CE 15008
Fluid Mechanics

LECTURE NOTES

Module-I

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COURSE CONTENT

CE 15008:

FLUID MECHANICS (3-1-0)

CR-04

Module-I **(12Hours)**

Introduction: Physical properties of fluids; Density; specific weight; Specific volume; Specific gravity; Compressibility; Elasticity; Surface tension; Capillarity; Vapour pressure; Viscosity; Ideal and real fluids; Concept of shear stress; Newtonian and non-Newtonian fluids.

Fluid statics: Pressure-density-height relationship; Manometers; Pressure on plane and curved surface; Centre of pressure; Buoyancy; Stability of immersed and floating bodies; Fluid masses subjected to uniform accelerations.

LECTURE NOTES

MODULE 1

INTRODUCTION

Fluid is a substance that continually deforms (flows) under an applied shear stress. Fluids are a subset of the phases of matter and include liquids, gases, plasmas and, to some extent, plastic solids. Fluids are substances that have zero shear modulus or, in simpler terms, a fluid is a substance which cannot resist any shear force applied to it.

Fluid mechanics is the branch of science which deals with the behavior of fluids(liquids or gases)at rest as well as in motion. It deals with the static, kinematics and dynamic aspects of fluids.

The study of fluids at rest is called fluid statics. The study of fluid in motion is called fluid kinematics if pressure forces are not considered if pressure force is considered in fluid in motion is called fluid dynamics.

PROPERTIES OF FLUIDS

DENSITY or MASS DENSITY

The density, or more precisely, the volumetric mass density, of a substance is its mass per unit volume. The symbol most often used for density is $\boldsymbol{\rho}$ (Greek letter rho).

Mathematically, density is defined as mass divided by volume

$$\rho = \frac{\mathrm{m}}{\mathrm{V}}$$

Where ρ is the density, m is the mass, and V is the volume. In some cases (for instance, in the United States oil and gas industry), density is loosely defined as its weight per unit volume.

SPECIFIC WEIGHT or WEIGHT DENSITY

The specific weight (also known as the unit weight) is the weight per unit volume of a matterial. It is denoted as the symbol w.

Mathematically,

$$\mathrm{w} = \frac{\text{weight of fluid}}{\text{Volume of fluid}}$$

$$=\frac{\text{mass of fluid} * \text{acceleration due to gravity}}{\text{Volume of fluid}}$$

$$=\frac{\mathrm{m}}{\mathrm{V}} * g$$

$$= \rho g$$

SPECIFIC GRAVITY

It is defined as the ratio of the weight density of a fluid to weight density of a standard fluid. For liquids the standard fluid is taken as water and for gases the standard fluid is given as air. It is denoted as S.

S(for liquids) = $\frac{\text{Weight density of liquid}}{\text{weight density of water}}$

S(for gases) = $\frac{\text{Weight density of gases}}{\text{weight density of air}}$

COMPRESSIBILITY

Compressibility is a measure of the relative volume change of a fluid or solid as a response to a pressure (or mean stress) change.

$$\beta = -\frac{dv}{vdp}$$

Where V is volume and p is pressure.

ELASTICITY

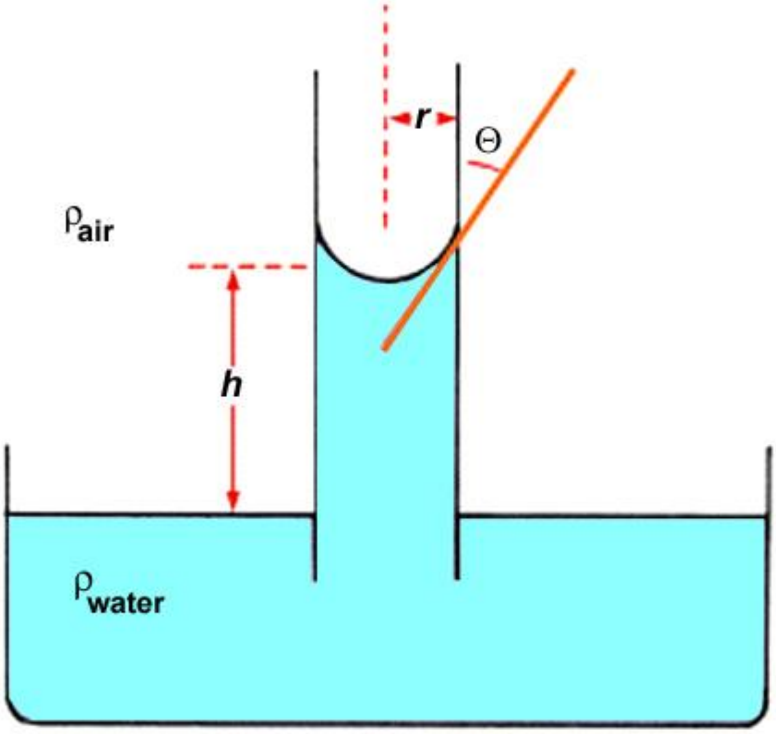
Elasticity is the ability of a body to resist a distorting influence or stress and to return to its original size and shape when the stress is removed. Solid objects will deform when forces are applied on them. If the material is elastic, the object will return to its initial shape and size when these forces are removed.

SURFACE TENSION

It is defined as the tensile force acting on the surface of a liquid in contact with a gas or on the surface between two immiscible liquids such that the contact surface behaves like a membrane under tension. The magnitude of this force per unit length of the free surface will have the same value as the surface energy per unit area. It is denoted as σ (called sigma).Unit is N/m.

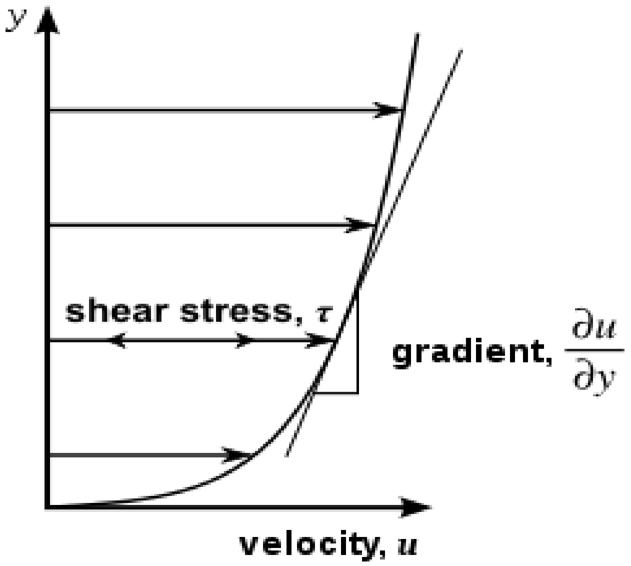
CAPILLARITY

Capillarity is defined as a phenomenon of rise or fall of a liquid surface in small tube relative to the adjacent general level of liquid when the tube is held vertically in the liquid. The rise of liquid surface is known as capillary rise while the fall of liquid surface is known as capillary depression. It is expressed in terms of cm or mm of liquid. Its value depends upon the specific weight of the liquid, diameter of the tube and surface tension of the liquid.



VISCOSITY

It is defined as the property of a fluid which offers resistance to the movement of one layer of fluid over another adjacent layer of the fluid. When two layers of a fluid, a distance ‘dy’ apart , move one over the other at different velocities, say u and u+du.

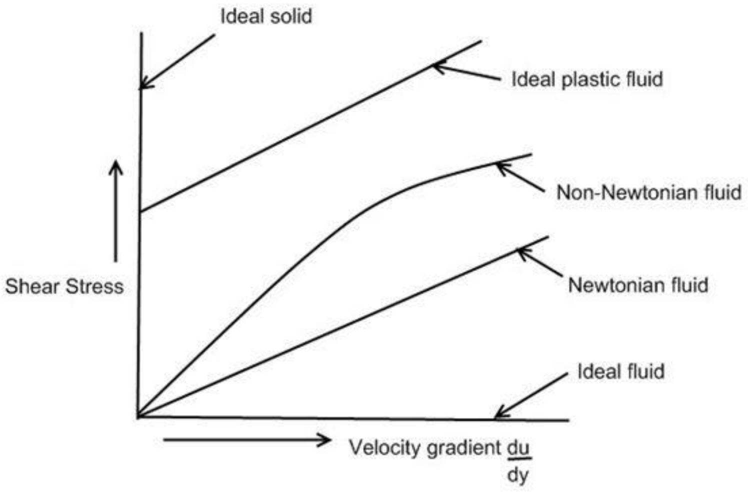


NEWTON’S LAW OF VISCOSITY

It states that the shear stress on a fluid element layer is directly proportional to the rate of shear strain. The constant of proportionality is called the coefficient of viscosity. Mathematically,

$$\tau = \mu \frac{du}{dy}$$

TYPES OF FLUIDS



Types of Fluid

Basically the fluids are classified into 5 types and these are

1. Ideal fluid
2. Real fluid
3. Newtonian fluid
4. Non-Newtonian fluid, and
5. Ideal plastic fluid

1. Ideal Fluid:

A fluid which can not be compressed and have no viscosity falls in the category of ideal fluid. Ideal fluid is not found in actual practice but it is an imaginary fluid because all the fluid that exist in the environment have some viscosity. There is in no ideal fluid in reality.

2. Real Fluid:

A fluid which has at least some viscosity is called real fluid. Actually all the fluids existing or present in the environment are called real fluids. for example water.

3. Newtonian Fluid:

If a real fluid obeys the Newton's law of viscosity (i.e the shear stress is directly proportional to the shear strain) then it is known as the Newtonian fluid.

4. Non-Newtonian Fluid:

If real fluid does not obeys the Newton's law of viscosity then it is called Non-Newtonian fluid.

5. Ideal Plastic Fluid:

A fluid having the value of shear stress more than the yield value and shear stress is proportional to the shear strain (velocity gradient) is known as ideal plastic fluid.

MANOMETER

A manometer is an instrument that uses a column of liquid to measure pressure, although the term is currently often used to mean any pressure instrument.

Two types of manometer, such as

1. Simple manometer

2. Differential manometer

The U type manometer, which is considered as a primary pressure standard, derives pressure utilizing the following equation:
$P = P2 - P1 = h\omega\ \rho g$
Where:
P = Differential pressure
P1 = Pressure applied to the low pressure connection
P2 = Pressure applied to the high pressure connection
$h\omega$ = is the height differential of the liquid columns between the two legs of the manometer
ρ = mass density of the fluid within the columns
g = acceleration of gravity

SIMPLE MANOMETER

A simple manometer consists of a glass tube having one of its ends connected to a point where pressure is to be measured and other end remains open to atmosphere. Common types of simple manometers are:

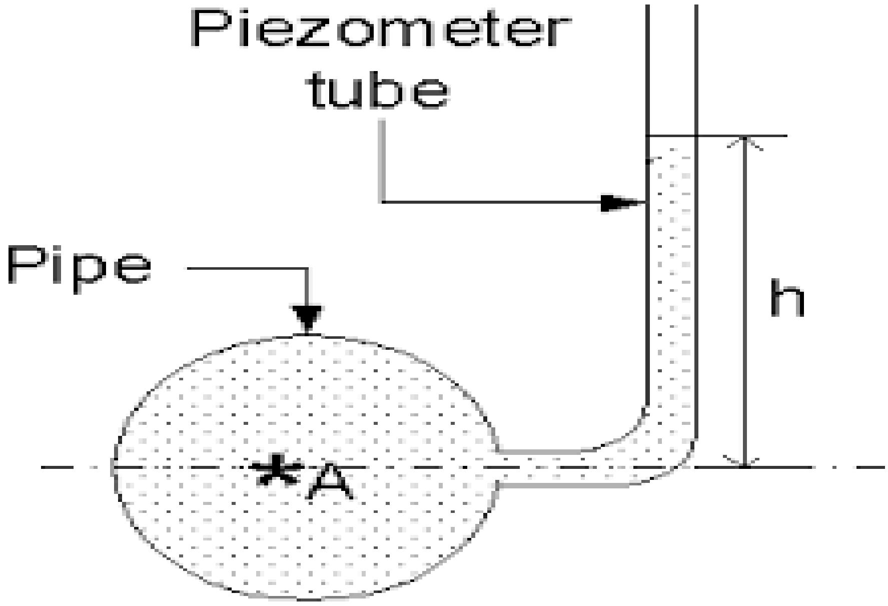
1.Piezometer

2.U tube manometer

3.Single Column manometer

PIEZOMETER

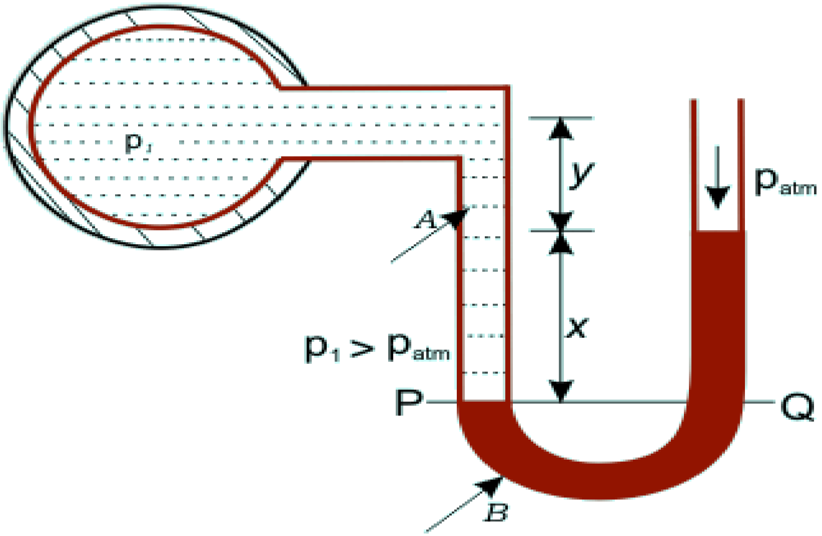
A piezometer is either a device used to measure liquid pressure in a system by measuring the height to which a column of the liquid rises against gravity, or a device which measures the pressure (more precisely, the piezometric head) of groundwater at a specific point. A piezometer is designed to measure static pressures, and thus differs from a pitot tube by not being pointed into the fluid flow.



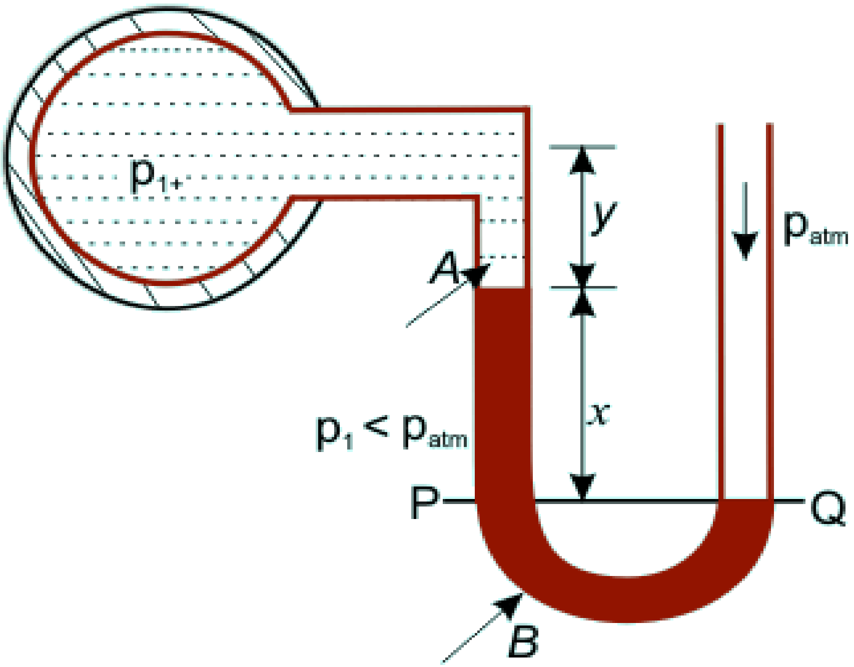
U TUBE MANOMETER

Manometers are devices in which columns of a suitable liquid are used to measure the difference in pressure between two points or between a certain point and the atmosphere.

Manometer is needed for measuring large gauge pressures. It is basically the modified form of the piezometric tube. A common type manometer is like a transparent "U-tube" as shown in Fig.



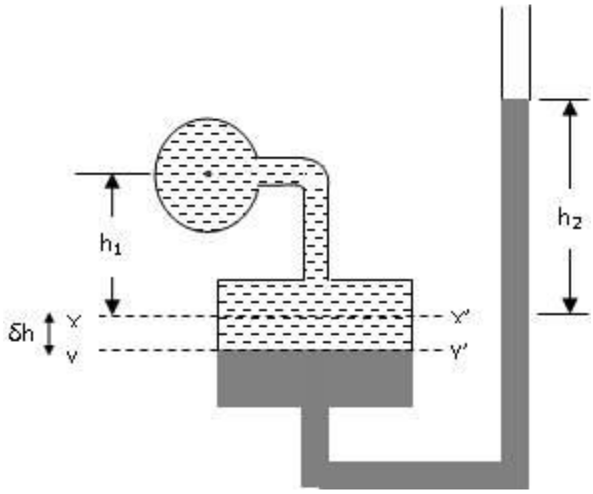
Simple manometer to measure gauge pressure



Simple manometer to measure vacuum pressure

SINGLE COLUMN MANOMETER

It is a modified form of a U tube manometer in which a reservoir having a large cross sectional area.



DIFFERENTIAL MANOMETER

Differential Manometers are devices used for measuring the difference of pressure between two points in a pipe or in two different pipes . A differential manometer consists of a U-tube, containing a heavy liquid, whose two ends are connected to the points, which difference of pressure is to be measure.

Most commonly types of differential manometers are:

1- U-tube differential manometer.
2- Inverted U-tube differential manometer

U-tube differential manometer

For two pipes are at same levels:-

$P_A - P_B = h.g(p_g - p_1)$

Where:

P_1=density of liquid at A=density of liquid at B.

For two pipes are in different level:-

$P_A - P_B = h.g\,(p_g - p_1) + p_2\,gy - p_1\,gx$

Where:

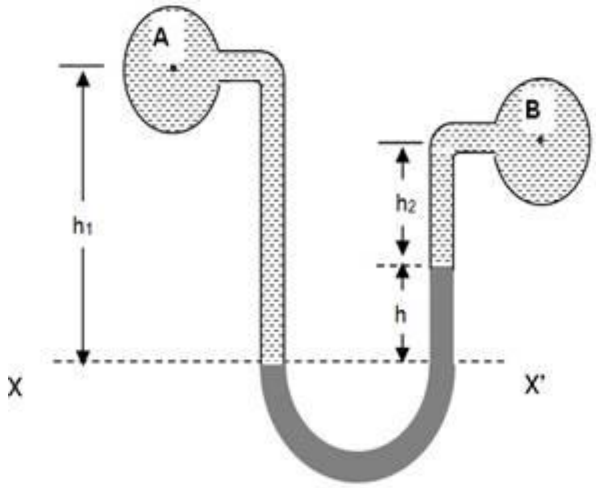
h = difference in mercury level in the U-tube

y = distance of the centre of B, from the mercury level in the right limb.

x = distance of the centre of A, from the mercury level in the left limb. P_1=density of liquid at A.

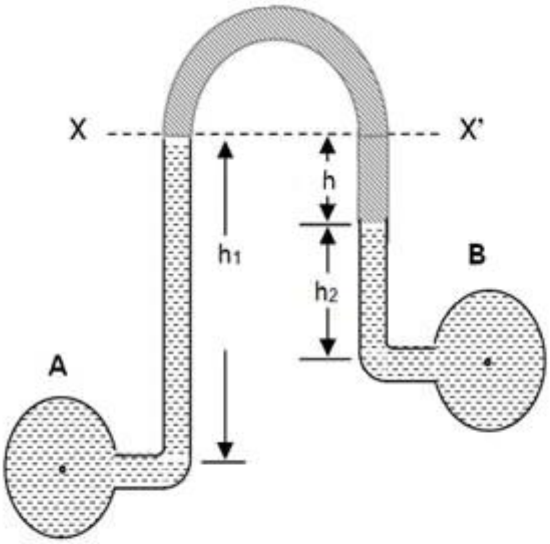
p_2=density of liquid at B.

p_g=density of mercury (heavy liquid)



Inverted U-tube differential manometer

It consists of inverted U-tube, containing a light liquid. The two ends of the tube are connected to the points whose difference of pressure is to be measured. It is used for measuring differences of low pressures.



$P_A - P_B = \rho_1 * g * h_1 - \rho_2 * g * h_2 - \rho_s * g * h$

Where;

h_1 = height of liquid in left limb below the datum line

h_2 = height of liquid in right limb

h=difference of light liquid

ρ_1 =density of liquid at A

ρ_2 =density of liquid at B

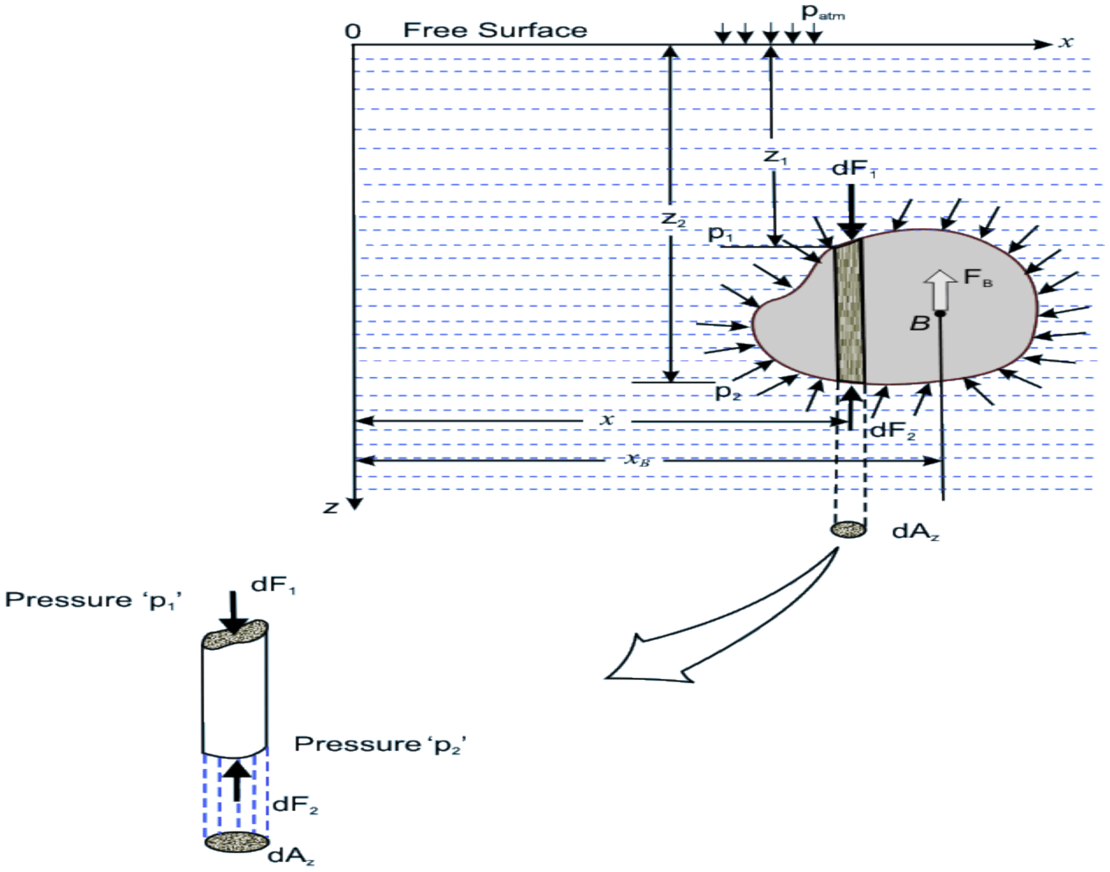
ρ_s =density of light liquid

P_A =pressure at A

P_B=Pressure at B

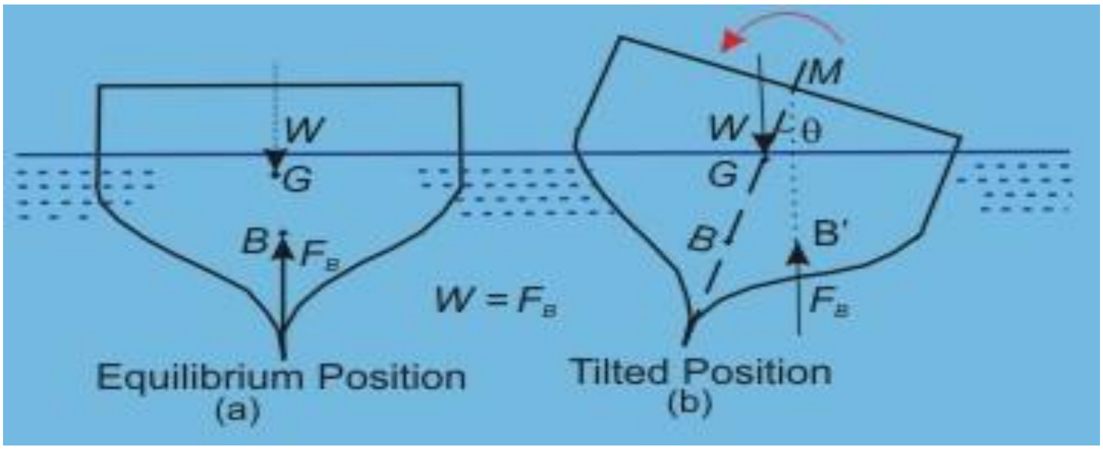
Buoyancy

- When a body is either wholly or partially immersed in a fluid, a lift is generated due to the net vertical component of hydrostatic pressure forces experienced by the body.
- This lift is called the buoyant force and the phenomenon is called buoyancy
- Consider a solid body of arbitrary shape completely submerged in a homogeneous liquid as shown in Fig. Hydrostatic pressure forces act on the entire surface of the body.



Stability of Floating Bodies in Fluid

- When the body undergoes an angular displacement about a horizontal axis, the shape of the immersed volume changes and so the centre of buoyancy moves relative to the body.
- As a result of above observation stable equilibrium can be achieved, under certain condition, even when G is above B. Fig illustrates a floating body -a boat, for example, in its equilibrium position.



Important points to note here are

a. The force of buoyancy F_B is equal to the weight of the body W

b. Centre of gravity G is above the centre of buoyancy in the same vertical line.

c. Figure b shows the situation after the body has undergone a small angular displacement q with respect to the vertical axis.

d. The centre of gravity G remains unchanged relative to the body (This is not always true for ships where some of the cargo may shift during an angular displacement).

e. During the movement, the volume immersed on the right hand side increases while that on the left hand side decreases. Therefore the centre of buoyancy moves towards the right to its new position B'.

Let the new line of action of the buoyant force (which is always vertical) through B' intersects the axis BG (the old vertical line containing the centre of gravity G and the old centre of buoyancy B) at M. For small values of q the point Impractically constant in position and is known as metacentre. For the body shown in Fig. M is above G, and the couple acting on the body in its displaced position is a restoring couple which tends to turn the body to its original position. If M were below G, the couple would be an overturning couple and the original equilibrium would have been unstable. When M coincides with G, the body will assume its new position without any further movement and thus will be in neutral equilibrium. Therefore, for a floating body, the stability is determined not simply by the relative position of B and G,ratherby the relati**ve** position of M and G. The distance of metacentre above G along the line BG is known as metacentric height GM which can be written as

$$GM = BM - BG$$

Hence the condition of stable equilibrium for a floating body can be expressed in terms of metacentric height as follows:

$GM > 0$ (M is above G)	Stable equilibrium
$GM = 0$ (M coinciding with G)	Neutral equilibrium
$GM < 0$ (M is below G)	Unstable equilibrium

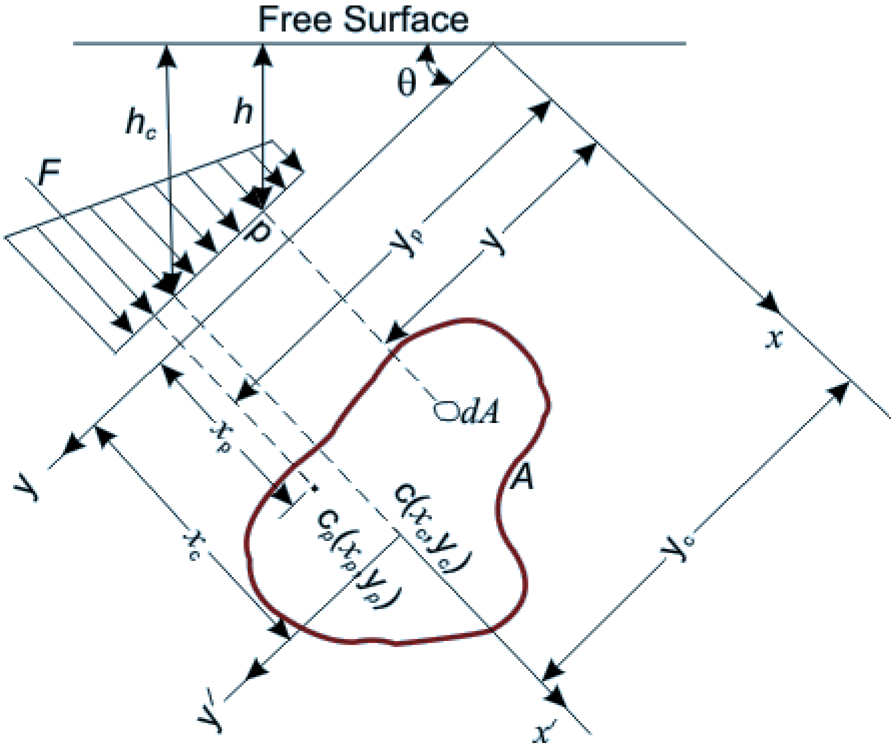
The angular displacement of a boat or ship about its longitudinal axis is known as 'rolling' while that about its transverse axis is known as "pitching".

Hydrostatic Thrusts on Submerged Plane Surface

Due to the existence of hydrostatic pressure in a fluid mass, a normal force is exerted on any part of a solid surface which is in contact with a fluid. The individual forces distributed over an area give rise to a resultant force.

Plane Surfaces

Consider a plane surface of arbitrary shape wholly submerged in a liquid so that the plane of the surface makes an angle θ with the free surface of the liquid. We will assume the case where the surface shown in the figure below is subjected to hydrostatic pressure on one side and atmospheric pressure on the other side.



Let p denotes the gauge pressure on an elemental area dA. The resultant force F on the area A is therefore

$$F = \iint_A p\, dA$$

$$F = \rho g \iint h dA = \rho g \sin\theta \iint y dA$$

Where h is the vertical depth of the elemental area dA from the free surface and the distance y is measured from the x-axis, the line of intersection between the extension of the inclined plane and the free surface (Fig.). The ordinate of the centre of area of the plane surface A is defined as

$$y_c = \frac{1}{A} \iint y dA$$

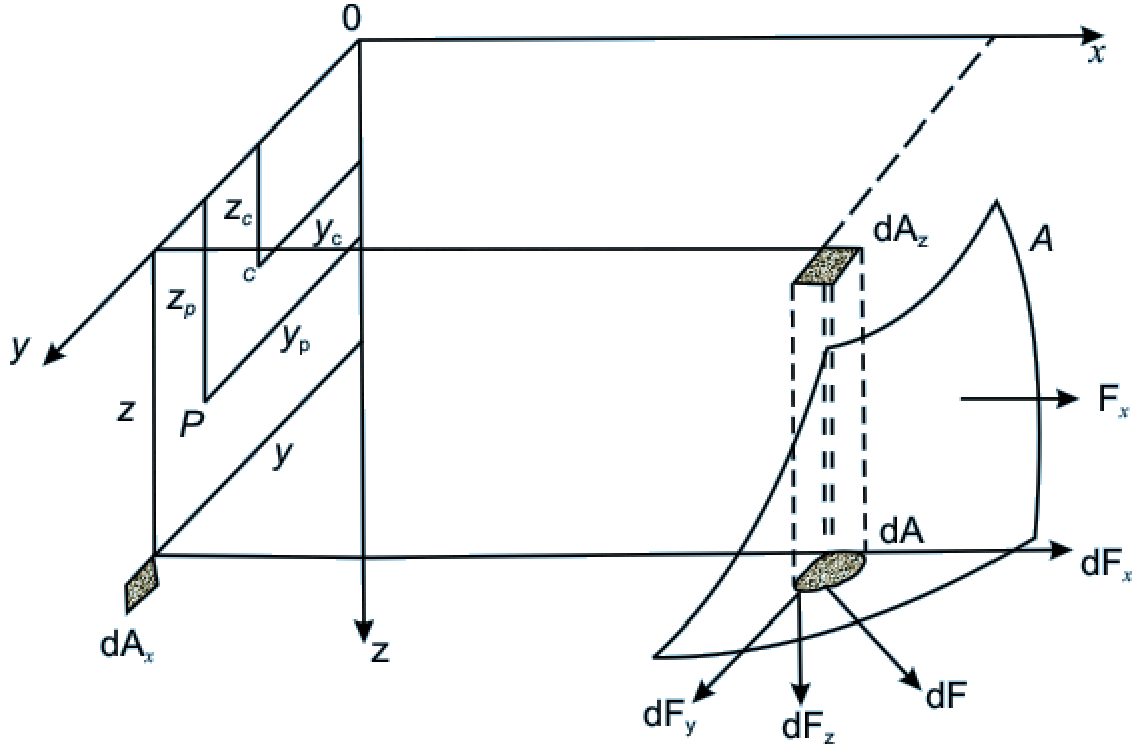
we get

$$F = \rho g y_c \sin\theta A = \rho g h_c A$$

where $h_c (= y_c \sin\theta)$ is the vertical depth (from free surface) of centre c of area .

Hydrostatic Thrusts on Submerged Curved Surfaces

On a curved surface, the direction of the normal changes from point to point, and hence the pressure forces on individual elemental surfaces differ in their directions. Therefore, a scalar summation of them cannot be made. Instead, the resultant thrusts in certain directions are to be determined and these forces may then be combined vectorially. An arbitrary submerged curved surface is shown in Fig. A rectangular Cartesian coordinate system is introduced whose xy plane coincides with the free surface of the liquid and z-axis is directed downward below the x - y plane.



Consider an elemental area dA at a depth z from the surface of the liquid. The hydrostatic force on the elemental area dA is

$$d\,F = \rho\, g\, z\, dA$$

and the force acts in a direction normal to the area dA. The components of the force dF in x, y and z directions are

$$dF_x = l dF = l \rho g z dA$$

$$dF_y = m dF = m \rho g z dA$$

$$dF_z = n dF = n \rho g z dA$$

Where l, m and n are the direction cosines of the normal to dA. The components of the surface element dA projected on yz, xz and xy planes are, respectively

$$dA_x = l\, dA$$

$$dA_y = m dA$$

$$dA_z = n\, dA$$

From equations,

$$dF_x = \rho g\, z\, dA_x$$

$$dF_y = \rho g\, z\, dA_y$$

$$dF_z = \rho g\, z\, dA_z$$

Therefore, the components of the total hydrostatic force along the coordinate axes are

$$F_x = \int\int \rho g z dA_x = \rho g z_c A_x$$

$$F_y = \int\int \rho g z dA_y = \rho g z_c A_y$$

$$F_z = \int\int \rho g z dA_z$$

where z_c is the z coordinate of the centroid of area A_x and A_y (the projected areas of curved surface on yz and xz plane respectively). If z_p and y_p are taken to be the coordinates of the point of action of F_x on the projected area A_x on yz plane, , we can write

$$z_p = \frac{1}{A_x z_c}\int\int z^2 dA_x = \frac{I_{yy}}{A_x z_c}$$

$$y_p = \frac{1}{A_x z_c}\int\int yz dA_x = \frac{I_{yz}}{A_x z_c}$$

where I_{yy} is the moment of inertia of area A_x about y-axis and I_{yz} is the product of inertia of A_x with respect to axes y and z. In the similar fashion, $z_p^{'}$ and $x_p^{'}$ the coordinates of the point of action of the force F_y on area A_y, can be written as

$$z'_p = \frac{1}{A_y z_c} \iint z^2 dA_y = \frac{I_{xx}}{A_y z_c}$$

$$x'_p = \frac{1}{A_y z_c} \iint xz dA_y = \frac{I_{xz}}{A_y z_c}$$

where I_{xx} is the moment of inertia of area A_y about x axis and I_{xz} is the product of inertia of A_y about the axes x and z.

We can conclude from previous Eqs that for a curved surface, the component of hydrostatic force in a horizontal direction is equal to the hydrostatic force on the projected plane surface perpendicular to that direction and acts through the centre of pressure of the projected area. From Eq. the vertical component of the hydrostatic force on the curved surface can be written as

$$F_z = \rho g \iint z\, dA_z = \rho g \forall$$

Where $\forall$is the volume of the body of liquid within the region extending vertically above the submerged surface to the free surface of the liquid. Therefore, the vertical component of hydrostatic force on a submerged curved surface is equal to the weight of the liquid volume vertically above the solid surface of the liquid and acts through the center of gravity of the liquid in that volume.

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