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An Improved Strain-Gauge Type of Load-Cell Thrust Transducer

By D. S. DEAN

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An Improved Strain-Gauge Type of Load-Cell Thrust Transducer

By D. S. Dean

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Summary. This paper describes the development of a novel type of load cell which possesses certain advantages over the normal pillar type. Sensitivity is greater since the two concentrically nested tubular load-carrying members are equally loaded in compression and tension and the strains of both are indicated. This construction is more tolerant of non-axial loading, and a simple modification allows the cell to respond only to the axial component of such loads. When the normal strain of the tubes is exceeded by overload, the base of the inner tube presses on the cell casing and the load is transmitted solidly, thereby allowing overloads of at least ten times normal full load to be carried without damage.

The theoretical compression of the cell for full load is 0·001 in. and by suitable choice of strain gauges the cell may be made to drive galvanometers directly, or give an output of up to 0·25 V into a high impedance.

1. *Introduction.* Thrust measurements have been made for the most part by means of pistons in liquid-filled cylinders or by bellows mechanisms. The former method is unsound in principle as it employs sliding members and considerable friction is possible under some circumstances. Its greatest virtue is that the piston area is accurately known and hence the thrust may be deduced from the pressure indicated by a pressure gauge which can be calibrated on a dead-weight tester. The bellows device is prone to suffer a change of effective area under load and this change is not always reproducible.

To replace these methods, site trials are being conducted on two further systems of measurement, a 'Macklow-Smith' capsule and electrical pressure gauge, and a load cell of the design described here. The capsule consists essentially of a flat piston and cylinder, bonded together by a flexible rubber ring, thus eliminating sliding friction. Results obtained with this system have been satisfactory, but the capsule and gauge must be carefully filled with liquid to avoid air bubbles, and the overload limit is that of the gauge. A load cell has the advantage of requiring no filling, and has a higher overload tolerance and a smaller deflection for a given load. Commercial load cells, however, have certain disadvantages, as described in Section 2, which indicated the need for a special cell to be developed.

2. *Comparison of Load Cells.* 2.1. *Usual Form.* In the form of strain-gauge load cell commonly used, the load is applied to the ends of a square-section pillar of elastic material. The longitudinal

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strain is measured by means of strain-gauges attached to its surface in the direction of the axis of the pillar. Similar gauges are attached at right-angles to these for temperature compensation and to measure the lateral strains in the pillar.

It is thus possible to make a complete Wheatstone bridge with the gauges, all arms of which will be active to some extent, although the change of resistance of the crosswise-mounted gauges can only be about one third that of the longitudinal gauges because of the values of Poissons ratio of possible materials for the bar.

Any overload must damage the cell unless the working range is restricted.

As the 'aspect ratio' of the pillar is rather high, particularly in cells for small thrust measurement, it is not only liable to buckle but is prone to error when subjected to eccentric axial loads and to non-axial loads. Further, as the perimeter of such a pillar is small, the length of the pillar must be sufficient to accommodate at least two rows of gauges, one to measure axial, and the other lateral strains in the material. If a high-resistance cell is required, more than two may be needed. Pillars of the necessary length may contract by some 0·010 in. under full load.

2.2. *New Improved Cell.* To overcome these shortcomings and to obtain a greater electrical output the cell described here has been developed.

The 'aspect ratio' of the load-carrying member was considerably decreased by employing instead of a solid pillar two concentrically nested tubes which for a given cross-sectional area allow an increase of diameter and a reduction of length while providing an increased surface area for attachment of the strain gauges. In practice the aspect ratio can be made 1 : 5 or less, instead of about 2 : 1 with the conventional type. This allows the load to be carried an appreciable distance off centre without error in indication, and the cell is more tolerant of side thrusts. A simple modification eliminates the effect of side thrusts of up to about one fifth the capacity of the cell.

This construction allows the incorporation of a robust overload stop which permits overloads of at least ten times the working load to be resisted without damage. By using two tubes, one in compression and the other in tension, it is possible to make all the strain-gauges active to the same extent and to use the cell up to its maximum load without danger to any individual gauge.

3. *Construction.* 3.1. *Load-Sensitive Element.* The cell, which is illustrated diagrammatically in Fig. 1 and pictorially in Figs. 2 and 3, consists basically of two tubes of suitable elastic material (high-tensile steel, Duralumin or beryllium copper); the force to be measured is applied through a ball and block to the internal face (A) of the inner tube. The open end of this tube is provided with a rim which bears on the face (B) of the outer tube, the other face (C) of which is spigoted on the thrust plate. The inner tube is thus subjected to tensile stress and the outer tube to compressive stress; the resultant strains may be made equal if the cross-sectional areas of the walls of the tubes are the same. The bolts holding the various parts of the cell together are strong enough to allow it to be used in tension up to half the normal compression load. The thrust unit under test may thus be hung from the cell and the upward thrust measured irrespective of the weight of the unit. A simple calculation of dimensions is given in Appendix I, but considerable variation is possible.

3.2. *Strain-Gauges.* The strains in the tubes are measured by means of gauges cemented to the walls. Enough gauges are attached side by side to cover the complete circumference of the inner tube and the same number of gauges are equally spaced around the outer tube. This ensures that the output of the cell is proportional to the integrated strain in the tubes, and hence off-centre loads will not affect the total strain recorded. It is possible to obtain woven strain-gauges in which the spacing of the wires may be varied as required, so that both the inner and outer tubes are completely covered with gauges of equal resistance.

The gauges are attached to the outside of the inner tube and inside of the outer tube so that they are in an air-tight and moisture-tight compartment. Leads are brought out through sealed terminals.

3.3. *Overload Stop.* As can be seen in Fig. 1, the clearance between the farther end of the inner tube and the thrust plate is purposely restricted to a few thousandths of an inch, so that in the event of an overload these two members make contact and the cell forms a solid metal pillar capable of withstanding forces up to its crushing load. The strain-gauges can thus survive a considerable overload, although they will ultimately fail before the pillar collapses as some further straining of the tube occurs even when the stop is in action, the sensitivity being reduced to about one tenth of its normal value.

To reduce the need for accurate machining it is usual to leave a gap of about 0·008 in. between the end of the inner tube and the thrust plate. Prior to attachment of the strain-gauges the cell is loaded to about ten times its normal working load so that the tubes undergo plastic deformation until the faces of the inner tube and thrust plate bed firmly together. On removal of the load the tubes partially regain their initial lengths; hence, during subsequent operation they will remain within their elastic limit up to the overload initially applied. To set the overload range more accurately the strain tubes are bolted together and their lower faces ground to the same level. The gap is obtained by steel shims under the outer tubes.

3.4. *Housing.* To protect the cell from damage it is surrounded by a stout casing welded to the base plate. The casing carries a clamp through which the electrical leads pass to the outer ends of the sealed terminals. The space between the cell and the casing is filled with waterproof grease which seals the terminals and the open end of the cable.

3.5. *Diaphragm for Inclined Loads.* When a cell has to withstand loads inclined at more than 3 deg from the axis of the cell, it is desirable to embody the modification illustrated in Fig. 4.

The outer face of the cell housing cylinder is used to support the outer rim of a diaphragm, the centre of which bears upon the flat end of the thrust block. The middle portion of the diaphragm is turned to a hemisphere and hardened; the centre of curvature of the hemisphere is equidistant from either face of the diaphragm. If the load is now applied to the hemisphere at an angle to the axis of the cell, the force vector will always pass through the centre of curvature, where it may be resolved into a force in the plane of the diaphragm and one normal to the surface of the thrust block. The thickness of the diaphragm is so chosen that with any probable lateral loads it will be only lightly stressed, but at the same time will have negligible stiffness in the direction of the main thrust as compared with the measuring members. The output of a cell fitted with this diaphragm and tilted at angles of up to $11\frac{1}{2}$ deg has not differed from the expected figure by more than 0·5 per cent.

4. *Frequency Response.* The frequency response of the thrust-measuring system depends upon the weight of the motor and moving parts of the rig and on the stiffness of the actual measuring device. The active length of the tubes carrying the strain-gauges has been made 0·5 in., so that as a strain of 0·1 per cent is regarded as the upper limit, the total deflection of the unit should be about 0·001 in. for maximum load.

The free axial motion of the system will be simple harmonic, and the natural frequency f_n is given by

$$f_n = \frac{1}{2\pi}\sqrt{\left(\frac{Fg}{l\,.\,m}\right)},$$

where F = load on cell (lb weight),
l = maximum deflection of cell for load F (ft),
m = mass of system (lb),
g = gravitational acceleration (ft/sec^2).

This formula assumes damping to be small, which is the case in practice.

As an example, take a motor weighing 200 lb and developing a thrust of 5,000 lb. The natural frequency of the system is about 500 c/sec, and it can be shown that not more than 15 per cent magnification of thrust fluctuations will be possible up to 250 c/sec (*i.e.*, 50 per cent the natural frequency of the system). In practice these fluctuations will be subject to some slight damping and the magnitude of the error will be correspondingly reduced.

If the response of the recording apparatus is higher than 50 per cent of the natural frequency of the system, it is usual to introduce filters to provide a more linear response.

A graph of natural frequency against stiffness of such a system is given in Fig. 5 for various weights of motor. In using the graphs it must be borne in mind that, with the small deflections of these cells, the stiffness of the thrust block is a major factor in determining the natural frequency of the system.

5. *Associated Recording Apparatus.* With suitable values of strain-gauge resistance (about 200Ω) the bridge may be energised with a 12-V accumulator and the output fed to an I.T. 1·5 galvanometer in the I.T. 3·9 camera, or some similar system. With this arrangement it is possible to obtain a deflection of 10 cm on the paper for maximum load, and a reasonably flat amplitude response up to 65 c/sec. Galvanometers are now available with double this sensitivity.

If a higher frequency response is required a carrier amplifier system may be employed, or the arm resistance may be increased to feed a d.c. amplifier. Cells may be constructed with 2,000Ω bridge arms, and the bridge energised with 120-V to give a full-scale output of $\frac{1}{4}$-V.

6. *Future Developments.* It is possible to increase the accuracy of thrust measurement over a limited range by employing a low-rate diaphragm, or other form of spring over the front of the cell. The spring will have a large total movement and thus may have a high maximum range despite its low spring rate. This will absorb the thrust up to the lower limit of the measuring range before coming into contact with the thrust block. The cell will then begin to measure the thrust, and continue to do so until the stop is reached. Since the spring rate of the cell is higher than that of the diaphragm, the cell will provide most of the stiffness in this region. By this means it is possible to record thrust accurately over a small preselected range which may be located at any thrust level between zero and maximum without damaging the cell. The main advantage of such a system is that the full width of the paper is used to record only a small portion of the thrust range, and more accurate reading is possible. One use of such a system is to measure small variations in thrust when the general thrust level is known.

7. *Difficulties Encountered during Development.* In the early type of cell, the spigot of the inner tube was a press fit in the outer tube and no flange bolts were fitted at face B (Fig. 1). This proved

satisfactory under steadily applied loads. Under impact loads occurring during firings the joint shifted, leading to variations of zero and sensitivity. These were ascribed to the fact that the vertical spigot faces were not truly cylindrical but tapered and hence the top of the outer tube was being expanded as the inner tube was driven into it. Similar effects were produced under laboratory conditions. The spigot face of the inner tube was therefore machined away by about 0·002 in. to make it a loose fit in the outer tube, and the two were bolted together. This eliminated the trouble under laboratory conditions, and future cells were constructed with a free fit between the tubes, the two being bolted together through a large flange.

The thickness of the flanges was calculated for a shear stress of 5,000 lb/sq in. across the flange of the inner tube at maximum load. This flange was found to be insufficiently stiff, and allowed bending to occur as shown diagramatically in Fig. 6. This affected the strain in the measuring tubes and caused the sensitivity to vary from the calculated figure, as was confirmed by placing the individual tubes between thick plates to prevent bending taking place. Even with the flanges bolted tightly together some slip occurred at the mating surfaces resulting in differences in indicated load on rising or falling loads of up to 1 per cent of full-scale output in bad cases.

It was evident, therefore, that the effect of bending was more serious than deflection due to shear forces, and the flange thickness was doubled. Since resistance to bending is proportional to the cube of the thickness, this resulted in an eightfold increase in stiffness. The cell with these modifications has now achieved the expected accuracy of $\pm$ 0·1 per cent of full-scale output; that is to say, that if it is calibrated on rising and falling loads, no errors will be greater than 0·1 per cent from the best straight line. A typical error curve is shown in Fig. 7.

8. *Summing of Outputs of Individual Cells.* It was required to measure the individual outputs of three 50,000-lb range cells, and at the same time to determine the total load carried by them.

To obtain these results two sets of strain-gauges were bonded in each cell, one giving the individual output. The other sets in each of the cells were connected in parallel as in Fig. 8 so that the output of the combination was the average of all three, or when multiplied by three was the total. For this to be so, it was necessary to make the sensitivity of each cell the same. This was adjusted to within 0·1 per cent by the addition of resistors A, A and B, B to the arms of the most sensitive cells. These resistors were also used to adjust the common centre points of the arms to the same potential to reduce circulating currents to a minimum. For accurate summing it was necessary that the cell outputs should be linear with load, which in fact they are.

With the three cells forming an equilateral triangle, the point of application of a constant load was moved within the triangle. With each cell in turn taking one fifth of the total indicated load, this total did not vary by more than 0·3 per cent. The cells were of the type with insufficiently stiff flanges, but the best three of a group of six were chosen. The experiment should give an even better result if repeated with the stiffened version.

The method of calculation of values of resistors A, A and B, B is given in Appendix II.

9. *Conclusion.* The load cell described here has achieved the performance intended. Its features may be summarised as follows:

Large output (3mV output/volt applied to the cell)

Large overload margin (10 times normal range)

Insensitivity to non-axial and out-of-line loads

Small deflection under load (about 0·003 in. for full load)

Linear output with load, and small hysteresis (errors from the best straight line less than 0·1 per cent of full output on rising or falling loads).

It has also been found possible to sum the outputs of three cells, such that the total load is indicated to within 0·3 per cent of the correct value with any two cells taking double the load of the remaining cell.

APPENDIX I

Calculation of Dimensions

For a thin tube of radius r and thickness t subjected to an axial thrust T the compressive strain is

$$T/2\pi r\, t\, E\,,$$

where E is Youngs modulus for the material of the tube. The strain under full load is usually taken as 0·001, so that the thickness of the tube is given by

$$t = T/0{\cdot}001\; 2\pi r\, E\,. \qquad (1)$$

The effective length of the stop in this type of cell is rather difficult to determine, but is approximately the sum of the thicknesses a and b in Fig. 1, *i.e.*, about the same as the active length of the two tubes combined. For the stop to be K times as stiff as the active tubes

$$\pi r^2 = K\, 2\pi r\, t$$

or

$$t = r/2K\,. \qquad (2)$$

The usual value of K is 10, so

$$t \doteq r/20. \qquad (3)$$

With $r/t = 20$ the error consequent upon using the expression $2\pi r\, t$ for the cross-sectional area of the tubes is less than $2\frac{1}{2}$ per cent.

Combining (1) and (3) gives

$$r = 100\sqrt{(T/\pi\, E)},$$
$$t = 5\sqrt{(T/\pi\, E)}.$$

APPENDIX II

Matching of Sensitivities

Consider a two-arm gauge as at (*a*) and let R_1 change by $-\ \delta R_1$ and R_2 change by $+\ \delta R_2$ when the load is applied to the member. If these resistance changes are small the output is proportional to

$$\frac{\delta R_1 + \delta R_2}{R_1 + R_2} = \alpha\,.$$

If we have a second gauge of sensitivity β (greater than α), where

$$\frac{\delta R_1' + \delta R_2'}{R_1' + R_2'} = \beta\,,$$

our problem is to reduce β to the value of α. We therefore add resistors r_1 and r_2, as at (*b*), such that

$$\frac{\delta R_1' + \delta R_2'}{R_1' + R_2' + r_1 + r_2} = \frac{\delta R_1 + \delta R_2}{R_1 + R_2} = \alpha\,.$$

Whence

$$\alpha(R_1' + R_2' + r_1 + r_2) = \delta R_1' + \delta R_2'$$

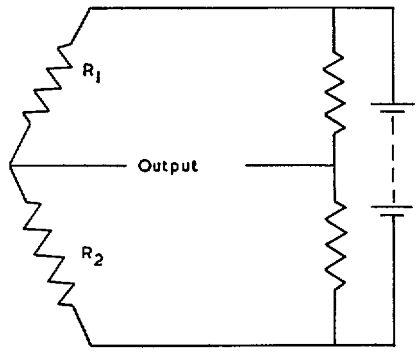
$$\alpha\left(\frac{R_1' + R_2' + r_1 + r_2}{R_1' + R_2'}\right) = \frac{\delta R_1' + \delta R_2'}{R_1' + R_2'} = \beta$$

and

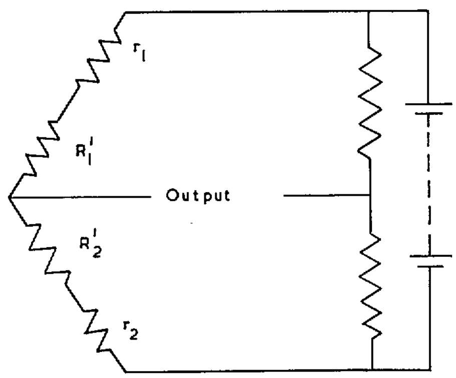
$$r_1 + r_2 = (R_1' + R_2')\left(\frac{\beta}{\alpha} - 1\right).$$

Note that r_1 and r_2 are so chosen that

$$\frac{R_1' + r_1}{R_2' + r_2} = \frac{R_1}{R_2}\,.$$



(a)



(b)

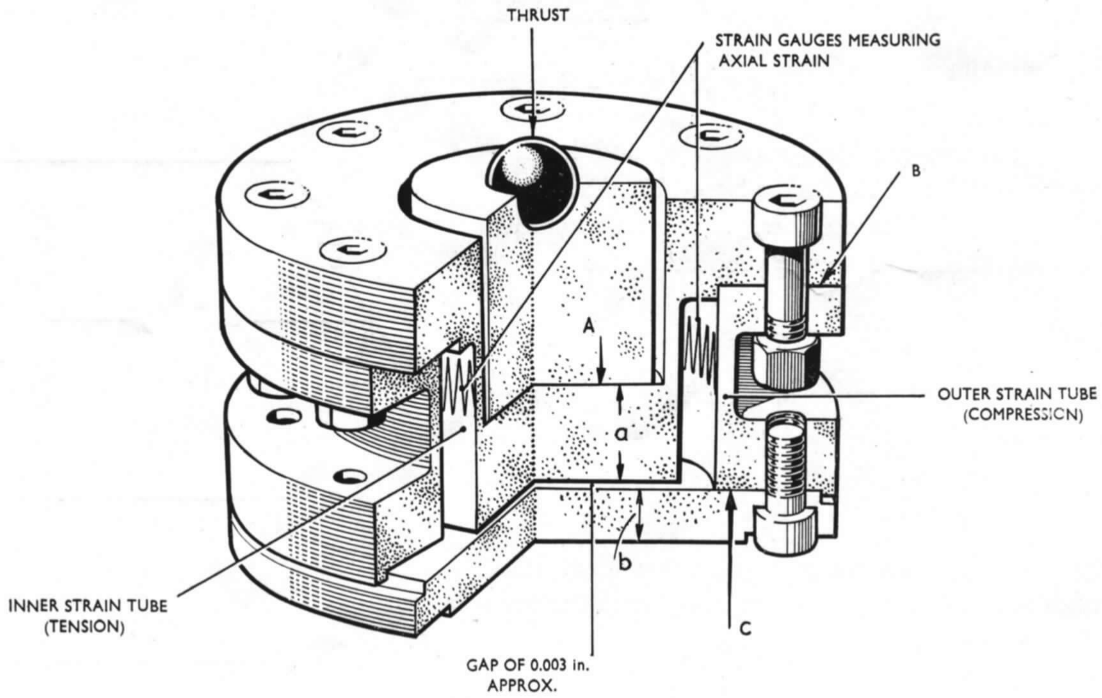


FIG. 1. Section through load cell.

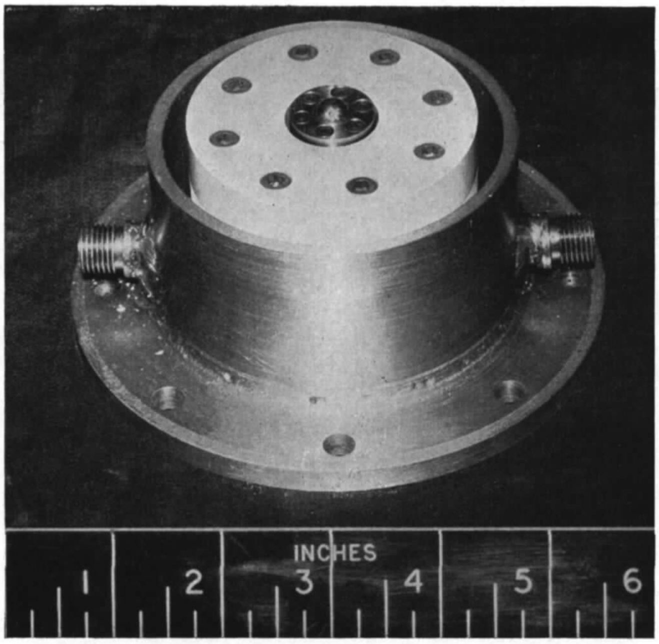


FIG. 2. 1,000-lb cell.

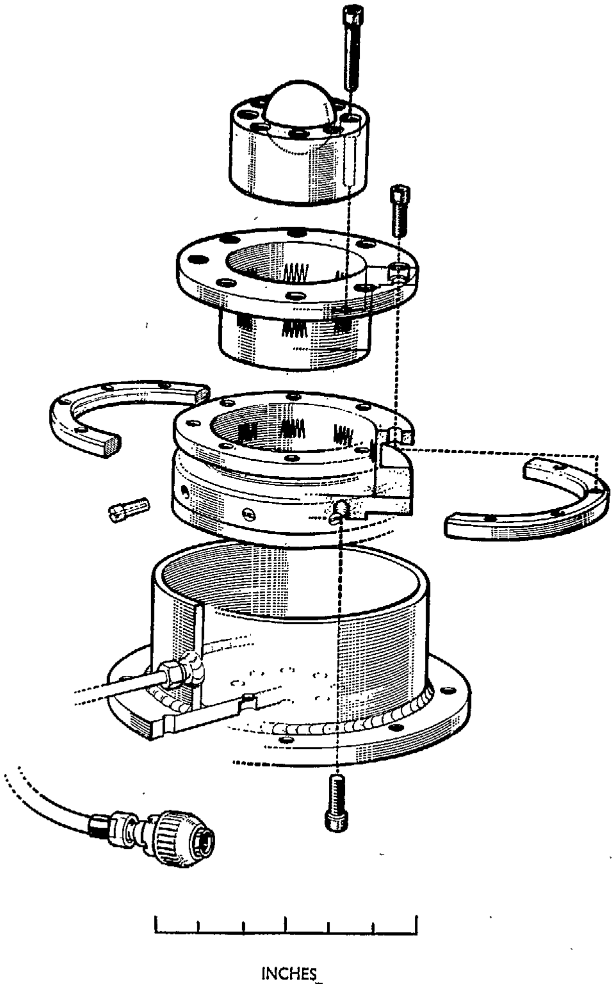


FIG. 3. 50,000-lb cell (Exploded view).

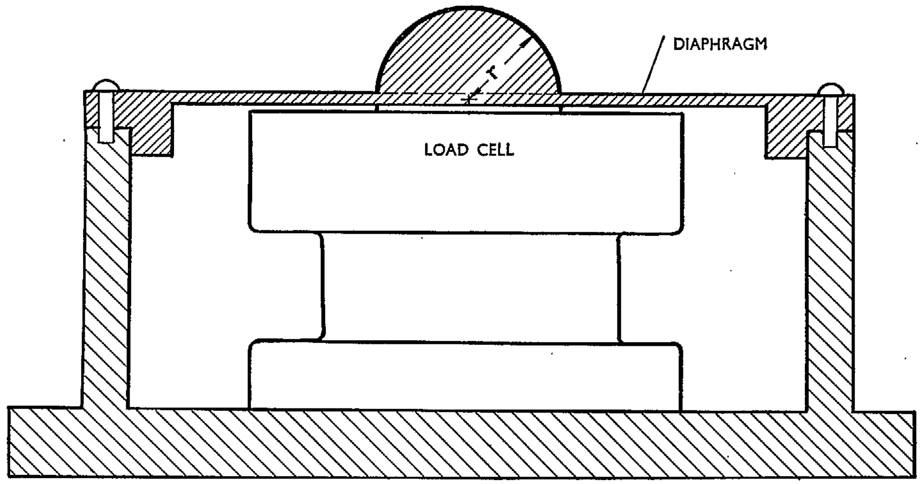


FIG. 4. Diaphragm for inclined loads.

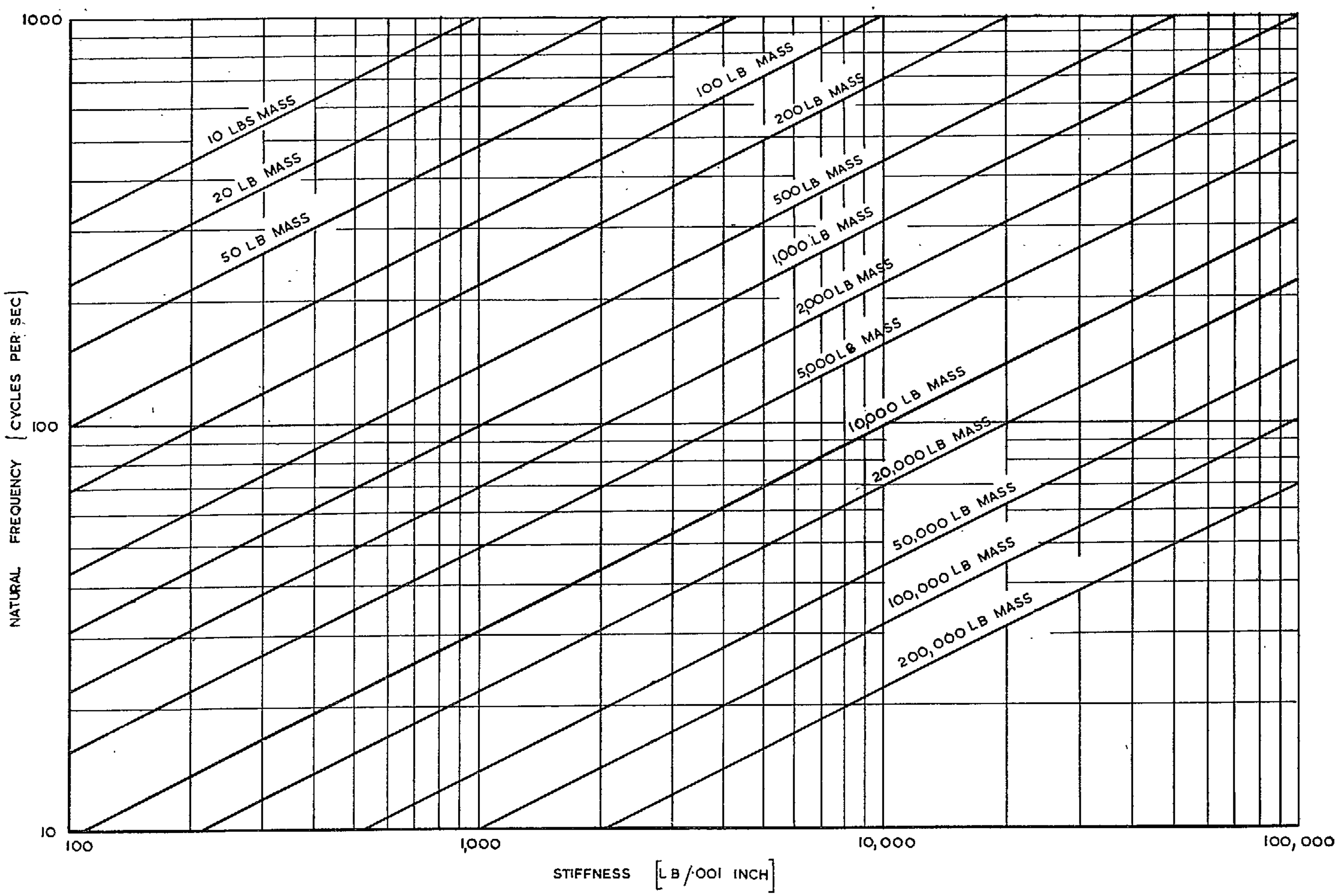


FIG. 5. Natural frequencies of spring and mass systems with one degree of freedom.

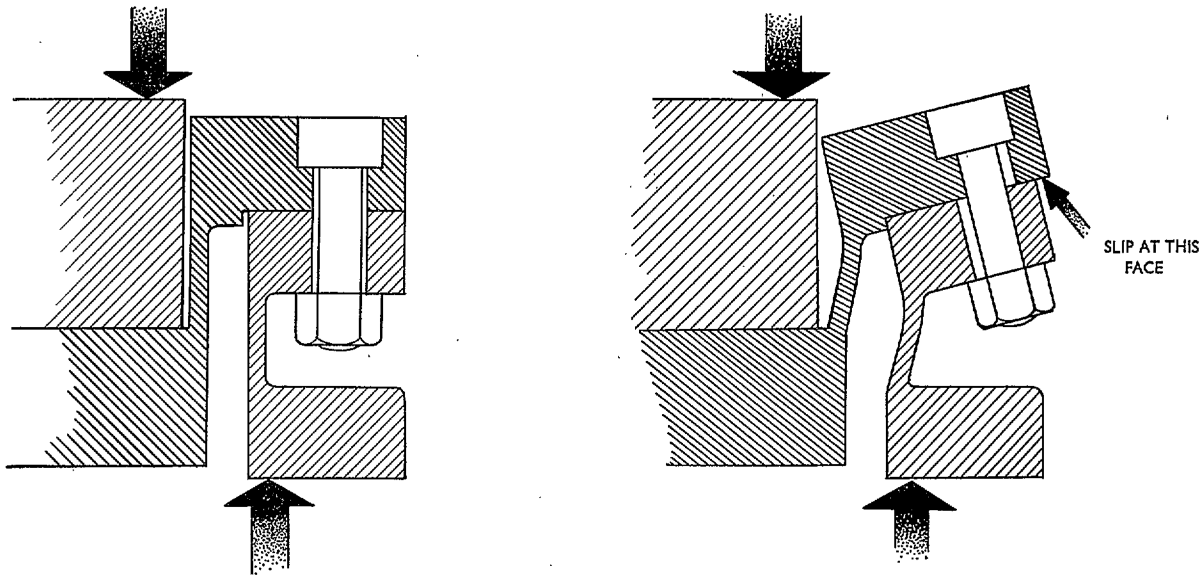


FIG. 6. Exaggerated effect of flange bending.

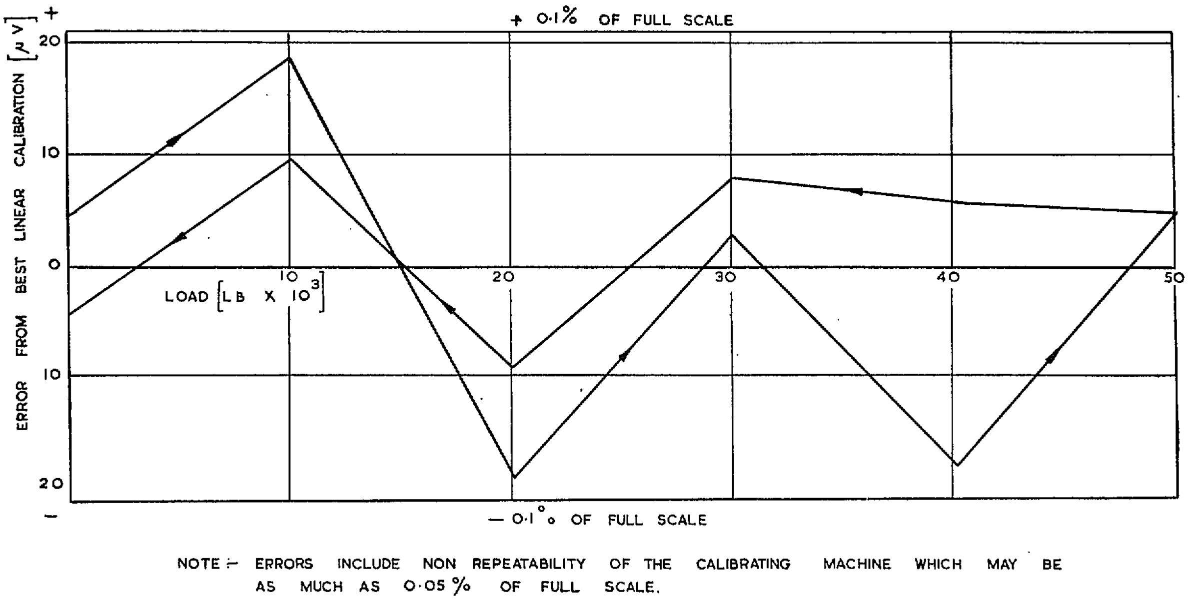


Fig. 7. Error curve for 50,000-lb load cell.

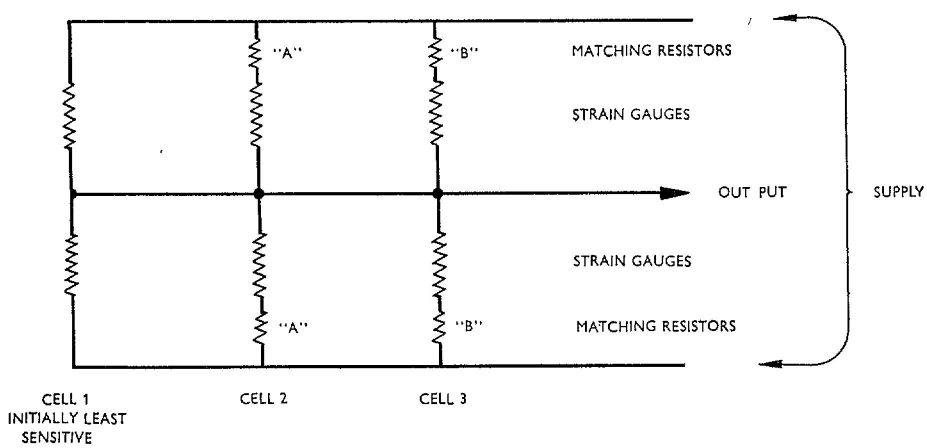


Fig. 8.

(78641) Wt. 54/8210 K7 6/60 Hw.

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