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ABSTRACT

A floating-element-type balance was successfully built to measure small forces, such as shear stress, on the bottom of a laboratory water flume floor. The balance was tested when it was used to measure shear stress values directly on a smooth wall. The values of shear stress were compared to those obtained by the Preston tube technique. Agreement was found to be good.

The surface area of the shear plate exposed to the flow was 24.2 square centimeters. Since the magnitude of shear stress varied from .0023 to 0.03 grams per square cm., the total measured force on this plate varied from .0462 grams to .607 grams.

The balance was calibrated for a maximum range of 1.000 grams. When the directly measured shear stress readings were compared to the Preston tube values, the maximum difference did not exceed .06 grams or 6% of the range of the balance. Low shear stress values of order 0.0023 grams per square centimeter can be measured satisfactorily if the maximum force range of the balance is reduced according to a design procedure outline in Appendix A.

Presented in this report are the experimental results, the design details, and other applications of the balance. The advantages of this design over other existing ones are also discussed.

Introduction

Shear stress is a very important parameter in the study of flow over a boundary. The Preston tube technique has been successfully used to determine the shear stress on a smooth boundary for equilibrium flows. The flow conditions near the wall are assumed to be a function of the shear stress at the wall and the kinematic viscosity of the fluid. However, for non-equilibrium flows, where the turbulent flow conditions change relatively rapidly in the flow direction, the log law is not obeyed and the Preston tube technique can not be used.

For rough walls Granville (1) pointed out that the shear velocity, u_* , can be obtained by finding the slope of u vs. $\log y$. He assumed that the log law for rough boundaries was universal in the form:

$$\frac{u}{u_*} = 5.75 \log_{10} \frac{y}{k} + B \qquad (1)$$

where u = the velocity at a distance y from the wall

u_* = shear velocity

y = distance from the wall

B = a constant depending on the relative roughness

k = a roughness length.

If the slope of u vs. $\log y$ is found, then the following relation is obtained from equation (1),

$$\frac{u_2 - u_1}{u_*} = 5.75 \left(\log y_2 - \log y_1\right) \qquad (2)$$

when u_2 and u_1 are velocities measured respectively at y_2 and y_1 from the wall.

The shear velocity u_* is proportional to the difference of velocities at different depths, and inversely proportional to $\log y_2 - \log y_1$. Smaller errors in velocity measurements produce large errors in u_*. For large roughness, the position $y = 0$ is difficult to define; this is a rather critical source of error. It is noted that the percent error in τ_o, the shear stress, is two times the percent error in u_* since $\tau_o \propto u_*^2$. It is concluded that a large error in τ_o can occur when Granville's method of measuring shear stress is used.

Hwang and Laursen (2) attempted to measure the shear stress on rough surfaces by the Preston tube technique. Granville (3) pointed out that this method was very inaccurate. Hwang and Laursen (4) later agreed that the Preston tube technique could only be used to obtain an order of magnitude for the shear stress.

Westkaemper and Hill (5) did a detailed study on the measurement of local skin friction by the Preston tube technique. They found that even on smooth surfaces, the measurement of shear stress is more accurate by the direct method than by the Preston tube technique.

Aeronautical investigators pioneered the measurement of skin friction directly. References (6), (7) and (8) give examples of satisfactory measurements made by floating element type balances.

O'Donnell (6) investigated the effect of floating element misalignment on the balance accuracy. In supersonic flow his measurements showed that the error was approximately 1% for each 0.06 mm of misalignment. For subsonic flow Smith and Walker (8) found that the surface of the floating element could be depressed by as much as 0.125 mm inches without any change in the measured surface shear.

Dhawan (7) studied effect of a gap on the measured value of shear stress. The dimensions of his floating element were .2 x 2.0 cm. Dhawan concluded that the effect of a 0.25 mm gap was negligible on the shear stress measurements. He also measured the velocity profile over a 0.2 cm slot and showed that there was no noticeable change in the profile. It was concluded that the effect of a 0.2 cm shot on the shear stress would also be negligible.

Relatively few skin friction balances have been built for determining wall shear stress in hydraulics.

Bursali (9) built a skin friction balance which measured shear stress satisfactorily on the bottom of a channel. The measuring plate size was 8.0 x 20.0 cm. The magnitude of the shear stress varied from .016 to .070 gm per square cm. The design of the balance incorporated strain gauges which were mounted on beams supporting the plate. The shear force was obtained from calibrated strain gauge readings. It was noted that the measured force is relatively large for this instrument.

Yakosi and Kadoya (10) built a device which was very similar to the design mentioned in the aeronautical references 6 to 8. The dimensions of the measuring surface were 6 cm x 15 cm. The measuring plate was suspended on nylon threads. The drag force was proportional to the measuring plate displacement which was determined by a differential transformer mounted in water. This design requires clean water to operate satisfactorily.

The design of the floating-element-type balance, presented in this report, is believed to be sturdier and simpler than the above two designs. The measuring surface area is a 24.2 square centimeters (or 2 inch diameter) disk which is much smaller in comparison with the large surface areas in the designs of Yakosi and Kadoya, and Bursali.

Design of Floating-Element-Type Balance

Figure 1 gives the side and upstream views respectively of the balance. Referring to Figure 1, the floating element, floating element holder, the support bars, the transformer core holder, and the transformer core all all held rigidly together. This rigid assembly is hung on thin stainless steel supports which are attached to the mounting plate.

Attached to the mounting plate is the brass box with the transformer holder and the differential transformer winding. The transformer winding with its core is generally referred to as a "linear variable differential transformer" or "LVDT." The LVDT is manufactured by Schaevitz Engineering, Pennsauken, New Jersey. In this balance the model used is the ".005 MS-L." The linear range is ± .005 inches from its null position. The LVDT accuracy is 1/2% of its range.

When the balance is assembled properly, the transformer core moves freely inside the transformer winding. The only resistance to the applied force is due to the weight of the hanging assembly and the resistance offered by the "beam-type" loading on the thin stainless steel supports. Appendix A outlines the method for calculating the moment of inertia of the stainless steel supports after one is given the maximum measured force and the maximum allowable displacement.

For the present design, the maximum applied force is 1 gram for a maximum displacement of 0.25 mm. It is therefore reasonable to choose a gap width between the floating element and mounting plate of 0.25 mm.

When the balance is mounted in the bottom of the flume, the mounting plate and the floating element form part of the flume floor, as shown in Figure 1.

It should be noted from Figure 1 that the floating element with its rigid assembly is completely submerged in water except for the LVDT. The main advantage of the present design compared to the design by Yakosi and Kadoya is that the LVDT is mounted in air. Therefore, dirt particles in the water can not plug the clearance between the transformer core and the transformer winding. Also, if the LVDT is mounted in water, there may be difficulty in removing all the air between the transformer core and the transformer winding when initially filling the box with water. If air comes out of solution from the water, air may be trapped between the transformer core and the winding; this also results in measurement errors due to surface tension effects.

These balance problems are eliminated in the present design. The force measurement is made without any friction, even when the water quality in the flume is poor.

Procedure for Measurement of Skin Friction

The following procedure was used for assembling and calibrating the balance.

The mounting plate with the attached brass box was placed on a table in the same position as when it was mounted in the flume. The rigid hanging assembly, including the floating element, floating element holder, support bars, transformer core holder and transformer core were all assembled and hung on the thin stainless steel supports as shown in Figure 1. Final adjustments of the floating element were made with the screws in the floating element holder. The floating element was positioned closer to the upstream side of the mounting plate to permit deflection in the downstream direction. The transformer holder was fixed to the brass box and the transformer core was attached to the transformer core holder. The transformer winding was then installed in the transformer holder. The transformer core and the transformer winding were positioned such that a linear voltage output was obtained when equal increments of downstream force were applied to the element. (For this particular LVDT, the linear range was from -0.125 mm to + 0.125 mm with the corresponding voltage ranging from -1.200 volts to +1.200 volts. The initial position of the core with no applied force on the element was therefore set such that the output voltage was -1.000 volts).

If the balance was used in a flume with a slope on it, then the buoyancy effect of the rigid assembly was eliminated by the following procedure. The zero force position of the element was adjusted as explained above. The volume of the material in the hanging rigid assembly was measured; the buoyancy force was equal to the weight of water displaced by the assembly. The buoyancy force was counteracted by placing an equivalent weight of lead on the horizontal support bars.

The balance was filled with water after having been installed in the flume and the buoyancy effects eliminated. It was then calibrated by a pully-weight system. If the balance was adjusted properly, then the calibration of force versus output voltage was linear as shown in the balance calibration curve, Figure 2. This is in agreement with the type of loading on the stainless steel supports as shown in Appendix A.

Experimental Results and Discussion of Errors

The balance was used to measure different magnitudes of shear stress. These measured values were compared to the shear stress values obtained by the Preston tube technique. The calibration curves used for the Preston tube are given in reference (11).

The shear stress values determined by the Preston tube technique were in error to some degree. Allowing for some error in the measurements made by the balance, the deviation between the shear stress values determined by the Preston tube and the balance could be relatively large.

For the experimental runs conducted, the outside diameter of the Preston tube was 1.24 mm. The equipment used to measure the Preston tube dynamic pressure included a Pace differential pressure transducer with a range of $\pm$ 1 psi, a Pace C-D-25 carrier demodulator, an averaging circuit, and a Mosely 680 strip chart recorder.

The order of magnitude of the shear stress varied from .0023 to .0300 grams per square cm as shown in Figure 3 and Table I. At the lowest shear stress reading the dynamic pressure on the Preston tube was only of order 1.02 mm of water. The accuracy of measurement was uncertain at such a low pressure differential. It was noted that the drift of the transducer alone was of order 0.25 mm of water; this could have contributed 25% error in the dynamic pressure reading for the Preston tube.

Table I shows that at the lowest shear stress value the force on the element was only 5% of the maximum calibrated balance range (1.000 grams). At such a low force, the balance error in measuring the shear force should also increase.

It was felt that low shear stress values of order .0023 grams per square cm can be measured satisfactorily if the maximum force range of the balance was reduced according to a design procedure as outlined in Appendix A. For the 2-inch diameter (or 51 mm diameter) element used in this work, a recommended maximum range on the balance would be 100 milligrams. Dhawan (7) was successful in calibrating his wind-tunnel balance up to a range of 20 milligrams. It is unknown whether such a low force range could be obtained for hydraulic balances.

From Table I and Figure 3 it was concluded that the directly measured shear stress values agree very well with the Preston tube measurements. This conclusion follows from the fact that there could be errors in the Preston tube measurements combined with errors in the balance measurements as discussed above. However, it was noted that the balance shear was equal to or greater than the Preston tube shear stress.

Table I shows that the balance error was less than 6% of the maximum calibration range (1.000 gm) for the balance. With more flexible members according to a design procedure presented in Appendix A, this error can be reduced significantly.

Other Applications of the Balance

Besides shear stress measurement, there are other applications where similar design principles can be used. Presently at Colorado State University a modified design is being used to measure the total drag of a cylinder representing a pier in open channel flow. In this case, the cylinder (instead of the floating element) is mounted on brass supports (which replace the thin stainless steel supports in the presented design). The main advantage of the present design in measuring pier drag is that the measured deflection is independent of where the force is applied on the pier. This design principle was proven by Hsi and Nath (12).

The drag force on individual roughness elements can be measured for flow over a rough boundary. The effect on drag of an upstream distribution of roughness elements can be measured directly.

If a fluctuating drag force exists, such as on a pier, then a damping plate must be installed on the frame holding the object under study.

Conclusions

A floating-element-type balance has been successfully designed, built and tested to measure wall shear stress in a laboratory flume. The balance shear stress values were compared with Preston tube measurements. Very satisfactory agreement was found if allowance was made in the experimental error in the Preston tube technique and the balance measurements. The magnitude of the shear stress deviation was less than 6% of the maximum range of the balance. Low shear stress of order 0.0023 grams per square centimeter can be measured satisfactorily if the maximum force range of the balance is reduced according to a design procedure outline in Appendix A.

If a better estimate of balance precision is desired, it is recommended that the balance be tested in a long pipe where wall shear stress can be determined more accurately.

Acknowledgment

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Table I

Run No.	Shear Stress (gms/cm^2) Preston Tube	Balance	Force on the Floating Element (grams) Based on Preston Tube Shear Stress	Measured by the Balance
1	.00228	.00227	.046	.046
2	.00363	.00459	.074	.093
3	.00637	.00834	.129	.169
4	.00982	.0110	.199	.223
5	.0115	.0126	.233	.256
6	.0148	.0172	.299	.348
7	.0214	.0233	.434	.472
8	.0300	.0328	.607	.665

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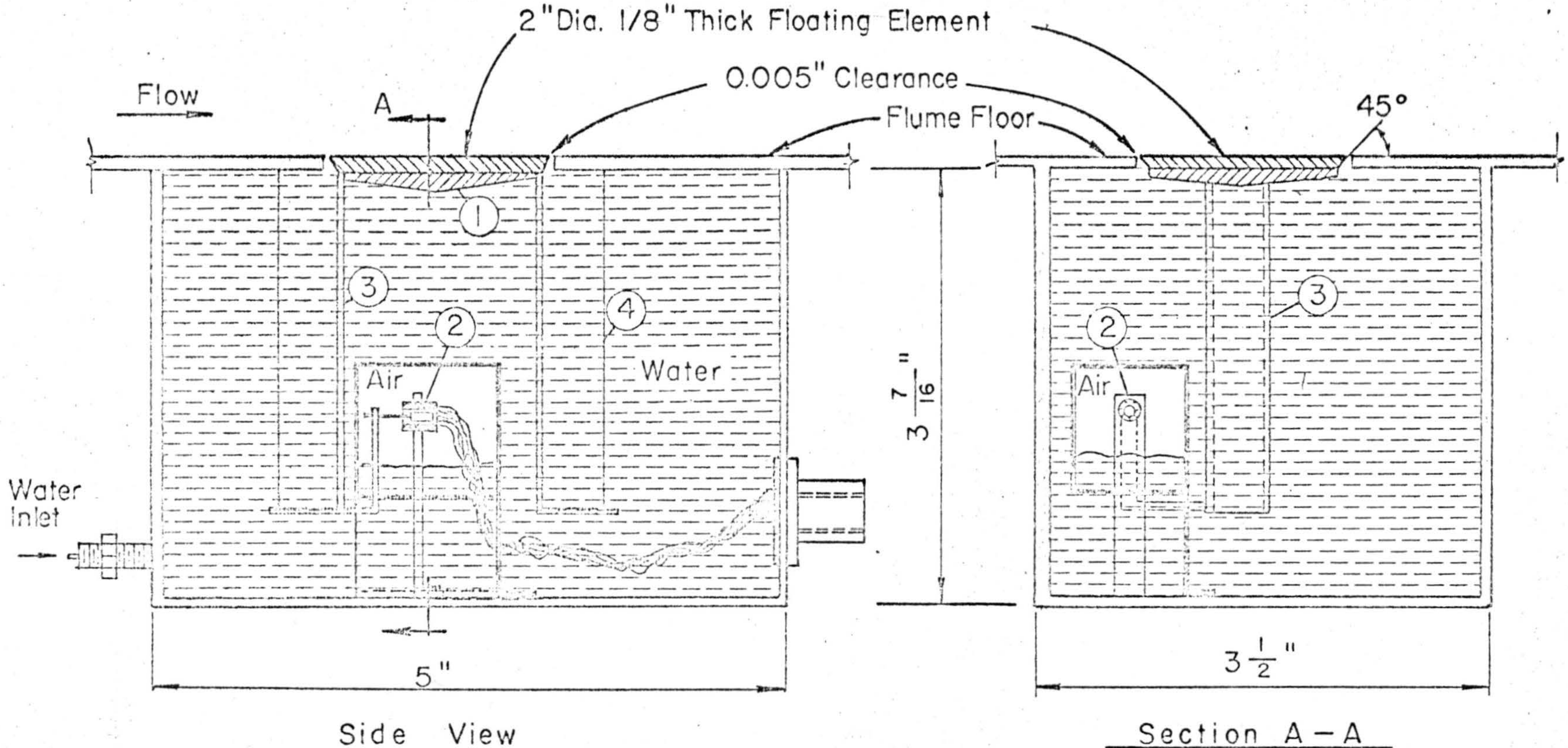

Notes:

(1) Bottom of Floating-element: It Forms a 170° Cone to Prevent Trapping of Air When the Box is Filled Through the Water Inlet.

(2) Schaevitz Differential Transfomer: (a) Model No. 0.005 M-L, (b) Max. Displacement for Linear Voltage Output is ± 0.005 in. from the (c) Supplier: Schaevitz Engineering U.S Route 130 & Union Ave. Pennsauken, N.J.

(3) Rigid Member

(4) Thin Flexible Rectangular Stainless Steel Member

FIGURE 1 HYDRAULIC FLOATING ELEMENT BALANCE

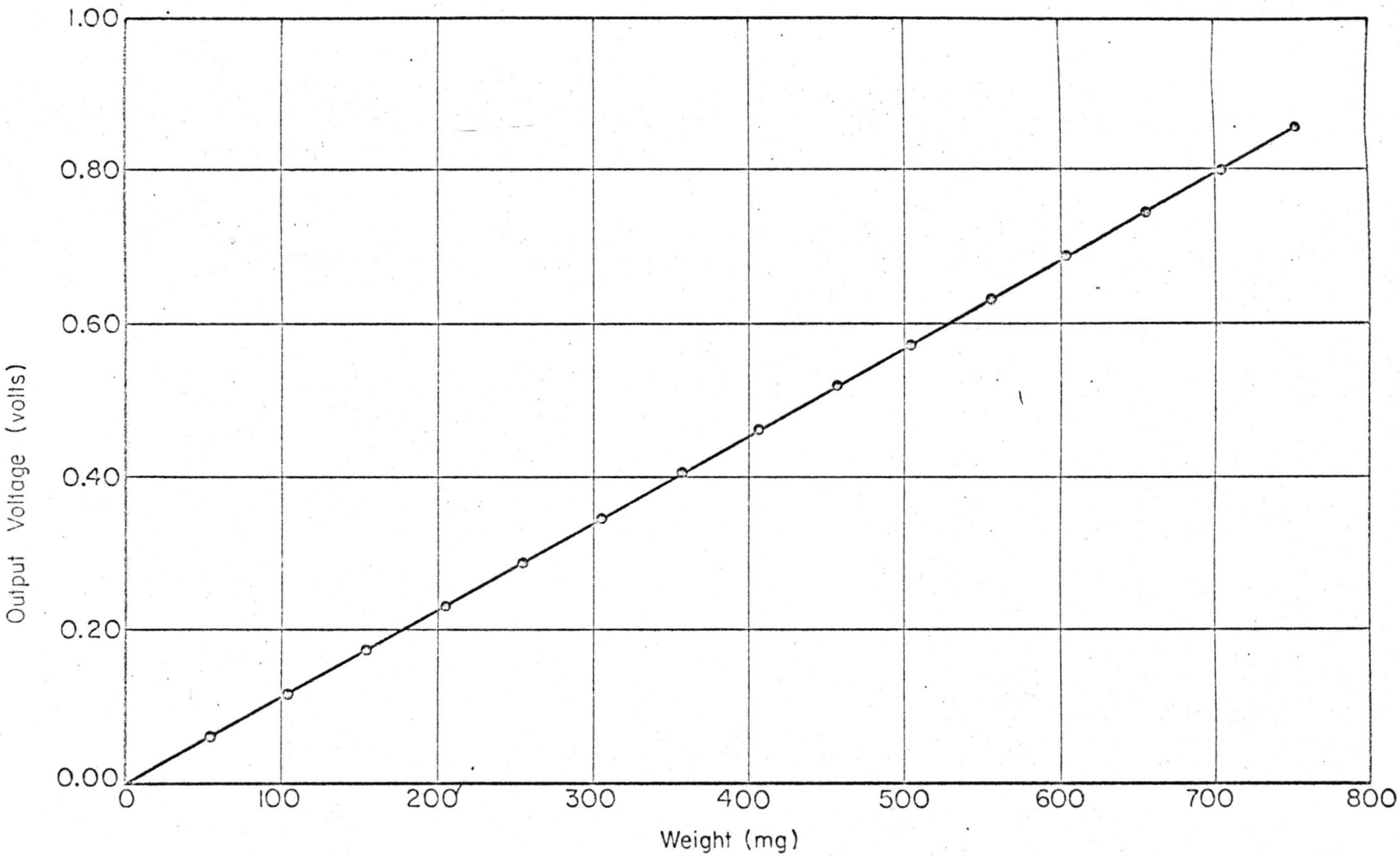

FIGURE 2 BALANCE CALIBRATION CURVE

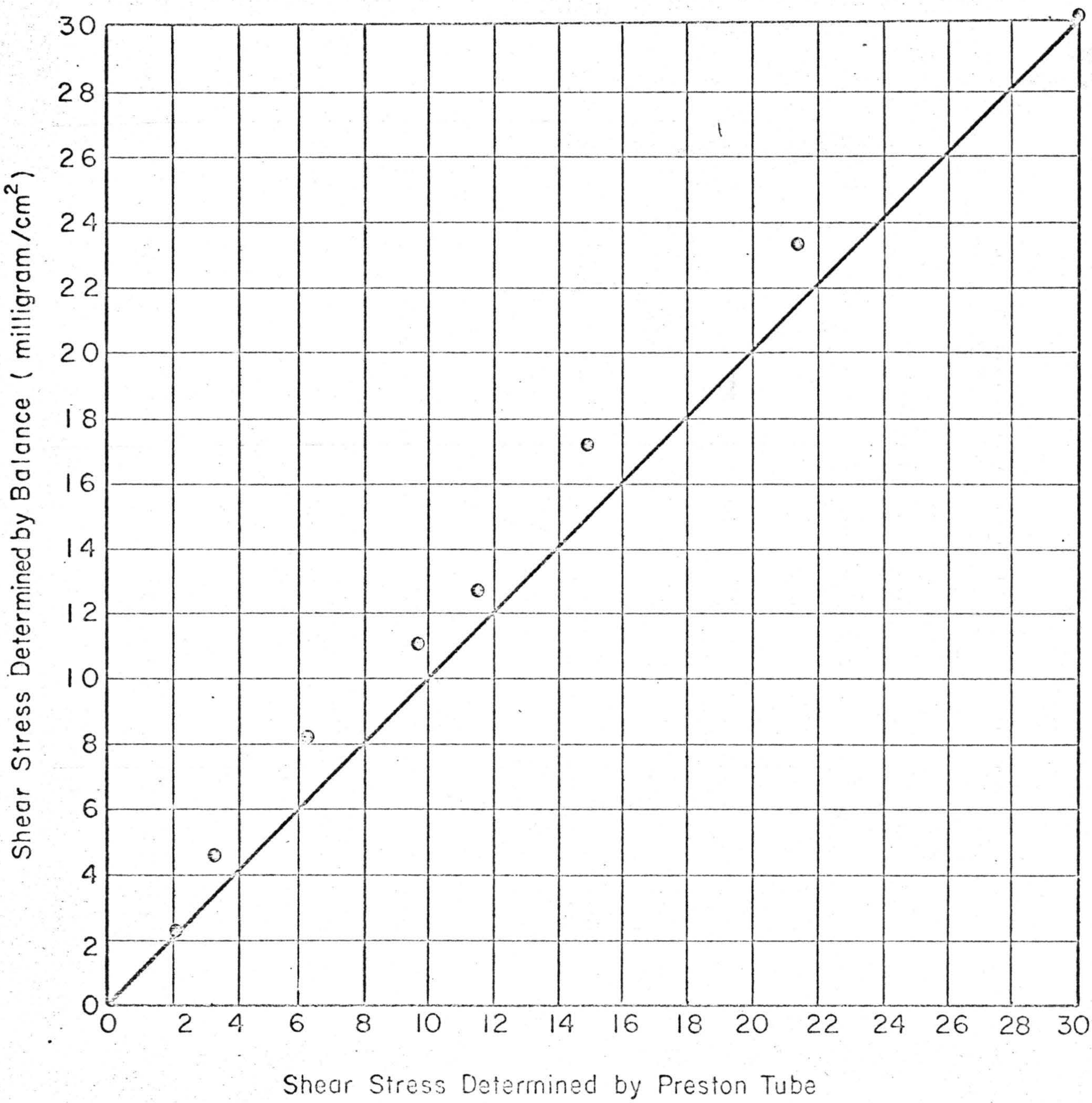
Shear Stress Determined by Balance (milligram/cm²)
Shear Stress Determined by Preston Tube
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30

FIGURE 3

APPENDIX A

Design Supports for Forces of Different Magnitudes

Shown below is a sketch of the balance without the LVDT.

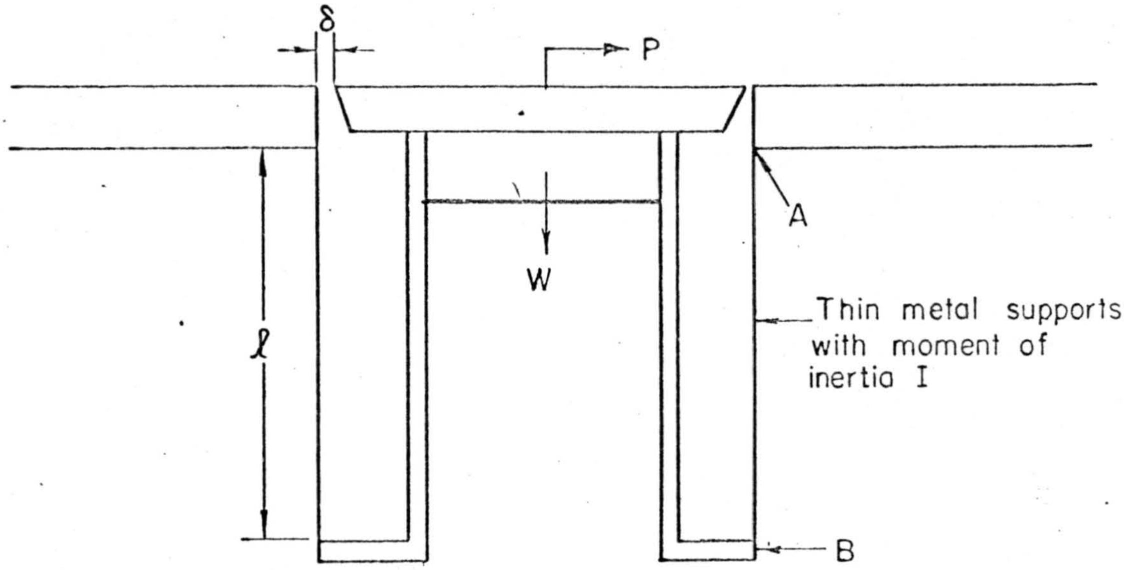

Diagram 1

The problem is to find the moment of inertia I, the length of the supports ℓ , and a submerged weight W , for a given maximum deflection δ caused by a force P.

Assume that the supports are rigidly held at A and B. Let the total weight of the hanging rigid assembly be W. A free body diagram showing the forces involved on a single support is given in Diagram 2(a)

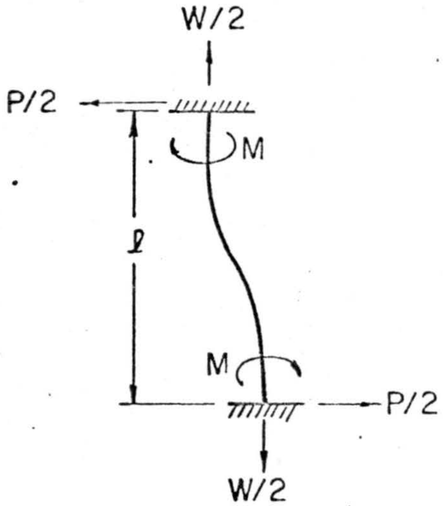

Diagram 2(a)

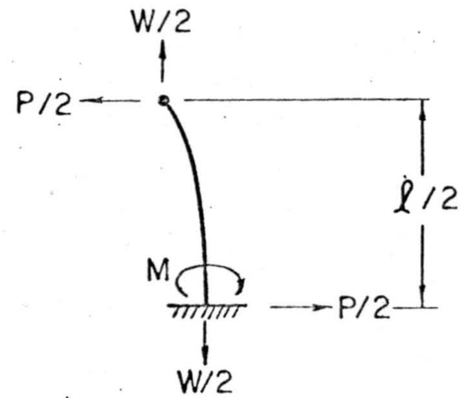

Diagram 2(b)

By symmetry the forces on the thin support may be represented as shown in Diagram 2(b). For a beam loading shown in Diagram 2(b), the maximum deflection is (see Roark* for example)

$$\frac{\delta}{2} = \frac{P}{W} \left[\frac{\ell}{2} - \frac{\sqrt{2EI}}{W} \tanh \left(\frac{\ell}{2} \sqrt{\frac{W}{2EI}}\right)\right] \qquad \text{(A1)}$$

where E is the modulus of elasticity of the support.

Therefore, the deflection δ is proportional to the applied horizontal force P.

For $\frac{\ell}{2} \sqrt{\frac{W}{2EI}} << 1$ the above expression reduces to

$$\frac{\delta}{2} = \frac{P}{W} \left[\frac{\ell}{2} - \left(\frac{\ell}{2}\right) \left(\frac{W}{6EI}\right)\right]$$

or

*Roark, R. J., Formulas for Stress and Strain, McGraw-Hill Book Co., 3rd Edition, 1954, pp. 134-137.

$$\frac{\delta}{2} = \frac{P\ell}{2W}\left(1 - \frac{W}{6EI}\right) \tag{A2}$$

For $\frac{W}{6EI} \ll 1$ equation (A2) simplifies to

$$\frac{\delta}{2} = \frac{P\ell}{2W} \tag{A3}$$

For $\frac{\ell}{2}\sqrt{\frac{W}{2EI}} \geq 5$, $\tanh\left(\frac{\ell}{2}\sqrt{\frac{W}{2EI}}\right) = 1$.

Therefore, equation (1) reduces to:

$$\frac{\delta}{2} = \frac{P}{W}\left(\frac{\ell}{2} - \sqrt{\frac{2EI}{W}}\right) \tag{A4}$$

The design problem is easily solved from equations (A1) to (A4). The variables W , ℓ and I are juggled until they satisfy the condition that the maximum deflection is δ for a given force P .