NOFT))+CYLEN*(KV-1.0)
      FPN=FLOAT(NO(ITIS))
      IF(IFIX(1000.*(R-V-F-AXLEN))) 99,99,120
   99 HT=FLOAT(IFIX(FLOAT(NO(ITIS))/9.9))*0.035+0.105
      HD=-0.04*(1.-THEN/90.0)+(1.-THEN/30.)*(-0.05*FLOAT(IFIX(FLOAT(
     +NO(ITIS))/9.9)))
      VH=-0.07*(1.-THEN/90.0)+0.19*H
      XXX=HD*CTH-VH*STH+R*CTH+XFT
      YYY=VH*CTH+HD*STH+R*STH+YFT
      CALL NUMB (XXX,YYY,HT,FPN,ANGLE+THEN,-1)
  100 CONTINUE
      HD=(1.-THEN/180.)*(0.20)
      VH=0.19*H
      XX=HD*CTH-VH*STH+R*CTH+XFT
      YY=VH*CTH+HD*STH+R*STH+YFT
      FPN=FLOAT(NFST+KV-1)
      CALL NUMB(XX ,YY ,0.105,FPN,ANGLE+THEN,-1)
      KV=KV+1
      GO TO 96
  120 CONTINUE
C---                              PLOT THE BIG TIC MARKS
C---
      CALL PLOT (XLT,YLT,+3)
      VK=1.0
  140 DO 150 ITE=1,NB
      ITLL=NB+1-ITE
      IF(IFIX(1000.*(10.**(1.-VK)*B(ITLL )-FLOAT(NOLT)))) 145,145,150
  145 R=F+V+AXLEN+CYLEN*0.4342944*ALOG(B(ITLL)/FLOAT(NOLT))-CYLEN*(VK-1.
     +0)
      XX=XFT+R*CTH
      YY=YFT+R*STH
      IF(IFIX(1000.*R)) 160,146,146
  146 CALL PLOT( XX,YY,+2)
```

```
      CALL PLOT( XX-0.1*H*STH,YY+0.1*H*CTH,+2)
      CALL PLOT( XX,YY,+2)
  150 CONTINUE
      VK=VK+1.0
      GO TO 140
  160 CONTINUE
C---                                            LABEL THE AXIS
C---
      R=AXLEN*0.5-0.070*(1.-THEN/90.)*(FLOAT(NCHAR)-1000.*(IFIX(FLOAT(N
     +CHAR)/1000.)))
      VH=-0.060+0.380*H+0.15*THEN/180.0
      ANGLE=ANGLE+THEN
      XX=XPAGE+R*CTH-VH*STH
      YY=YPAGE+R*STH+VH*CTH
      CALL SYMB(XX,YY, 0.14,IBCD,ANGLE,NCHAR)
C---
C---                                   FINALLY, PLOT LITTLE TIC MARKS
      CALL PLOT (XLT,YLT,+3)
      VK=1.0
      IF(NL-1) 190,190,170
  170 DO 180 ITE=1,NL
      ITLL=NL+1-ITE
      IF(IFIX(1000.*(10.**(1.0-VK)*TL(ITLL)-FLOAT(NOLT)))) 175,175,180
  175 R=F+V+AXLEN+CYLEN*0.4342944*ALOG(TL(ITLL)/FLOAT(NOLT))-CYLEN*(VK-
     +1.0)
      XX=XFT+R*CTH
      YY=YFT+R*STH
      IF(IFIX(1000.*R)) 190,176,176
  176 CALL PLOT (XX,YY,+2)
      CALL PLOT (XX-0.060*H*STH,YY+0.060*H*CTH,+2)
      CALL PLOT (XX,YY,+2)
  180 CONTINUE
      VK=VK+1.0
      GO TO 170
  190 CONTINUE
      RETURN
      END
// DUP
*DELETE             LOGAX     01FF
*STORE      WS  UA  LOGAX           01FF
```