Force Measurement

1. **Force is defined by $F = m.a/g_c$ ($g_c = 1\ kg.m/N.s^2$)**

   Mass is a fundamental quantity and Acceleration a depends on the standards of two fundamental quantities such as Length and Time.

2. **In case of Weight, a = g. The actual value of g at a given location depends on latitude ϕ, and also slightly with time. For given h,**

$$g = 978.049(1 + 0.0052884\sin^2\phi - 0.0000059\sin^2 2\phi) \quad cm^2/s$$

With the correction factor for altitude "h" in meters above the MSL is

$$Correction = -(0.00030855 + 0.00000022\cos 2\phi)h + 0.000072\left(\frac{h}{1000}\right)^2 \quad cm^2/s$$

Basic Methods of Force Measurement

1. Balancing the unknown force against the known gravitational force directly or through a system of levers
2. Measuring the acceleration of a body of known mass which is subjected to a unknown force.
3. Balancing the unknown force against a magnetic force developed by interaction of a current carrying coil and a magnet.
4. Transmitting the unknown force into a fluid
5. Measuring the deflection of a elastic member caused by the unknown force
6. Measuring the change in natural frequency of a wire tensioned by an unknown force.

Classification of Balances

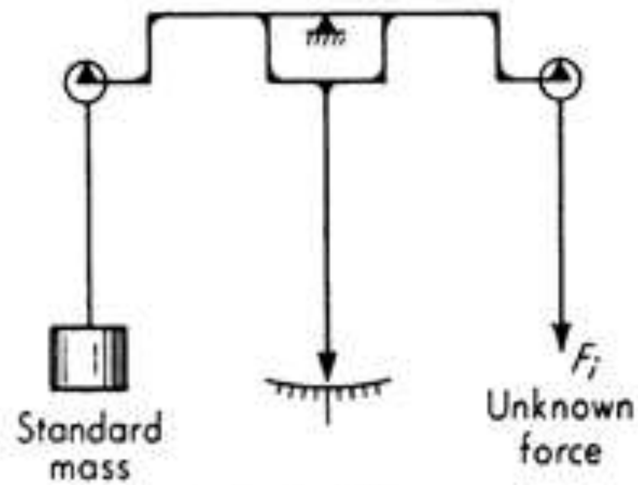
Description	Range (g)	Resolution (g)
Macro analytical	200- 1,000	10^{-4}
Semimicro analytical	50- 100	10^{-5}
Micro analytical	10- 20	10^{-6}
Micro balance	less than 1	10^{-6}
Ultra micro balance	less than 0.01	10^{-7}

Source: E.O.Doebelin, Measurements systems.

Force Measurement -Balances

Types : Analytical, Pendulum Scale, Platform

Analytical Balance:



Analytical balance

1. **Simplest balance**
2. **Operates on the principles of moment comparison**

   The moment produced by the unknown weight or force is compared with that produced by the known weight or force. When null balance is obtained, the two weights are equal provided the arm length are equal.

3. **Careful design : The frame should be designed in such a way that the center of mass is only slightly below the knife edge pivot point (50 to 200 μ).**
4. **Symmetry of the Frame: Check the arm length by exchanging the known and unknown weights**

Force Measurement -Balances

For Better Accuracy:

1. Buoyancy forces acting on unknown and known weights should be considered.

   Due to immersion of mass in air.

   If the measurement is carried out in vacuum the effect of buoyancy forces is negligible.

2. Measurement should be taken place in a controlled temperature chamber. Especially for micro scale measurement.

Effect of Buoyancy Force on the Weight Measurement

The two forces exerted on the balance arms are given by

$$W_1 = (\rho_u - \rho_a)V_u \ ; W_2 = (\rho_s - \rho_a)V_s$$

Where the suffice u, s and a represents that for the unknown sample, standard sample and air, respectively .

Neglecting Buoyancy effects, the true weights of the unknown and standard are

$$W_u = \rho_u V_u \ ; \quad W_s = \rho_s V_s$$

Buoyancy effect will be more significant for lesser density materials.

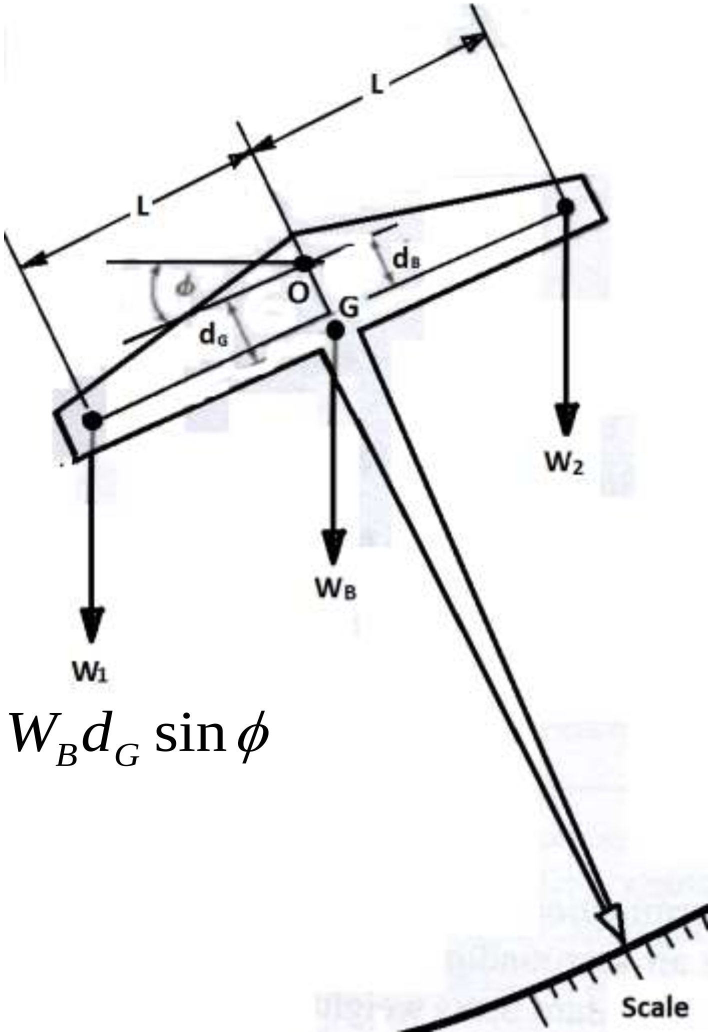
At null deflection, $W_1 = W_2$

$$W_u = W_s \left[1 + \frac{\rho_a(\rho_s - \rho_u)}{\rho_s(\rho_u - \rho_a)} \right]$$

(or)

$$W_u = W_s \left[\frac{\rho_u(\rho_s - \rho_a)}{\rho_s(\rho_u - \rho_a)} \right]$$

Sensitivity of the balance, $s = \dfrac{\phi}{|W_s - W_u|}$ where, ϕ = beam deflection in radians



$$s = \frac{\phi}{\left|W_s - W_u\right|}$$

$$W_1\left(L\cos\phi - d_B\sin\phi\right) = W_2\left(L\cos\phi + d_B\sin\phi\right) + W_B d_G \sin\phi$$

$$W_1\left(L - d_B\phi\right) = W_2\left(L + d_B\phi\right) + W_B d_G \phi$$

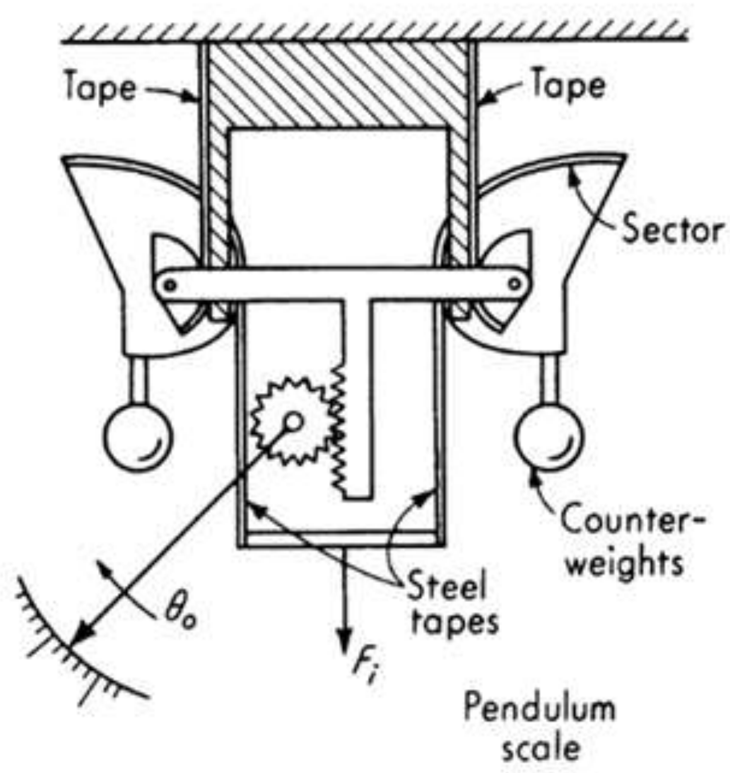
$$\frac{\phi}{\Delta W} = \frac{L}{(W_1 + W_2)d_B + W_B d_G}$$

If the fulcrum is constructed so that dB 0, then

$$s = \frac{L}{W_B d_G}$$

Pendulum Balance

- **Deflection type Instrument.**
- **Unknown force is converted to a torque that is then balanced by the torque of a fixed standard mass(pendulum).**
- **Specially shaped sectors and steel tapes linearize the non-linear torque-angle relation of a pendulum.**



Old Pendulum type Balance

Old-fashioned

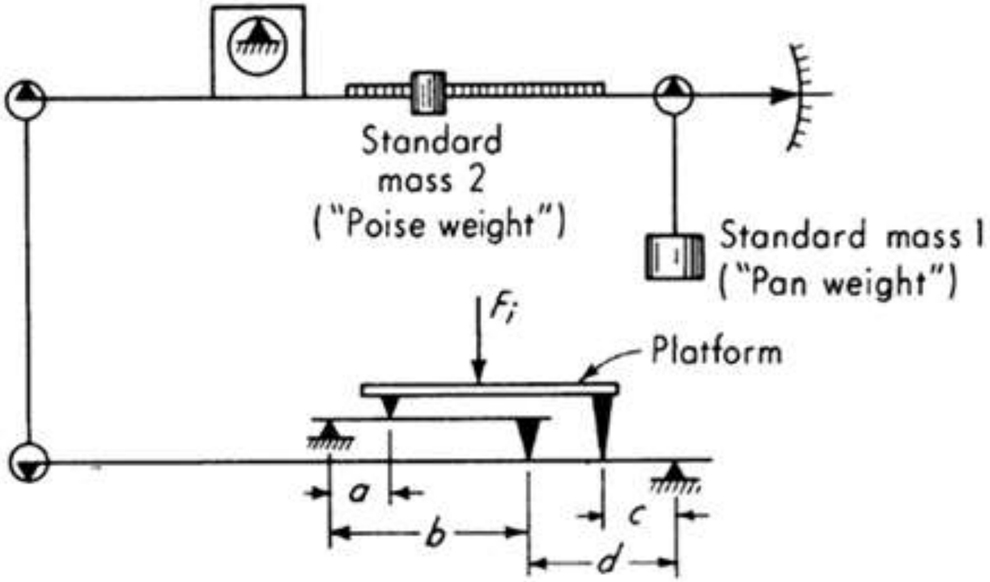
Pendulum Balance

(For small range of force measurement)

Platform Balance

1. **Moments of unknown force is balanced using a system of levers and standard mass combination.**
2. **System is made Null by a proper combination of weights and lever arm lengths.**
3. **Measurement of large forces in terms of much smaller weights.**
4. **Reading of the scale is independent of the location of force F_i on the platform if**

$$\frac{a}{b} = \frac{c}{d}$$



Electromagnetic Balance

- Electromagnetic force to balance the unknown force
- Used in deflection and null models
- Easy to handle, compact
- Less sensitivity to the environmental change
- Fast response, can be used for dynamic force measurements
- Electrical signal is very convenient for continuous recording and automatic control of process.
- Balance with built in microprocessor also is available
- Automatic tare-weight systems available for net weight requirements.

Load Cells

- Hydraulic and Pneumatic types
- Hydraulic cell uses an incompressible oil
- Cell cavity initially preloaded with oil around 2 bar
- Application of load increases the oil pressure, which is read on an accurate pressure gauge or Transducer
- Cells are very stiff, deflections only a few thousands of an inch
- Capacities up to about 5000 tonnes
- Accuracy up to $\pm$ 1% of FS.
- Temperature sensitivity unto $\pm$ 0.25 % for 10^{o}F

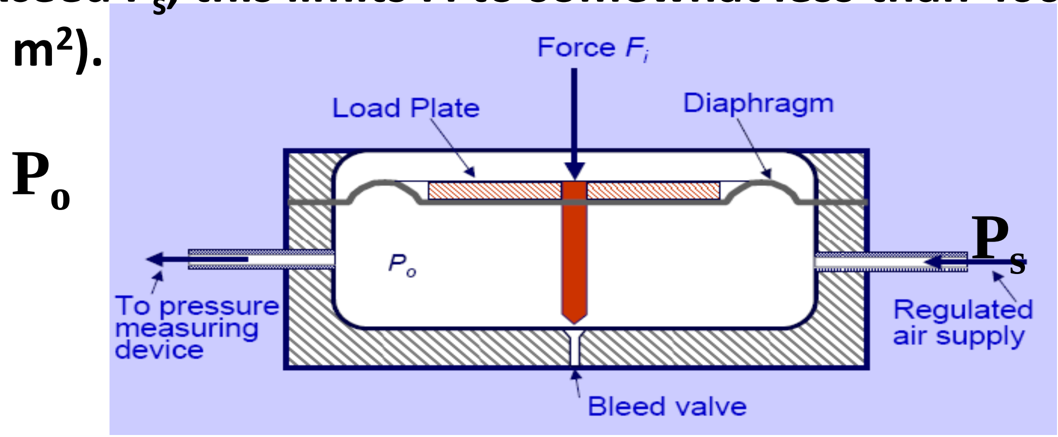
Pneumatic Load Cells

Application of force F_i causes the diaphragm deflection which in turn causes an increase in pressure p_o

Increasing the pressure acting on the diaphragm produces an effective force F_p that tends to return the diaphragm to its initial position.

Pressure under the diaphragm is controlled by both changing the supply pressure and position of bleed valve.

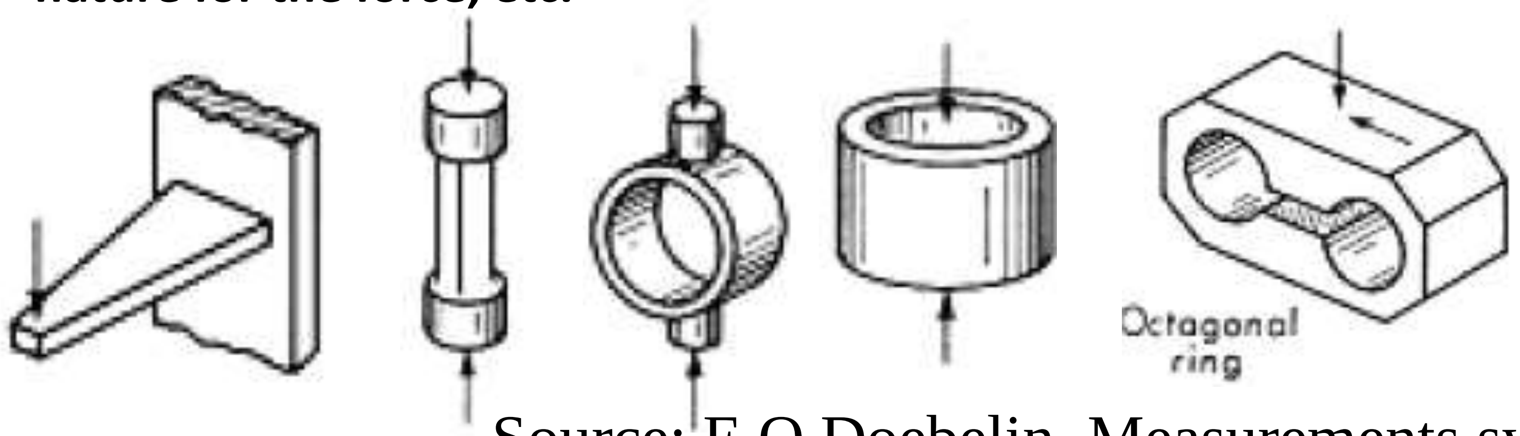
A typical supply pressure P_s is about 4 bar and the maximum value of P_o can not exceed P_s, this limits Fi to somewhat less than 400 A kN (A= area of diaphragm, in m^2).



Capacity up to about 50,000 tonnes

Elastic Load Cells

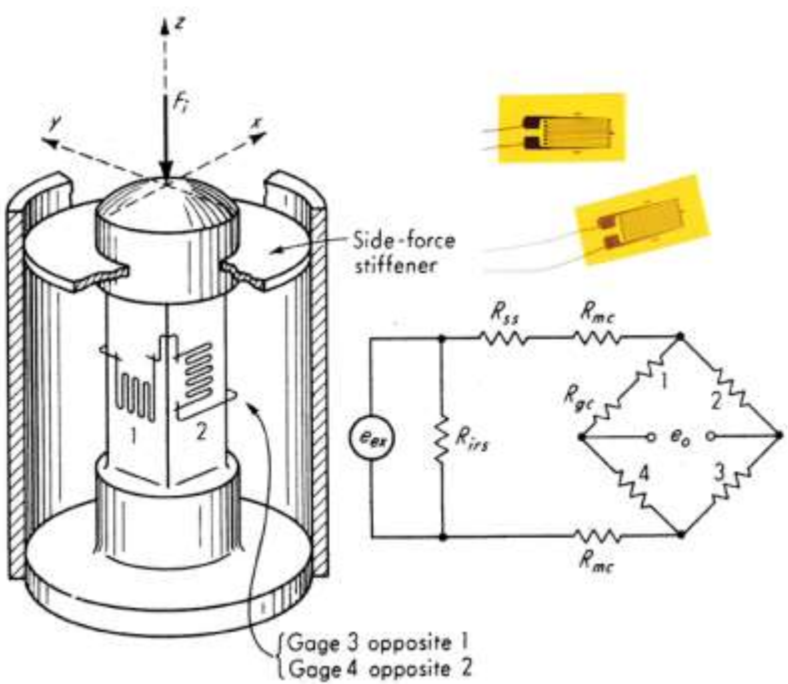
- Elastic load cells are widely used for both static and dynamic force measurements (Frequency about 100 Hz.)
- All are spring and mass systems
- Strain gages may be located to sense the force in terms of strain.
- Designed for specific directions.
- Load cells are tailored depends on the applications, load magnitude, nature for the force, etc.



Source: E.O.Doebelin, Measurements systems.

Bounded Stain gage Transducers

Four strain gages are employed (refer figure). They should be placed symmetric. To achieve high accuracy, additional temperature compensation resistors are used. Further, additional resistors may also be used for adjusting the input resistance and sensitivity.



1,3 direct strain and 2,4 transverse strain

Deflection under full load will be in the order of 0.001 to 0.015 in

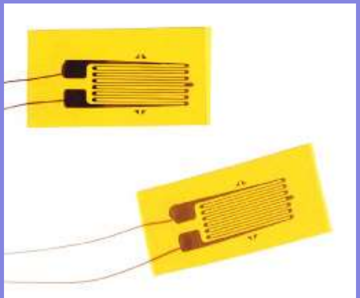
Material used SS – 4340, SS-17-4 PH, 2024-T4 aluminum alloy, etc.

When maximum output is desired, Use low modulus materials (e.g. Al)
However, Low modulus usually reduces stiffness leading to excessive hysteresis, low fatigue life, etc.

Different types of load cells and their ranges

- Compression cylinder (50 kN - 50 MN)
- Compression cylinder (hollow) (10 kN - 50 MN)
- Toroidal ring (1 kN - 5 MN)
- Ring (1 kN - 1 MN)
- S-beam (bending or shear) (200 N - 50 kN)
- Double-ended shear beam (20 kN - 2 MN)
- Double-bending beam (500 N - 50 kN)
- Shear beam (1 kN - 500 kN)
- Double-bending beam (100 N - 10 kN)
- Tension cylinder (50 kN - 50 MN)

Commercially available load cells



Piezoelectric load cells

Mainly used for dynamic force measurement.

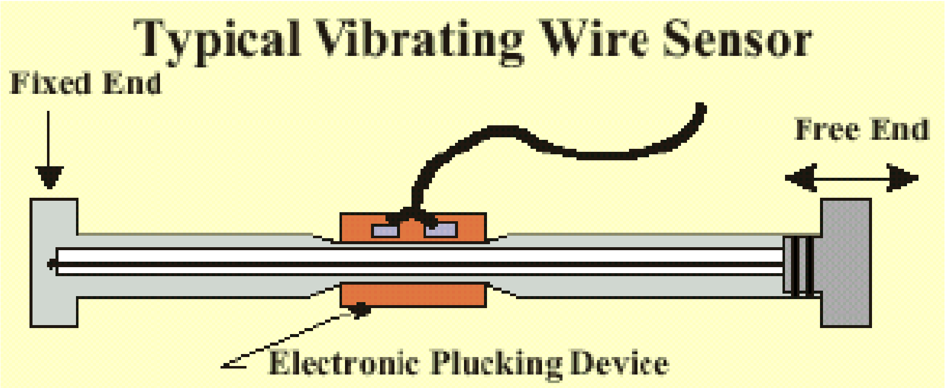
Cell with large time constant may be used for short term static force.

Mounting Screws

Vibrating Wire Transducers

- First natural frequency ω of a string of length L and mass per unit length m, which is tensioned by the force F to be measured

$$\omega = \frac{1}{2L}\sqrt{\frac{F}{m}}$$

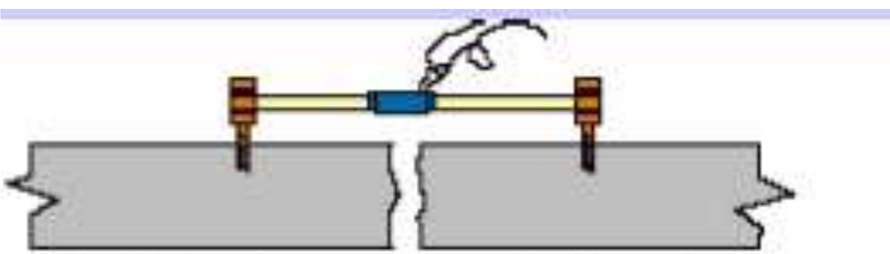


Frequency is measured and then it is related to the applied force. **Frequency is measured by conventional digital counters.**

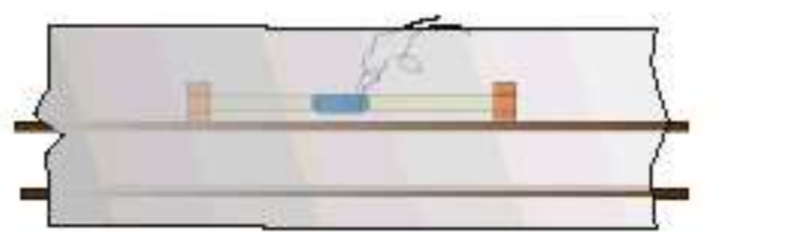
- Wires are thin electrically conducting metals placed in the fields of permanent magnets.
- Temperature sensitivity (tension of the wire changes with temperature)
- Non – Linear relation

Vibrating Wire Transducer Applications

1. **Embedded in concrete to measure reinforcing steel stress**
2. **Underwater crack movement**
3. **Joint movement between two structural members**
4. **Minute rotational movement of structural members**



VW Strain gauge positioned across a crack to measure crack movement



VW Strain gauge welded to reinforcing steel and embedded in concrete to measu reinforcing steel stress

Plastic Deformation Method

- Records the Plastic deformation of the sample which is being subjected to an applied force.
- The deformation for a particular size, shape and material properties may be calibrated by testing of similar elements.

Magneto Elastic Force Transducer

- When a ferromagnetic material is subjected to mechanical force, the magnetic properties of the material are altered and the change is proportional to the applied force.
- The magneto-elastic load cell can be used in rough and electrically disturbed environments such as in rolling mills.
- Ranges are 2 KN – 5 MN.

Optical Strain Gages

- **Formed similar to resistance strain gages using optical fibers instead of wires / foils.**

- **If monochromatic light passes through two optical strain gages experiencing different strain levels, the phase difference between them is the measure of applied force.**

Resolving forces and moments

- **To test aircraft and rocket engine**

  Major objects is to resolve three components of forces and moments resulting from the engine thrust.

- **Wind tunnel balance**

  For measuring forces on wind tunnel model

- **Lathe and other machines**

  For resolving cutting forces in lathe tool machines

Illustrative Example

A quantity of a light weight insulating material having a density of about 24 kg/m^3 is weighed on a standard equal –arm balance. Balance conditions are archived with MS weights totaling 500 g at a ambient temperature of about 30^{o}C. The density of MS may be taken as 8500 kg/m^3. Calculate the true weight of the insulating material and percentage of error caused due to the buoyancy effect.

Solution

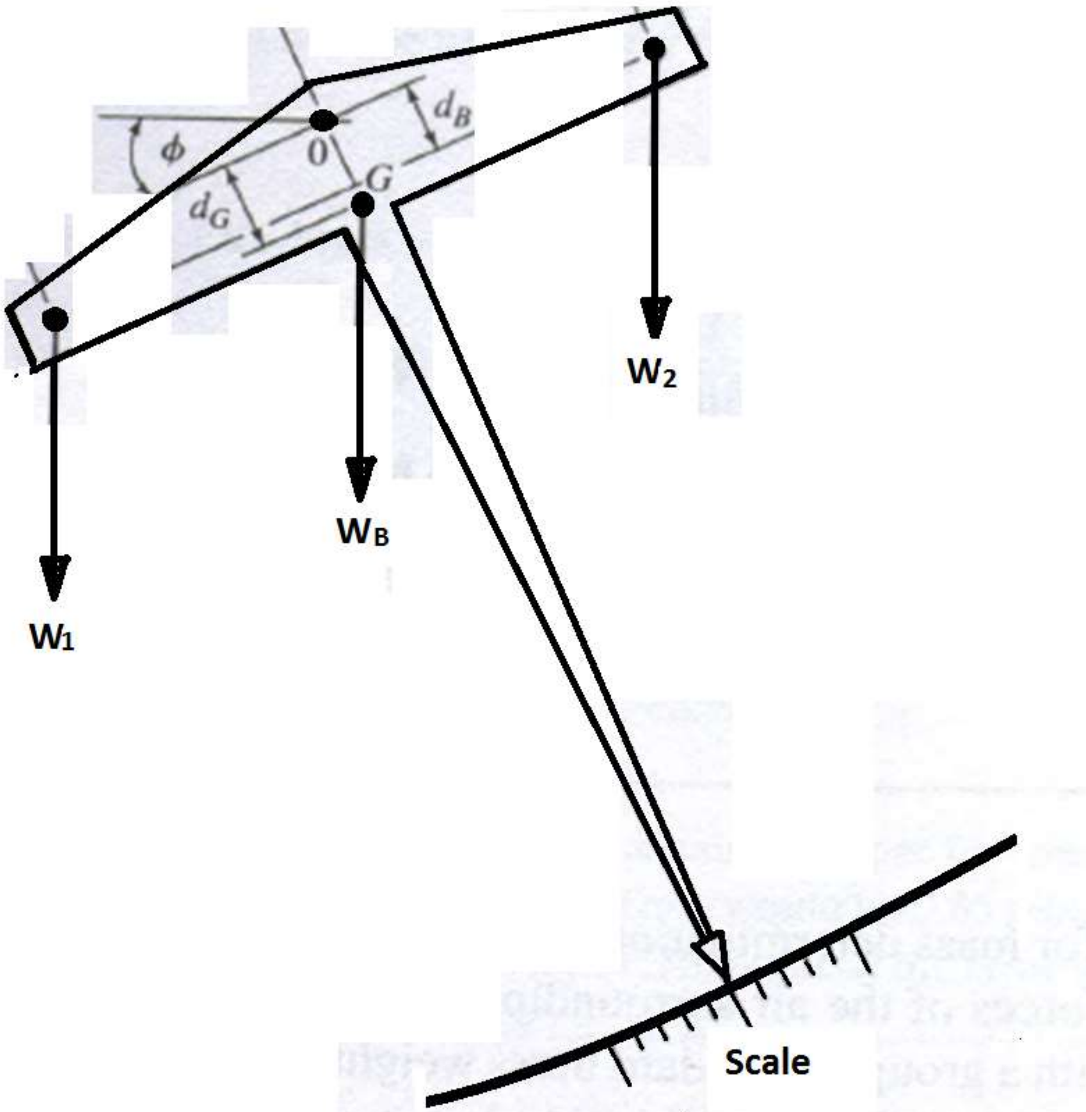
The density of the air at **30^{o}C is**

$$\rho_a = \frac{p}{RT} = \frac{1.0132\ x\ 10^5}{287\,x\ 303} = 1.17 kg/m^3$$

True weight is given by

$$W_u = 500\left[1 + \frac{1.17(8500-24)}{8500(24-1.17)}\right] = 525.55g$$

Error in the measurement = 5.1%



d_B
ϕ
0
G
d_G
W_2
W_B
W_1
Scale