Pressure Measurements

Pressure definition

- Pressure is the action of one force against another over, a surface. The pressure P of a force F distributed over an area A is defined as:

$$P = F/A$$

Units of Measure

System	Length	Force	Mass	Time	Pressure
MKS	Meter	Newton	Kg	Sec	N/M^2 = Pascal
CGS	CM	Dyne	Gram	Sec	D/CM^2
English	Inch	Pound	Slug	Sec	PSI

How Much is a Pascal (Pa)

- A Newton is the force necessary to accelerate a mass of 1 kg at a rate of 1 meter per second per second.
- The acceleration of gravity is 9.8 m/sec^2
- The force due to gravity on a 1 kg mass is 9.8 N is 1 kg weight.
- 1 Newton is 0.102 kg weight.

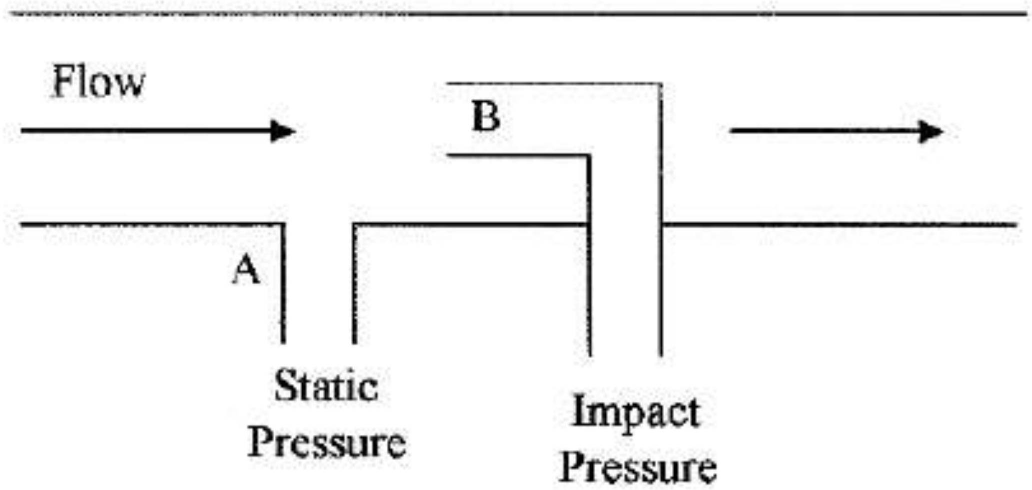
How Much is a Pascal (Pa)

- 1 N/m^2 is a very small pressure
- Therefore kilopascal (kPa)
- 1 atmosphere (14.7 psi, 750mmHg) is approximately 100 kPa = 1 bar
- 1 kPa is about 7 mmHg
- 1% of a gas at our altitude is about 7 mmHg

How is pressure generated?

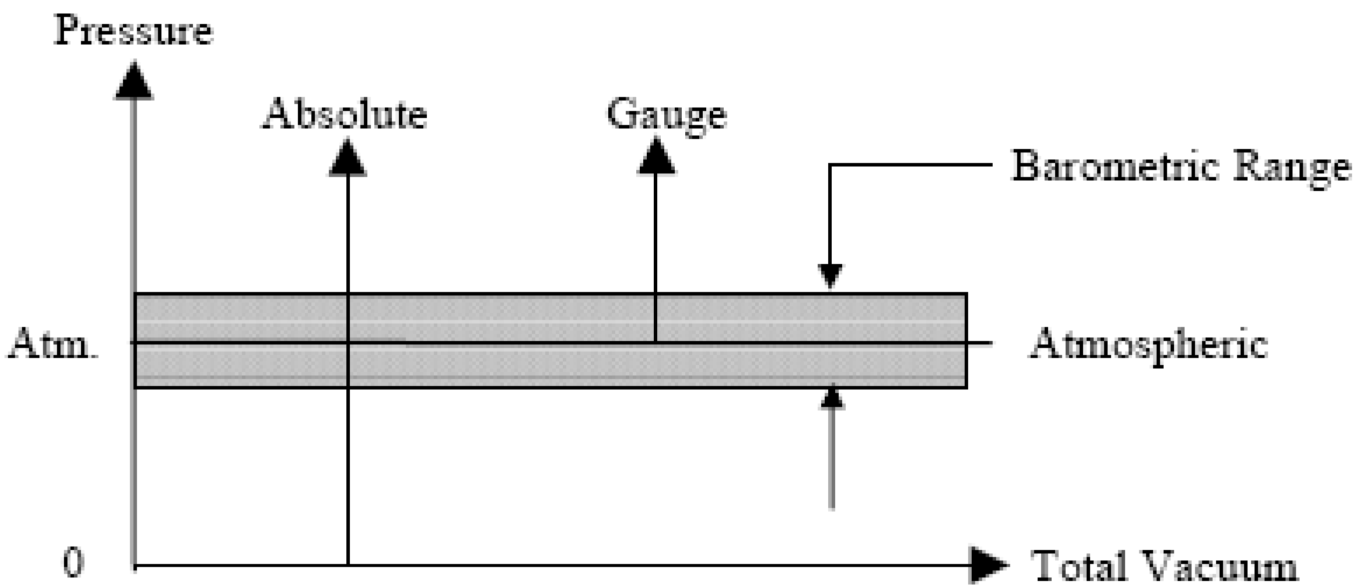
- Collision of molecule with wall
- Momentum is mass x velocity
- Change of momentum is double
- Collision is isothermal = perfectly elastic
- Sum collisions over area to get force

Static, dynamic, and impact pressures



- *Static pressure* is the pressure of fluids or gases that are stationary or not in motion.
- *Dynamic pressure* is the pressure exerted by a fluid or gas when it impacts on a surface or an object due to its motion or flow. In Fig., the dynamic pressure is (*B* − *A*).
- *Impact pressure* (total pressure) is the sum of the static and dynamic pressures on a surface or object. Point *B* in Fig. depicts the impact pressure.

Definition Of Pressure



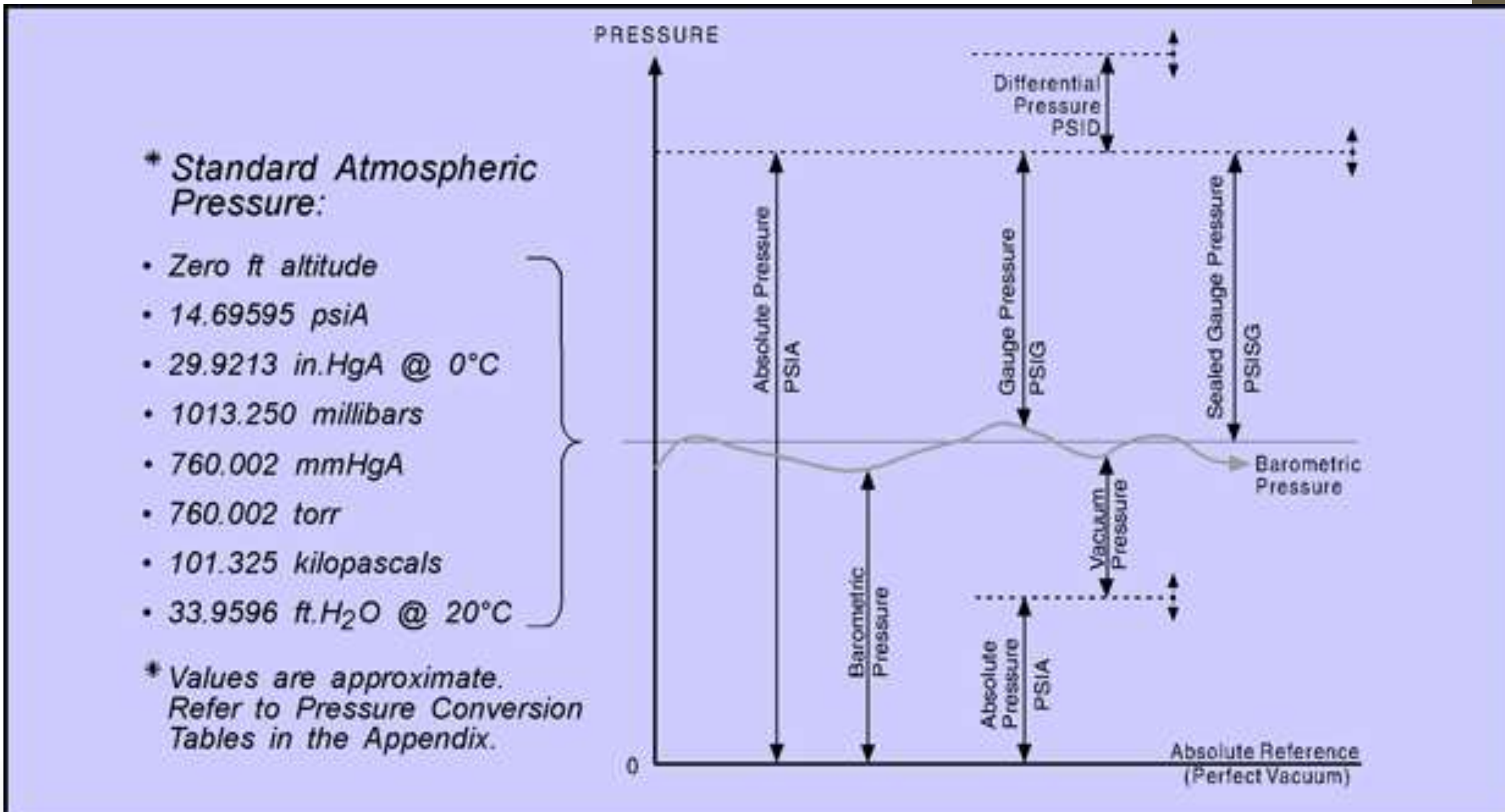
Definition Of Pressure

Absolute pressure
The pressure is referenced to zero absolute pressure and has units of psia. Absolute pressure can only have a positive value.

Gauge pressure
The pressure is referenced to atmospheric pressure and by convention is measured in the positive direction, i.e. 7 psig.

Vacuum pressure
The pressure is referenced to atmospheric pressure and by convention is measured in the negative direction, i.e. -50 mm Hg.

Standard Atmospheric Pressure



Pressure Measurement

A number of *measurement units* are used for pressure. They are as follows:

1. Pounds per square foot (psf) or pounds per square inch (psi)
2. Atmospheres (atm)
3. Pascals (N/m^2) or kilopascal (1000Pa)*
4. Torr = 1 mm mercury
5. Bar (1.013 atm) = 100 kPa
6. 14.696 lbf/in2 equals 33.9 feet of H2O
7. 14.696 lbf/in2 equals 29.921 inches of of Hg

Pressure Units

- As previously noted, pressure is force per unit area and historically a great variety of units have been used, depending on their suitability for the application.
- For example, blood pressure is usually measured in mmHg because mercury manometers were used originally.
- Atmospheric pressure is usually expressed in in mmHg for the same reason.
- Other units used for atmospheric pressure are bar and atm.

Pressure Units

The following conversion factors should help in dealing with the various units:

1 psi= 51.714 mmHg

= 2.0359 in.Hg

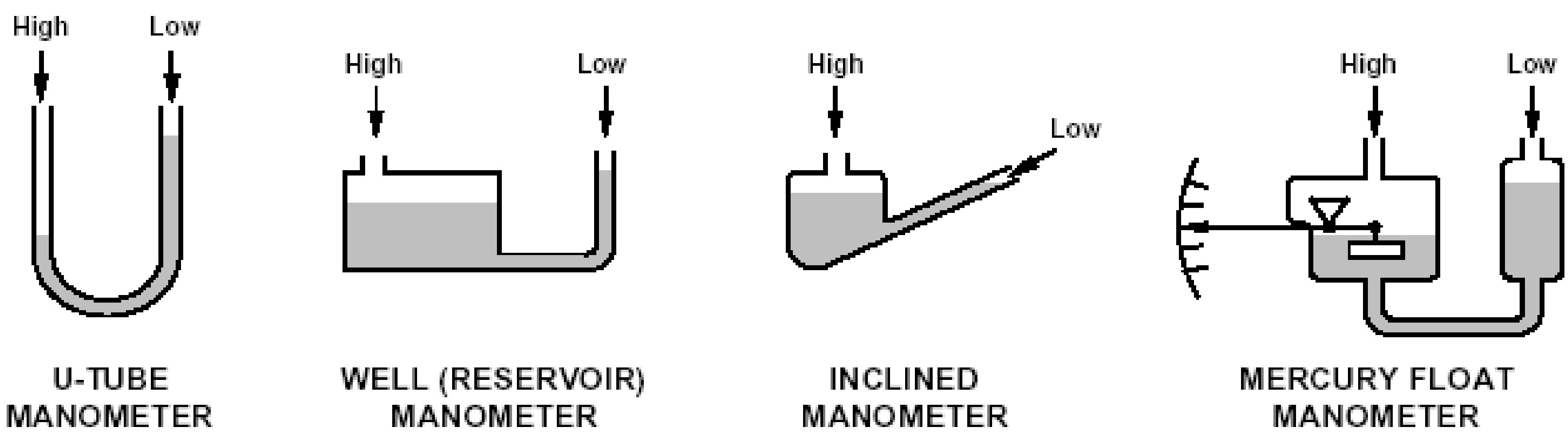
= 27.680 in.H2O

= 6.8946 kPa

1 bar= 14.504 psi

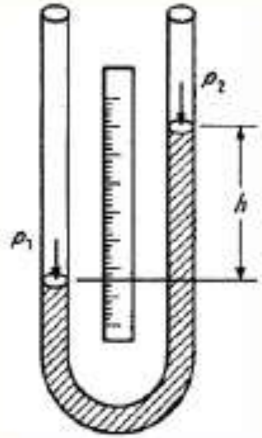
1 atm. = 14.696 psi

Wet Meters (Manometers)

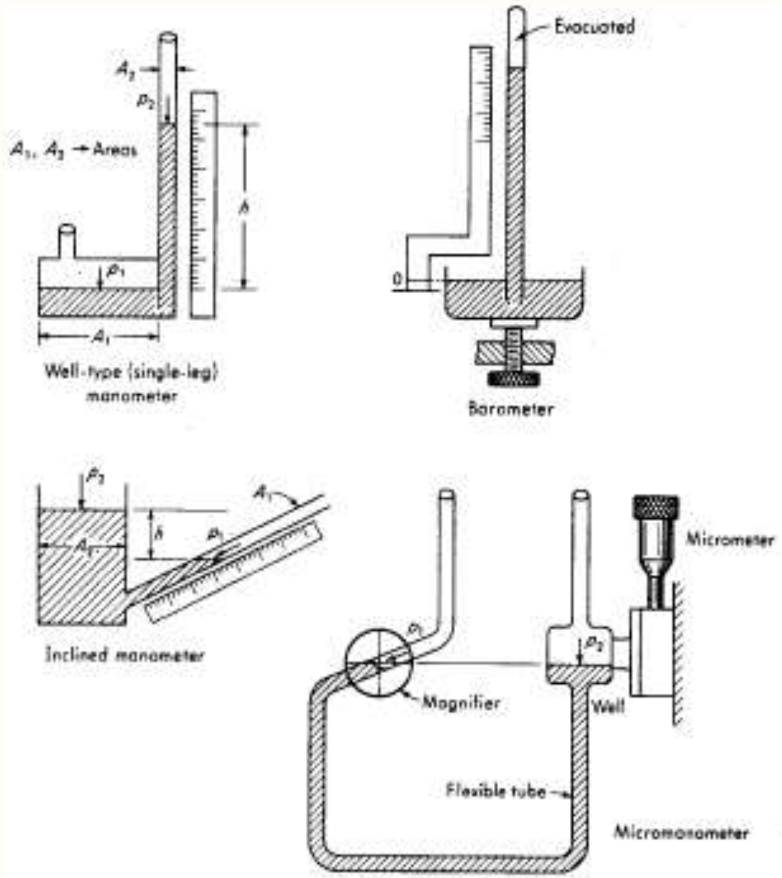


Pressure Gages

- Direct reading gages
  - Manometers



$$h = \frac{p_1 - p_2}{\rho g}$$



- Different fluid provides different uncertainty

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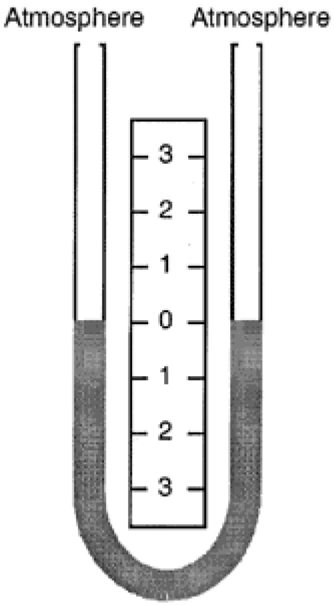
Manometer basics

- Characterized by its inherent accuracy and simplicity of operation.
- It's the U-tube manometer, which is a U-shaped glass tube partially filled with liquid.
- This manometer has no moving parts and requires no calibration.
- Manometer measurements are functions of gravity and the liquid's density, both physical properties that make the U-tube manometer a NIST standard for accuracy.

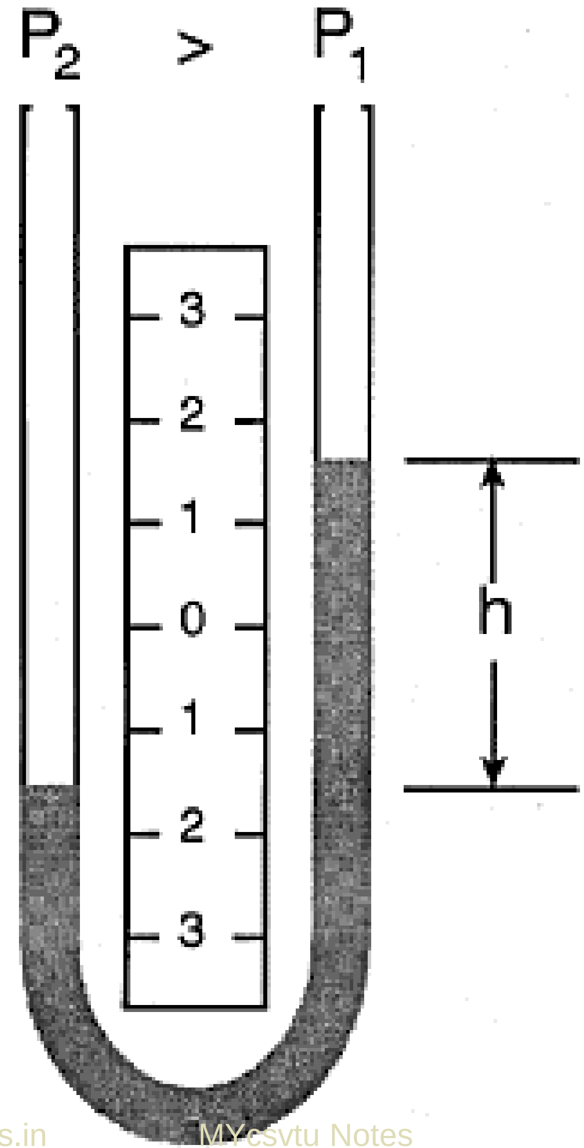
Manometer

With both legs of a U-tube manometer open to the atmosphere or subjected to the same pressure, the liquid maintains the same level in each leg, establishing a zero reference.



Manometer

- With a greater pressure applied to the left side of a U-tube manometer, the liquid lowers in the left leg and rises in the right leg.
- The liquid moves until the unit weight of the liquid, as indicated by h, exactly balances the pressure.



Manometer

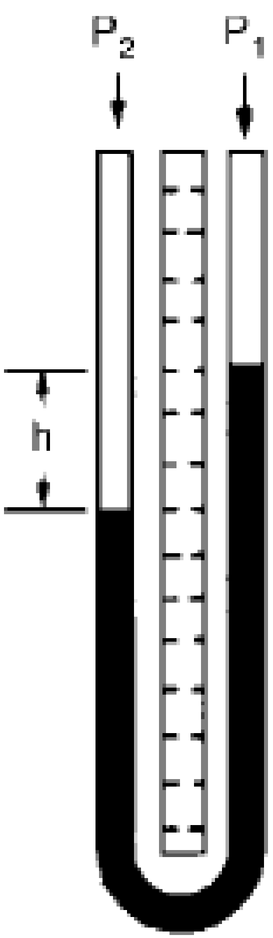
- When the liquid in the tube is mercury, for example, the indicated pressure *h* is usually expressed in inches (or millimeters) of mercury. To convert to pounds per square inch (or kilograms per square centimeter), $P_2 = \rho h$

Where

P_2 = pressure, (kg/cm^2)

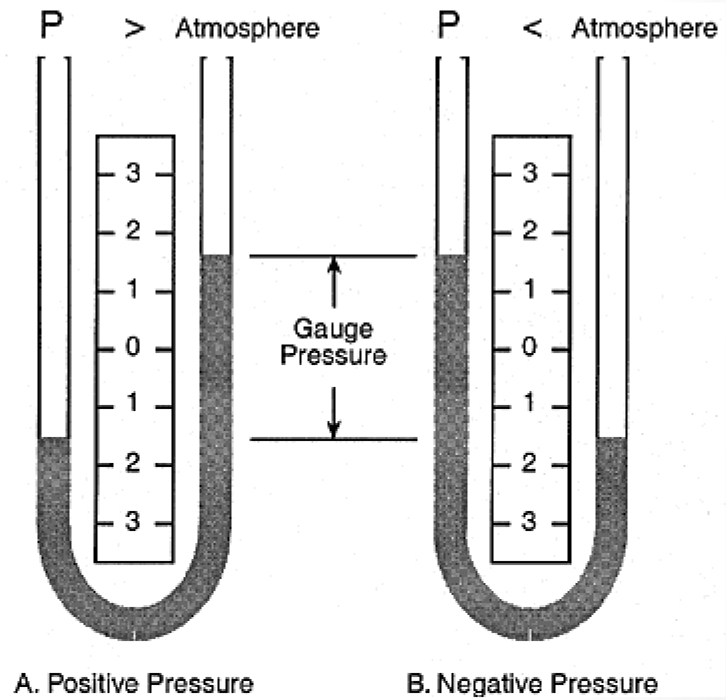
ρ = density, (kg/cm^3)

h = height, (cm)



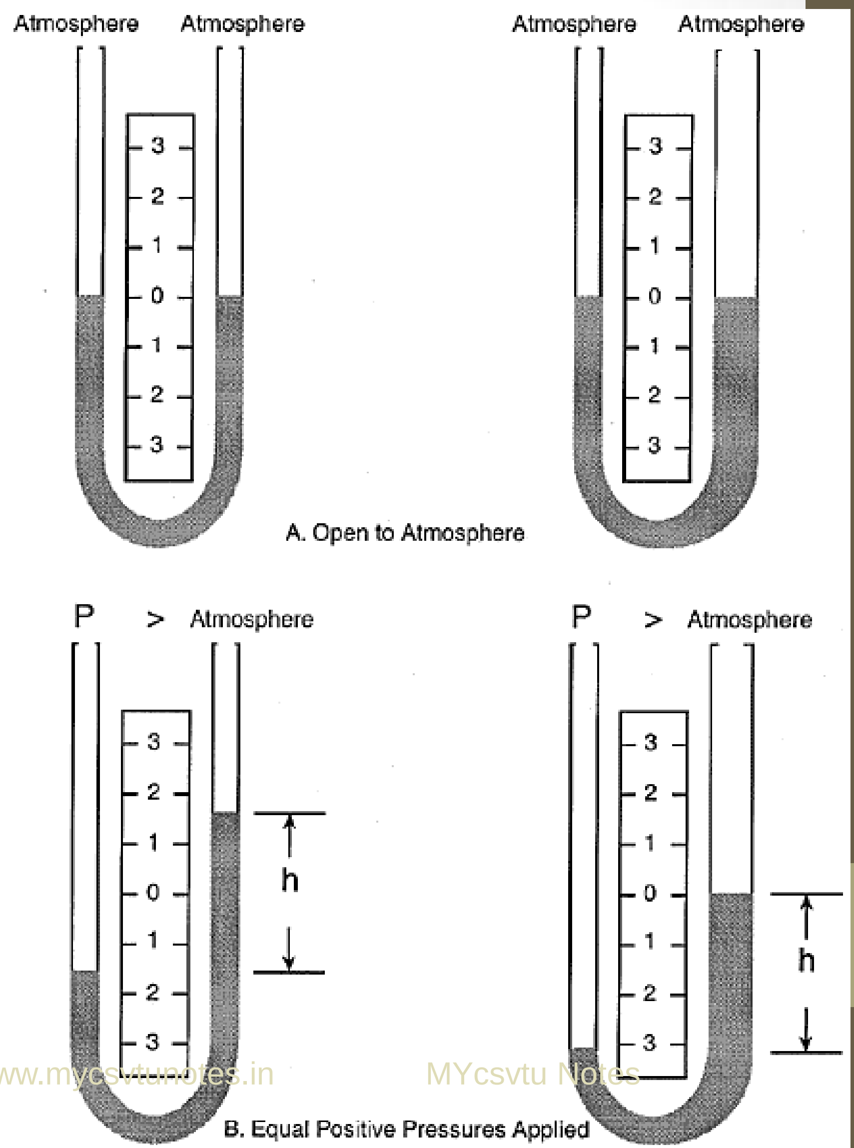
Manometer

- Gauge pressure is a measurement relative to atmospheric pressure and it varies with the barometric reading.
- A gauge pressure measurement is positive when the unknown pressure exceeds atmospheric pressure (A), and is negative when the unknown pressure is less than atmospheric pressure (B).



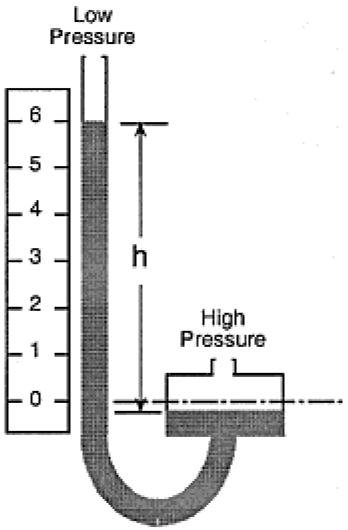
Variations on the U-Tube Manometer

- The pressure reading is always the difference between fluid heights, regardless of the tube sizes.
- With both manometer legs open to the atmosphere, the fluid levels are the same (A).
- With an equal positive pressure applied to one leg of each manometer, the fluid levels differ, but the distance between the fluid heights is the same (B).



Reservoir (Well) Manometer

In a well-type manometer, the cross-sectional area of one leg (the well) is much larger than the other leg. When pressure is applied to the well, the fluid lowers only slightly compared to the fluid rise in the other leg.



Reservoir (Well) Manometer

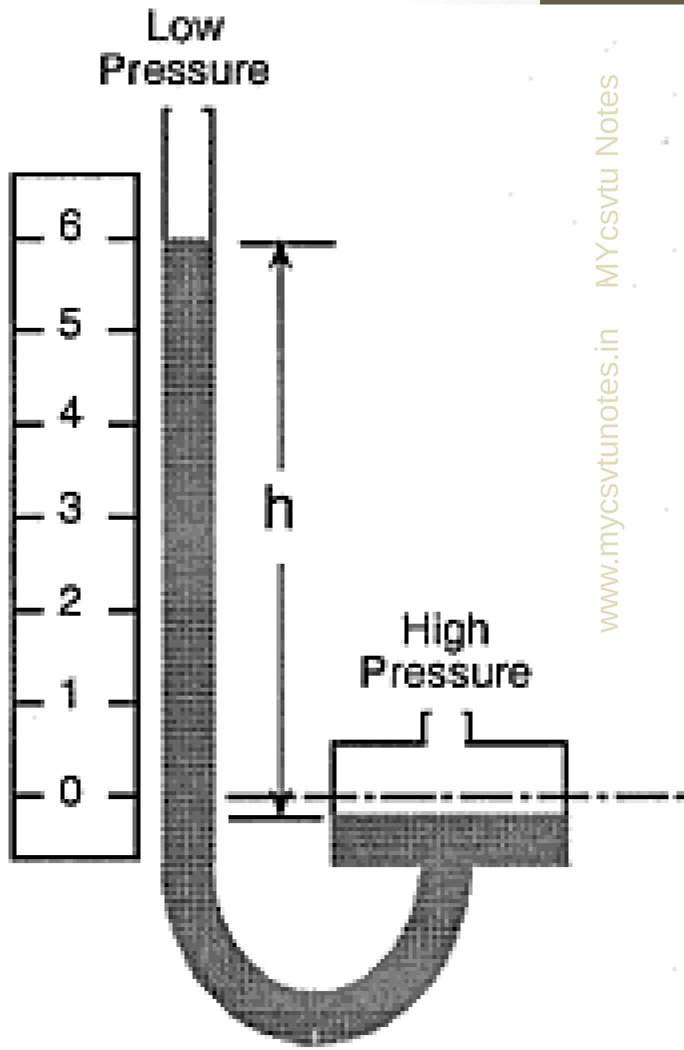
- In this design one leg is replaced by a large diameter well so that the pressure differential is indicated only by the height of the column in the single leg.
- The pressure difference can be read directly on a single scale. For static balance,

$$P2 - P1 = d\,(1 + A1/A2)\,h$$

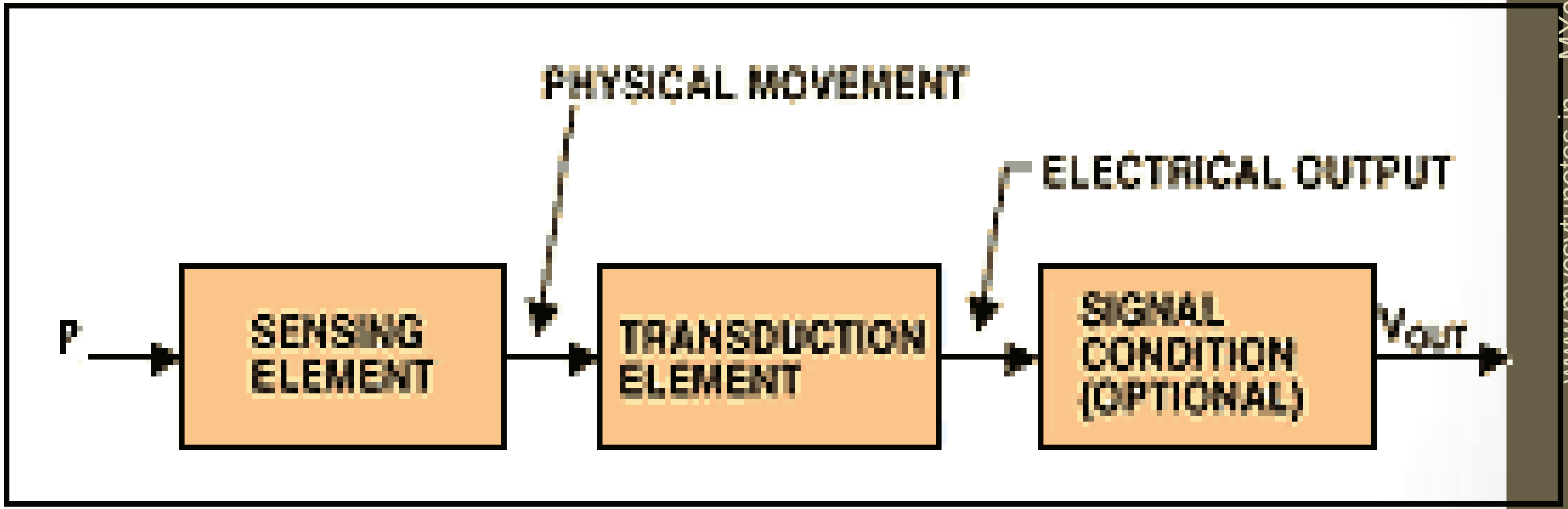
Where

- $A1$ = area of smaller-diameter leg
- $A2$ = area of well

If the ratio of $A1/A2$ is small compared with unity, then the error in neglecting this term becomes negligible, and the static balance relation becomes $P2 - P1 = dh$



Typical pressure sensor functional blocks.



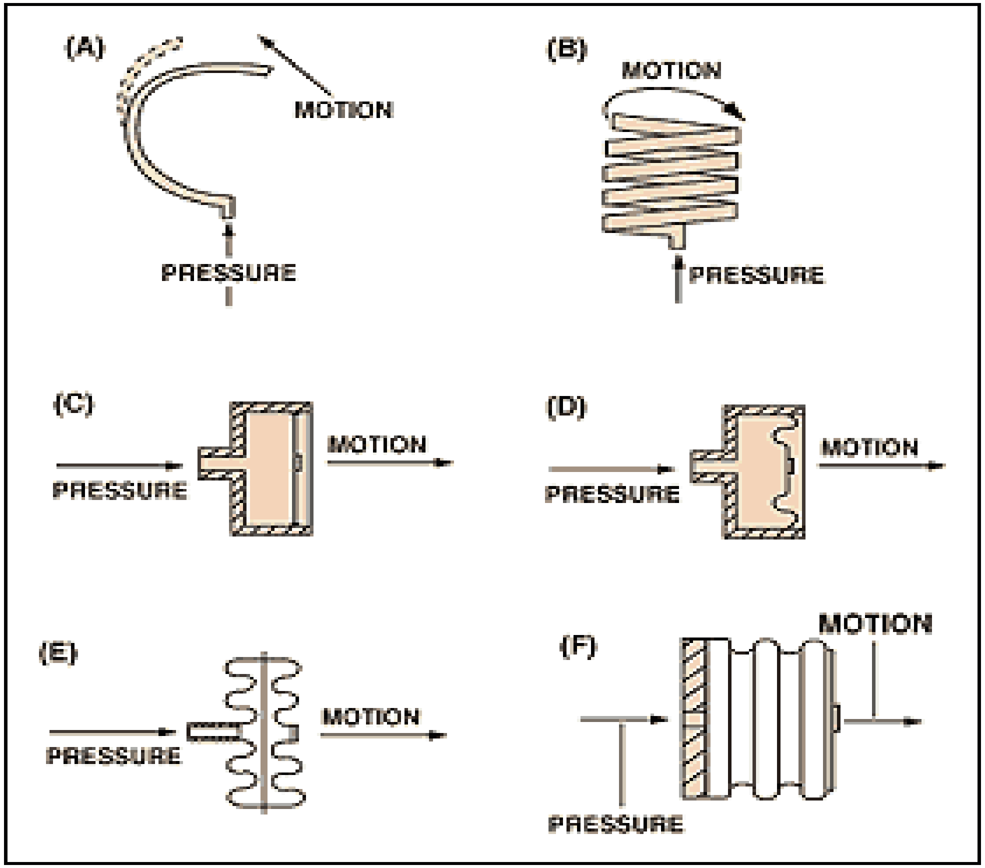
Sensing Elements

The main types of sensing elements are

- Bourdon tubes,
- diaphragms,
- capsules, and
- bellows .

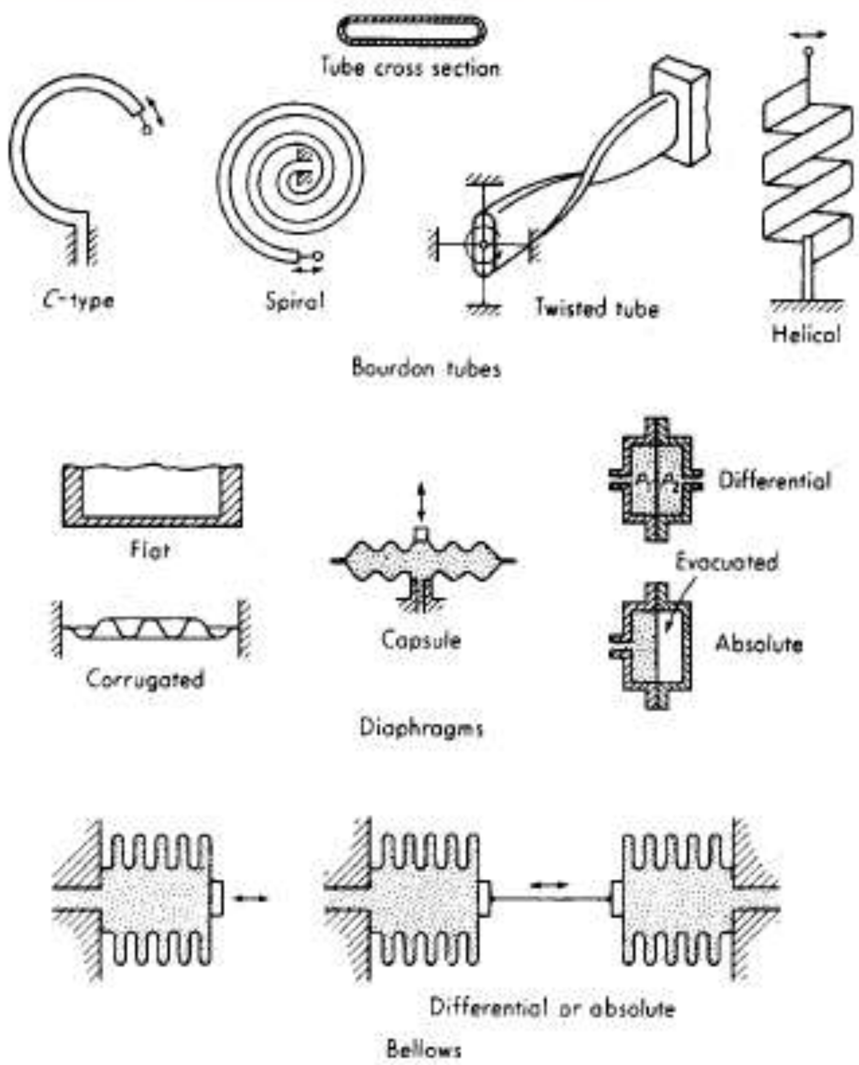
All except diaphragms provide a fairly large displacement that is useful in mechanical gauges and for electrical sensors that require a significant movement.

Sensing Elements

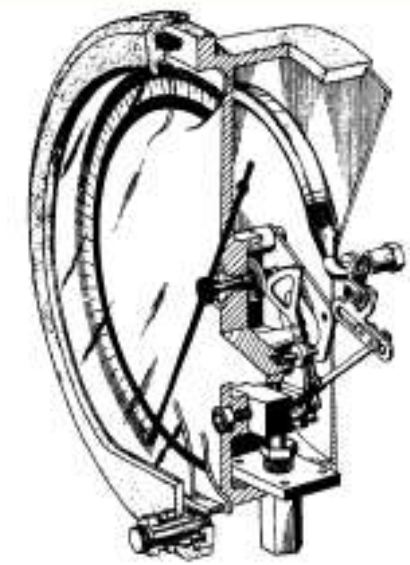


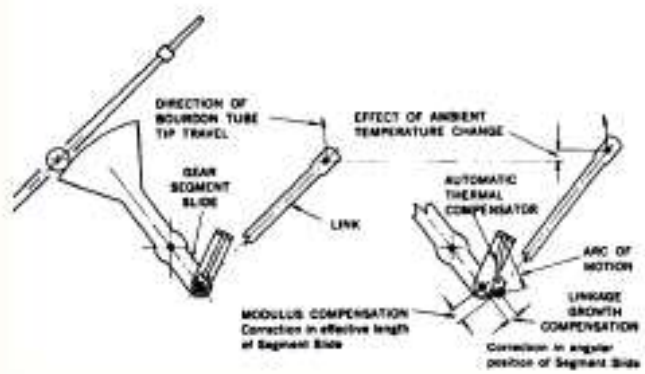
The basic pressure sensing element can be configured as a C-shaped Bourdon tube (A); a helical Bourdon tube (B); flat diaphragm (C); a convoluted diaphragm (D); a capsule (E); or a set of bellows (F).

- Elastic pressure transducers



Bourdon-tube gage (0.1% accuracy)





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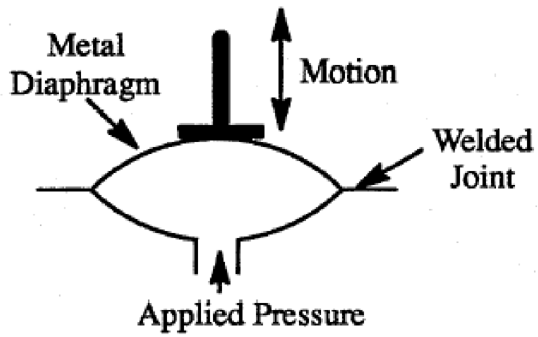
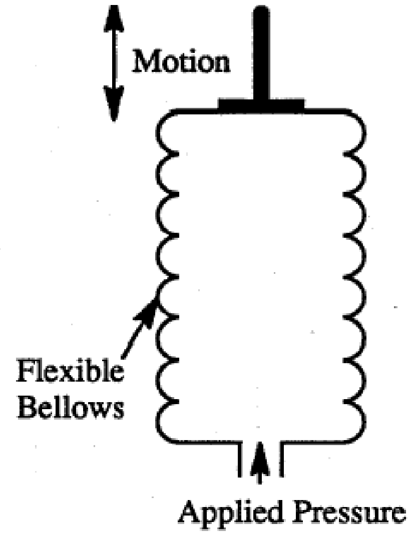
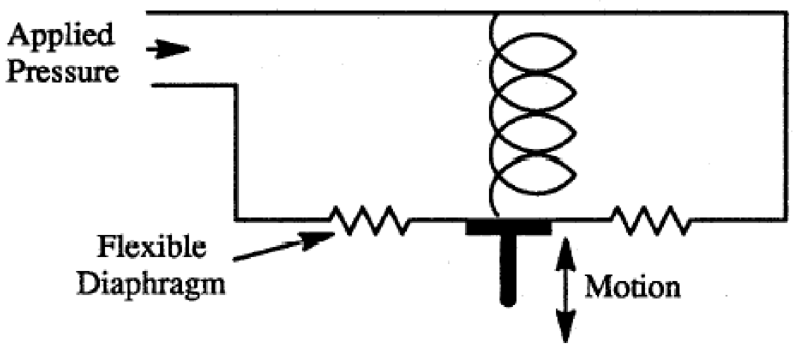
Primary Pressure Elements
Capsule, Bellows & Spring Opposed Diaphragm



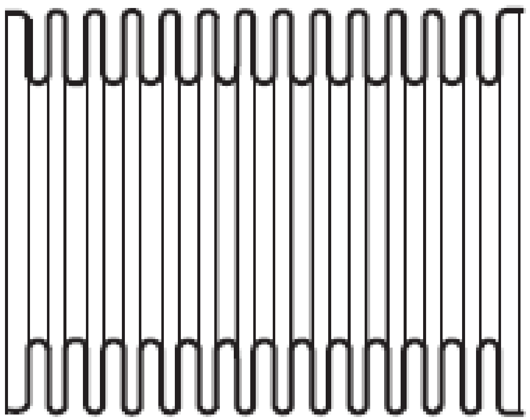
Pressure Capsule

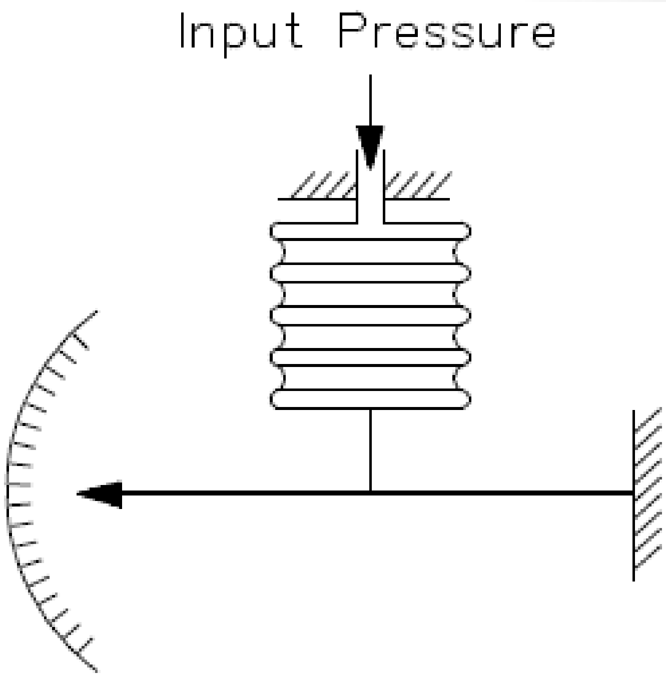


Pressure Bellows



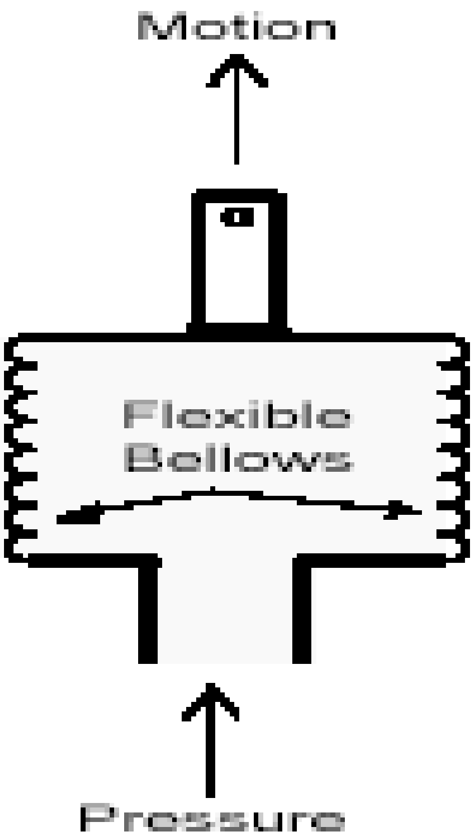
Bellows





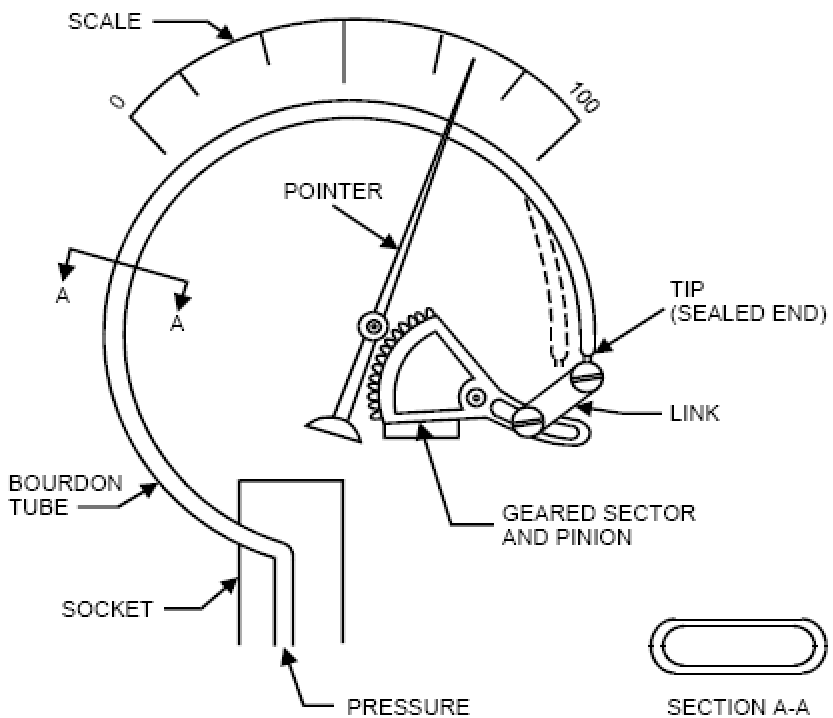
- Made of Bronze, S.S., BeCu, Monel etc..
- The movement is proportional to number of convolutions
- Sensitivity is proportional to size
- In general a bellows can detect a slightly lower pressure than a diaphragm
- The range is from 0-5 mmHg to 0-2000 psi
- Accuracy in the range of 1% span

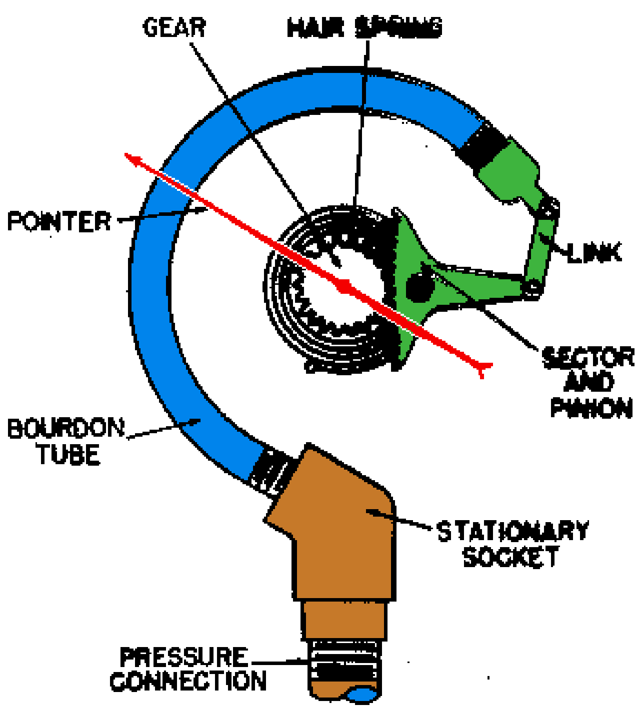
Bellows



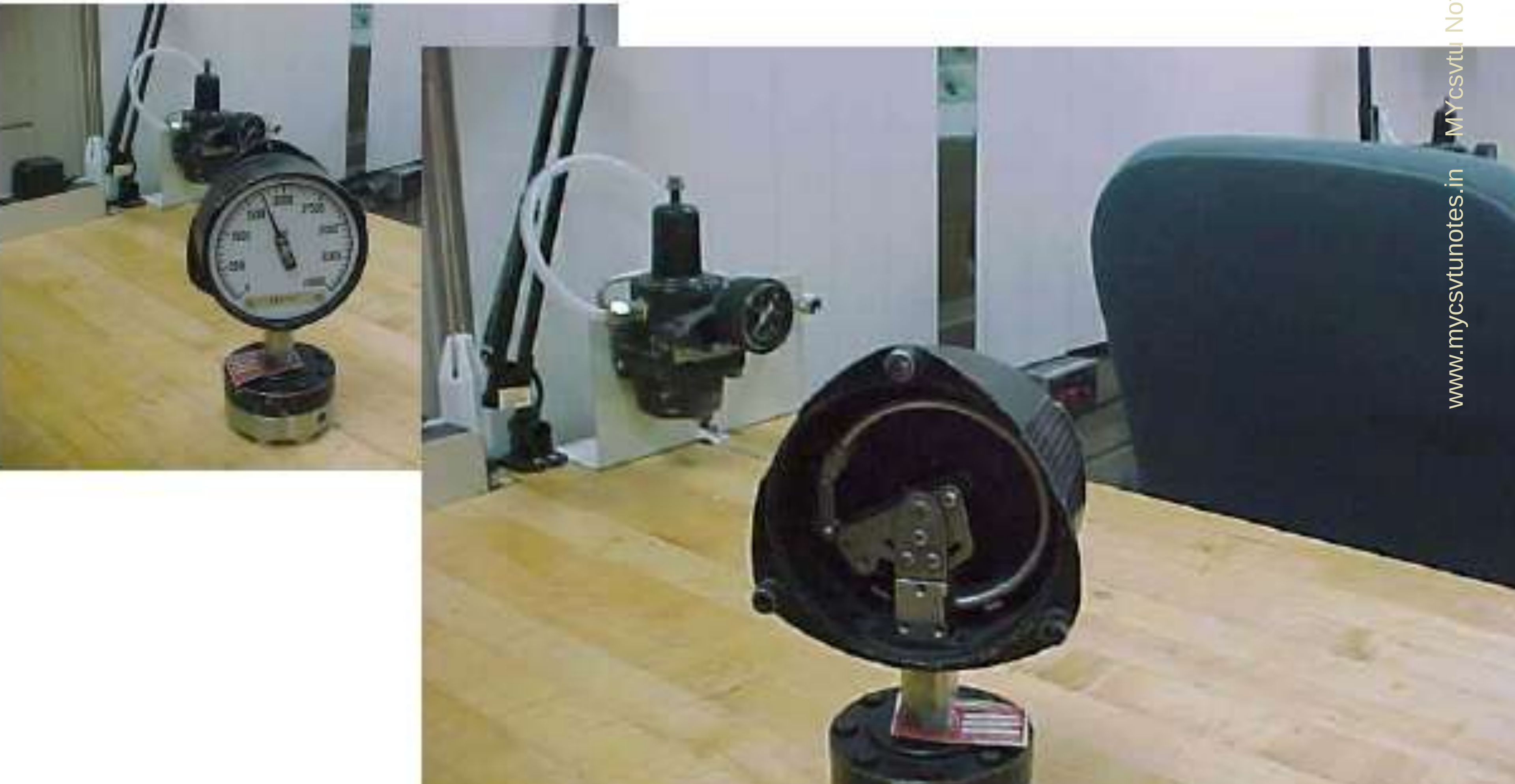
Bellows Gauges

Bourdon Tube

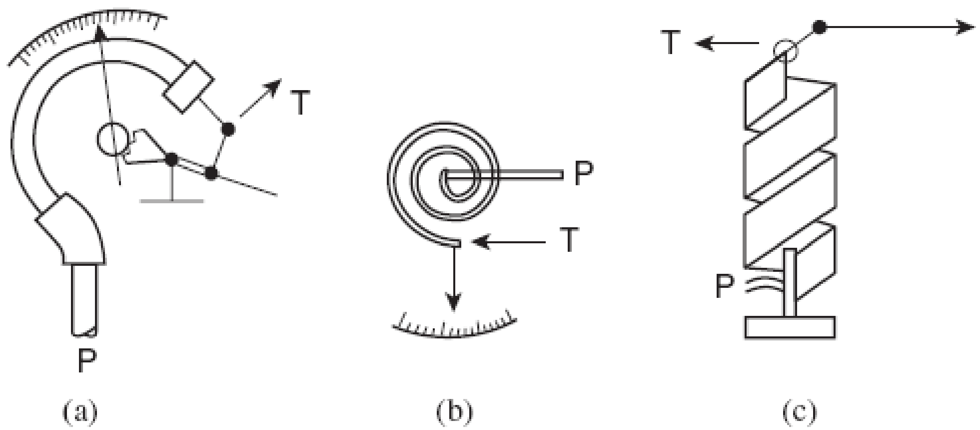




Bourdon Tube Gauge



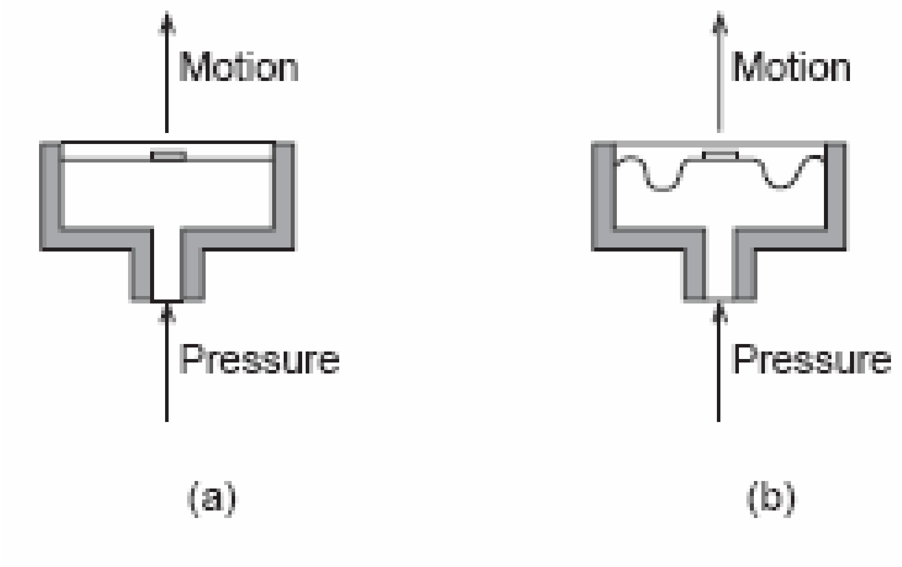
Bourdon Tubes



- (a) C-type tube.
- (b) Spiral tube.
- (c) Helical tube

Bourdon Tubes

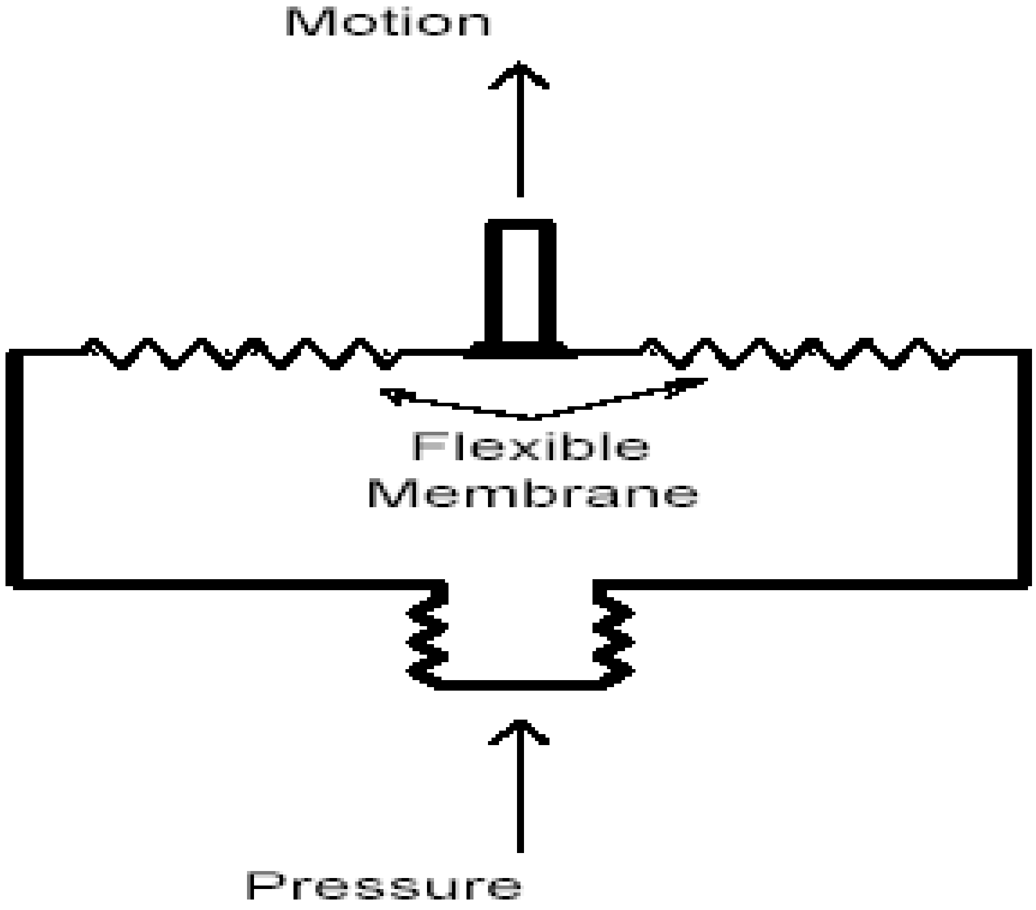
Diaphragm



(a) flat diaphragm; (b) corrugated diaphragm

- A diaphragm usually is designed so that the deflection-versus-pressure characteristics are as linear as possible over a specified pressure range, and with a minimum of hysteresis and minimum shift in the zero point.

Diaphragm



- Strain gage pressure sensors

$$p = \frac{16Et^4}{3R^4(1-\nu^2)}\left[\frac{y_c}{t} + 0.488\left(\frac{y_c}{t}\right)^3\right]$$

where
$p \triangleq$ pressure difference across diaphragm
$E \triangleq$ modulus of elasticity
$t \triangleq$ diaphragm thickness
$\nu \triangleq$ Poisson's ratio
$R \triangleq$ diaphragm radius to clamped edge

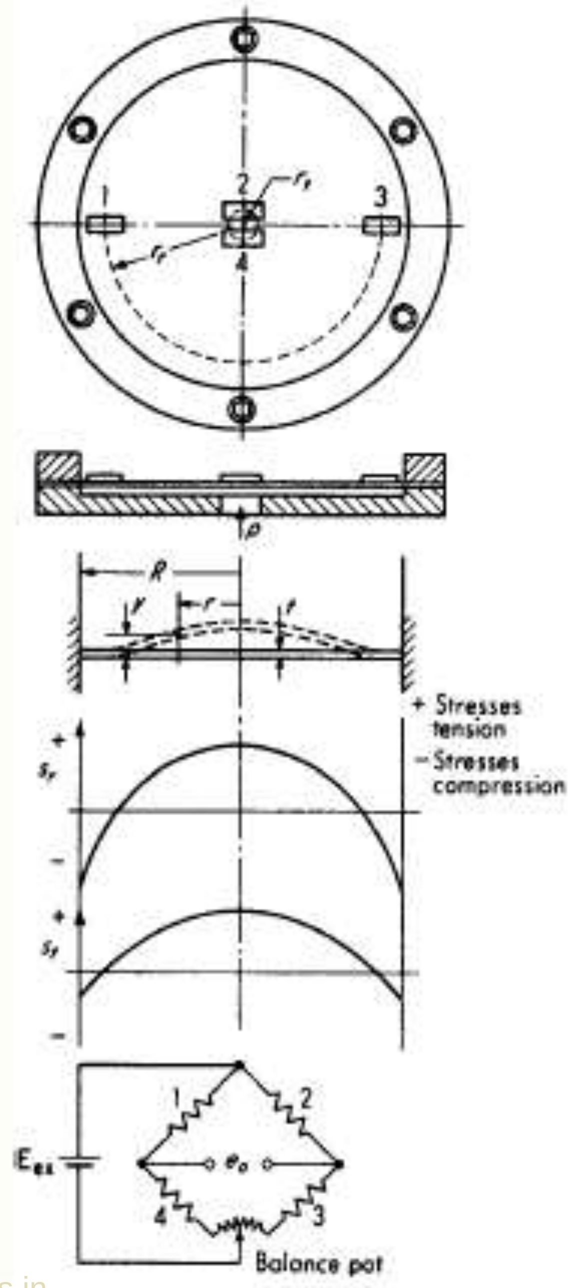
$$s_r = \frac{3pR^2\nu}{8t^2}\left[\left(\frac{1}{\nu}+1\right) - \left(\frac{3}{\nu}+1\right)\left(\frac{r}{R}\right)^2\right]$$

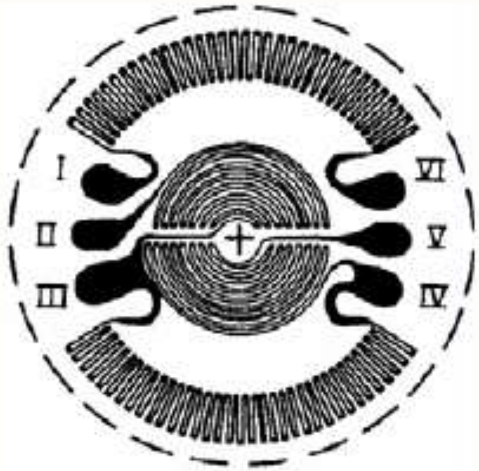
$$s_t = \frac{3pR^2\nu}{8t^2}\left[\left(\frac{1}{\nu}+1\right) - \left(\frac{1}{\nu}+3\right)\left(\frac{r}{R}\right)^2\right]$$

$$y = \frac{3p(1-\nu^2)(R^2-r^2)^2}{16Et^3}$$

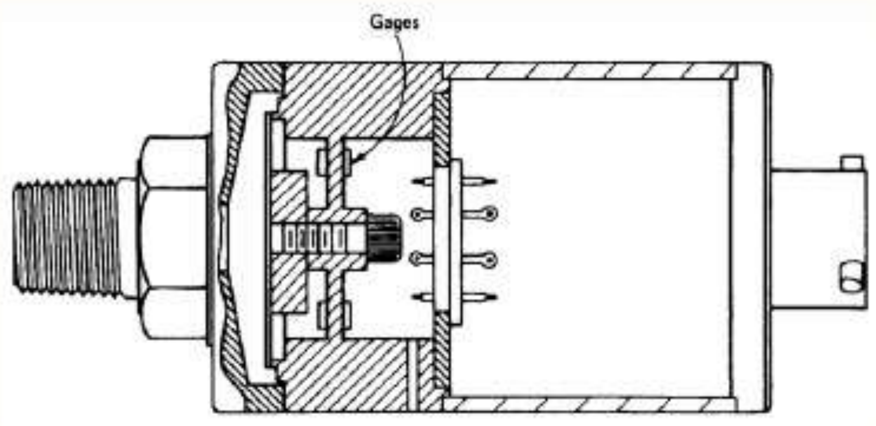
$$\omega_n = \frac{10.21}{CR^2}\sqrt{\frac{Et^2}{12\rho_d(1-\nu^2)}} \quad \text{rad/s}$$

$$C \triangleq \sqrt{1 + 0.669\,\frac{\rho_f}{\rho_d}\frac{R}{t}}$$





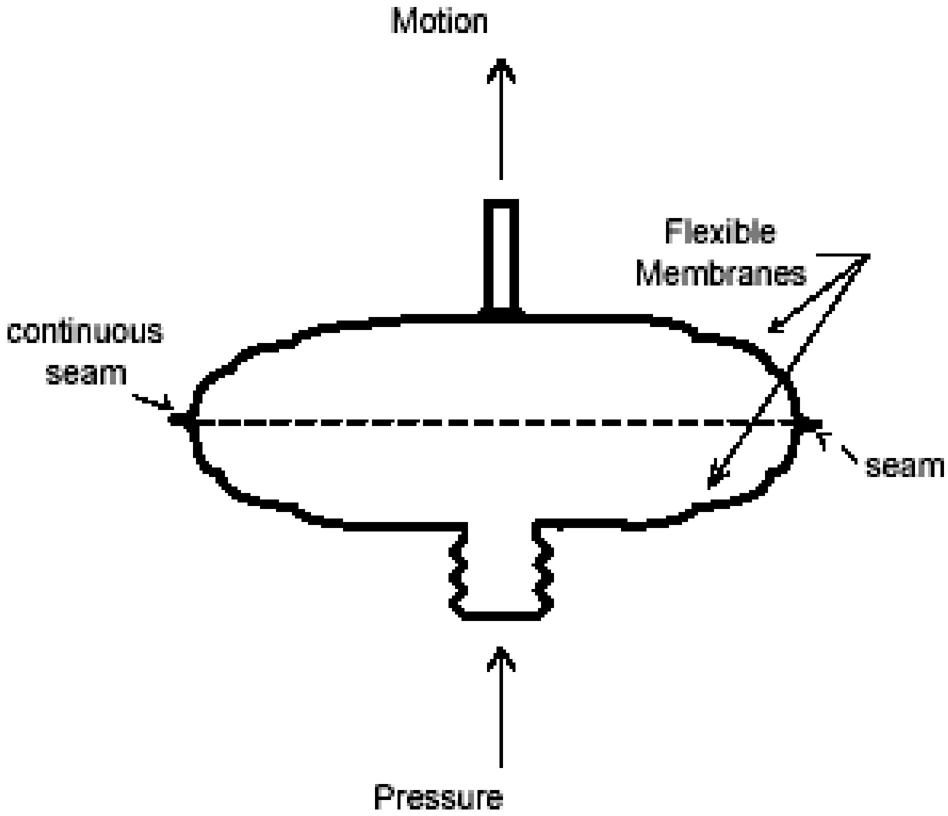
Pressure-diaphragm rosette



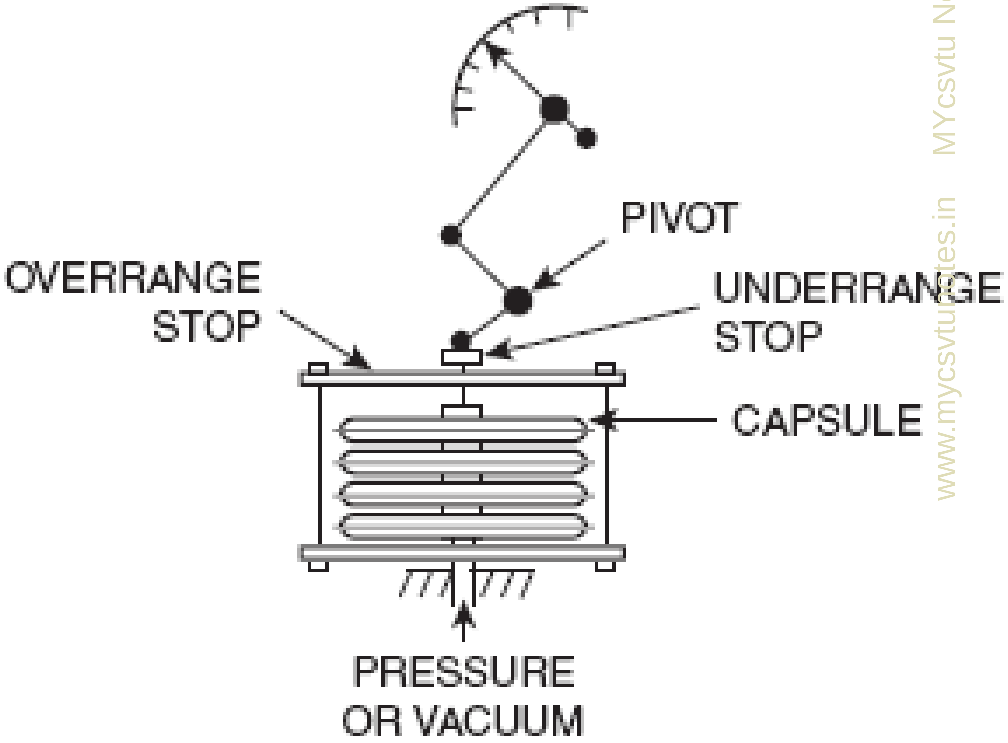
Capsule

A capsule is formed by joining the peripheries of two diaphragms through soldering or welding.

Used in some absolute pressure gages.



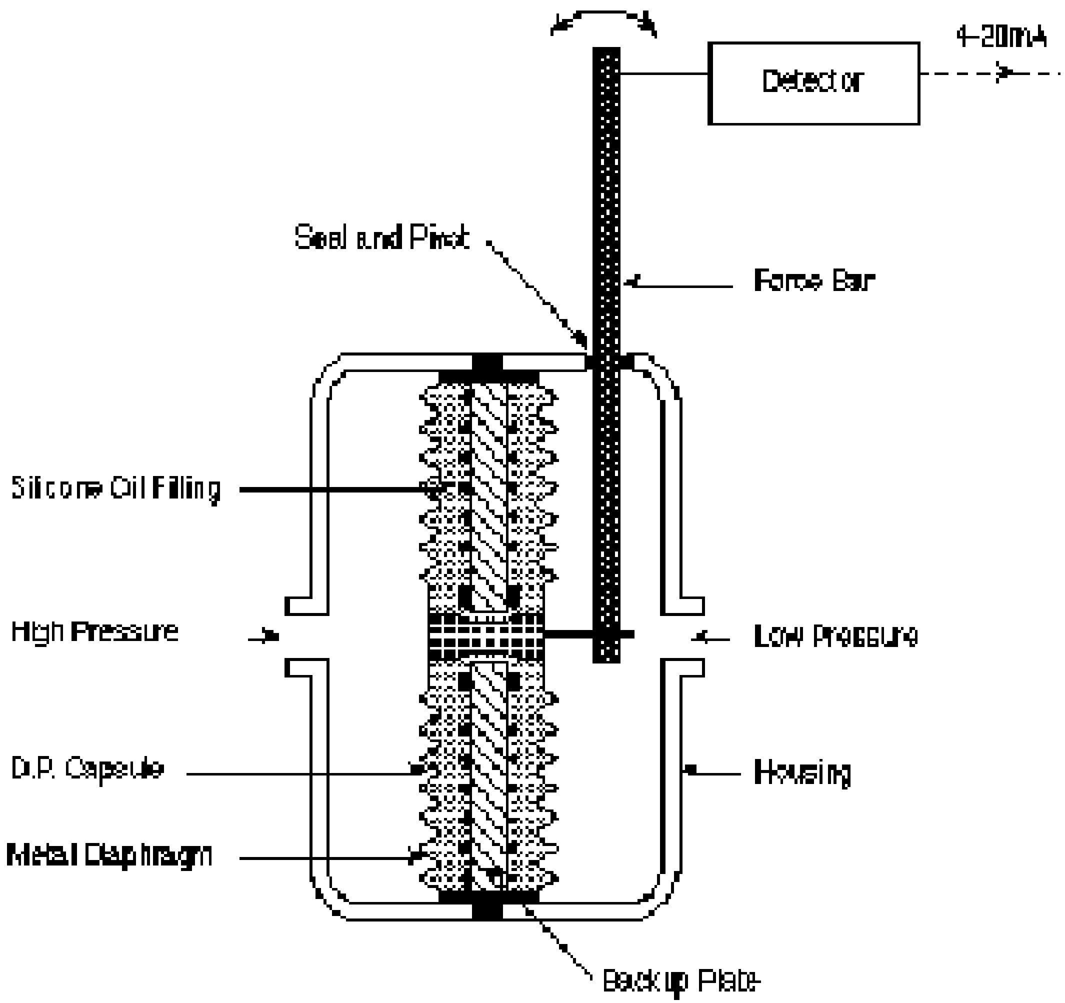
Use of capsule element in pressure gage



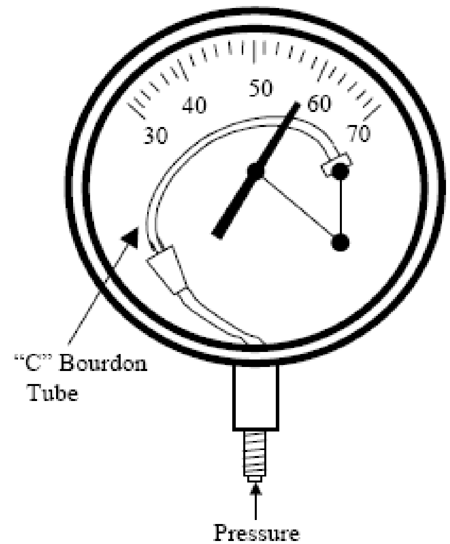
Range of Elastic-Element Pressure Gages

Element	Application	Minimum Range	Maximum Range
Capsule	Pressure	0–0.2 in (0.5 cm) H_2O	0–1000 psig (70.3 kg/cm^2)
	Vacuum	0–0.2 in (0.5 cm) H_2O	0–30 in (76.2 cm) Hg vacuum
	Compound vacuum and pressure	Any span within pressure and vacuum ranges, with a total span of 0.2 in (0.5 cm) H_2O	—
Bellows	Pressure	0–5 in (12.7 cm) H_2O	0–2000 psig (141 kg/cm^2)
	Vacuum	0–5 in (12.7 cm) H_2O	0–30 in (76.2 cm) Hg vacuum
	Compound vacuum and pressure	Any span within pressure and vacuum ranges, with a total span of 5 in (12.7 cm) H_2O	—
Bourdon	Pressure	0–5 psig (0.35 kg/cm^2)	0–100,000 psig (7030 kg/cm^2)
	Vacuum	0–30 in (76.2 cm) Hg vacuum	—
	Compound vacuum and pressure	Any span within pressure and vacuum ranges, with a total span of 12 psi (0.84 kg/cm^2)	—

Differential Pressure Cell



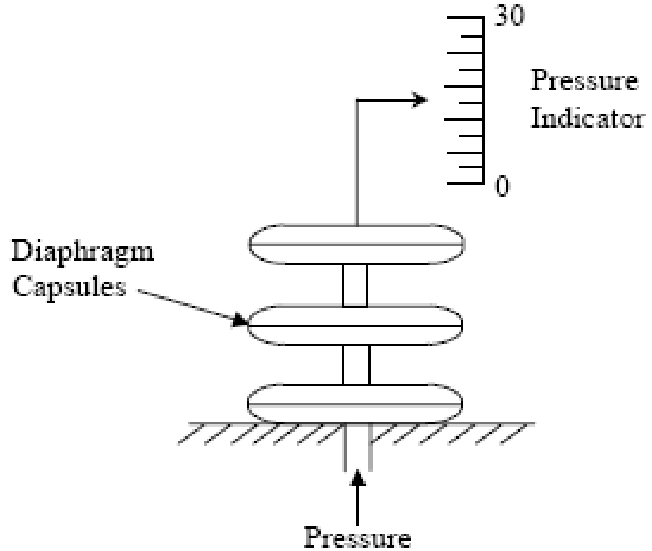
Pressure Gauges



Bourdon tube pressure gauge

- In "C" type Bourdon tube, a section of tubing that is closed at one end is partially flattened and coiled.
- When a pressure is applied to the open end, the tube uncoils.
- This movement provides a displacement that is proportional to the applied pressure.
- The tube is mechanically linked to a pointer on a pressure dial to give a calibrated reading.

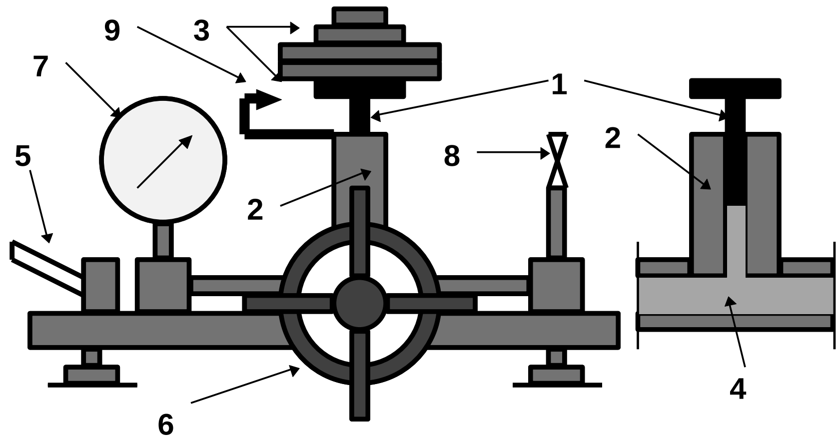
Pressure Gauges



Diaphragm-type pressure gauge

- To amplify the motion that a diaphragm capsule produces, several capsules are connected end to end.
- Diaphragm type pressure gauges used to measure gauge, absolute, or differential pressure.
- They are normally used to measure low pressures of 1 inch of Hg, but they can also be manufactured to measure higher pressures in the range of 0 to 330 psig.
- They can also be built for use in vacuum service.

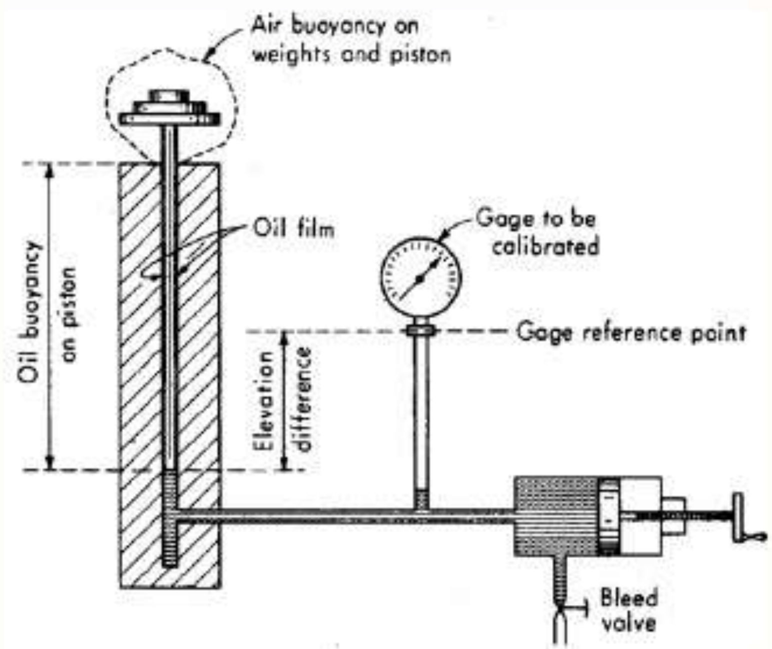
Dead-weight pressure gauge



- A cylindrical piston ***1*** is placed inside a stainless-steel cylinder ***2***.
- The measuring pressure is supplied through the vent ***8*** to the fluid ***4***.
- The gravitational force developed by calibrated weights ***3*** can balance this force and the piston itself..
- The balance should be achieved for a certain position of the piston against a pointer ***9*** of the stainless-steel cylinder.
- A manual piston pump ***5*** is used to achieve approximate force balance (to increase pressure in the system), whereas a wheel-type piston pump ***6*** serves for accurate balancing.
- A Bourdon-type pressure gauge ***7*** is used for visual reading of pressure.

Calibration of Pressure Sensing Devises

NTU50235100



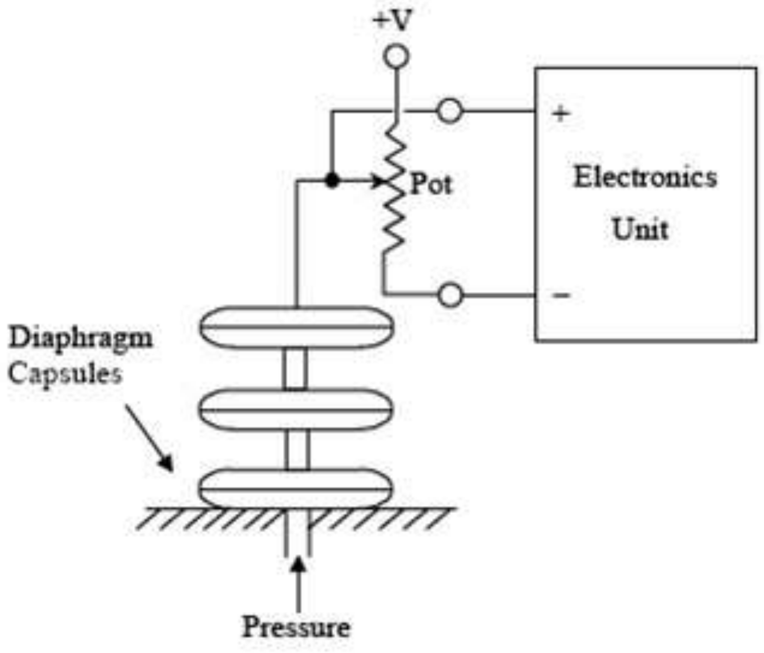
$$\text{Gauge pressure} = \frac{M g_1 \left(1 - \frac{\rho_{air}}{\rho_{mass}}\right) + \pi D T}{A_{(20,\,0)} \cdot [1 + (\alpha_p + \alpha_c)\cdot(\theta - 20)]\cdot(1 + \lambda P)} - (\rho_{fluid} - \rho_{air})\cdot g_1 h$$

From Mechanical to Electronic

- The free end of a Bourdon tube (bellows or diaphragm) no longer had to be connected to a local pointer, but served to convert a process pressure into a transmitted (electrical or pneumatic) signal.
- At first, the mechanical linkage was connected to a pneumatic pressure transmitter, which usually generated a 3-15 psig output signal for transmission over distances of several hundred feet,
- The force-balance and later the solid state electronic pressure transducer were introduced.

Potentiometric type sensor

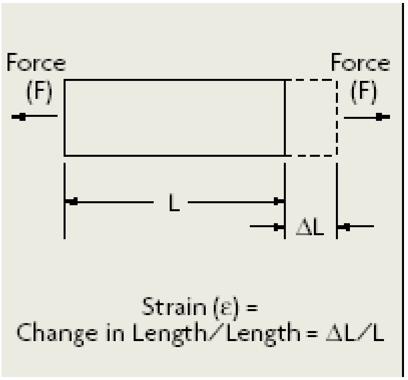
- A mechanical device such as a diaphragm is used to move the wiper arm of a potentiometer as the input pressure changes.
- A direct current voltage (DC) V is applied to the top of the potentiometer (pot), and the voltage that is dropped from the wiper arm to the bottom of the pot is sent to an electronic unit.
- It normally cover a range of 5 psi to 10,000 psi.
- Can be operated over a wide range of temperatures.
- Subject to wear because of the mechanical contact between the slider and the resistance element.
- Therefore, the instrument life is fairly short, and they tend to become noisier as the pot wears out.



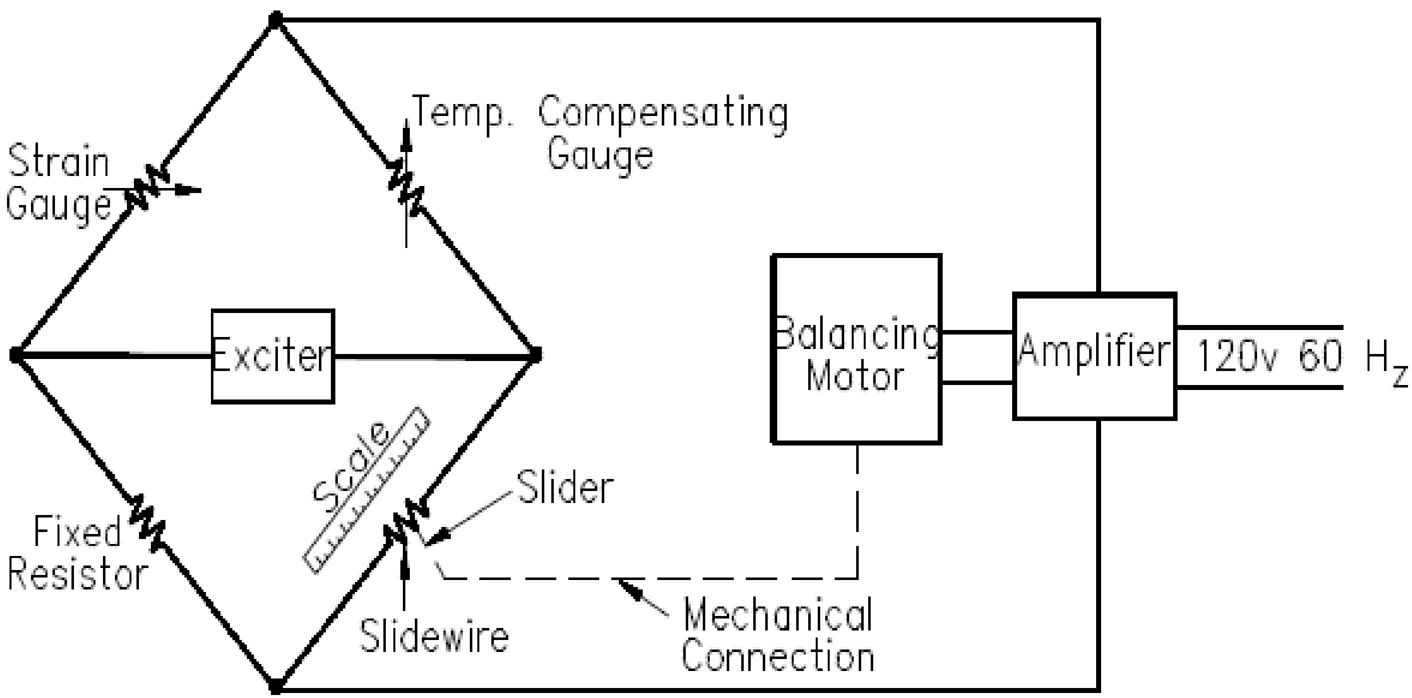
Strain Gage

- If a wire is held under tension, it gets slightly longer and its cross-sectional area is reduced. This changes its resistance (R) in proportion to the strain sensitivity (S) of the wire's resistance.

- The strain sensitivity, which is also called the gage factor (GF), is given by: GF = $(\Delta R/R)/(\Delta L/L) = (\Delta R/R)/$ Strain

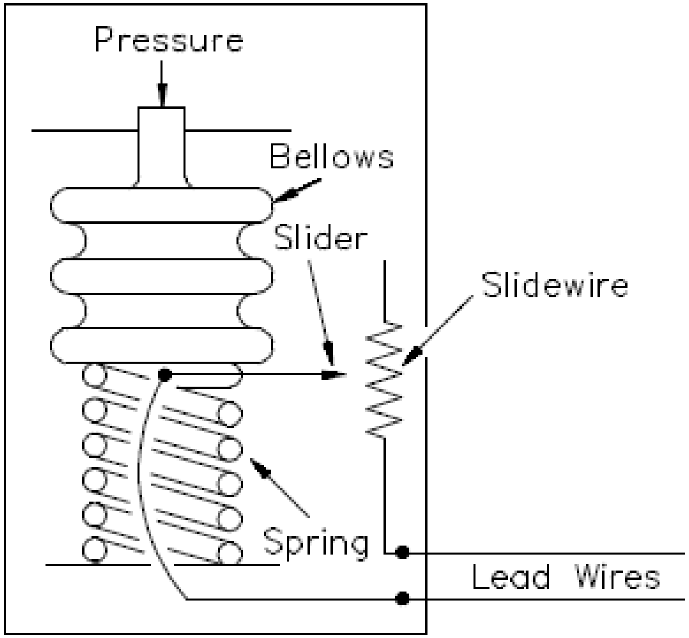


Strain Gauge Used in a Bridge Circuit

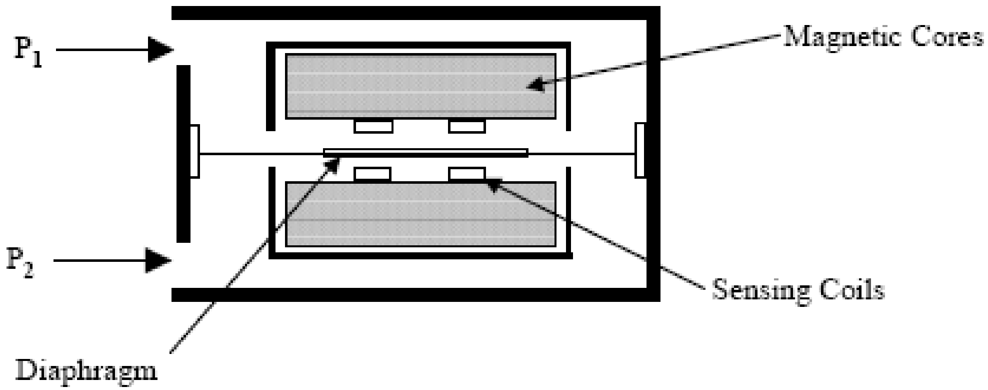


Bellows Resistance Transducer

- Bellows or a bourdon tube with a variable resistor.
- Bellow expand or contract causes the attached slider to move along the slidewire.
- This increase or decrees the resistance.
- Thus indicating an increase or decrease in pressure.



Inductance-Type Transducers

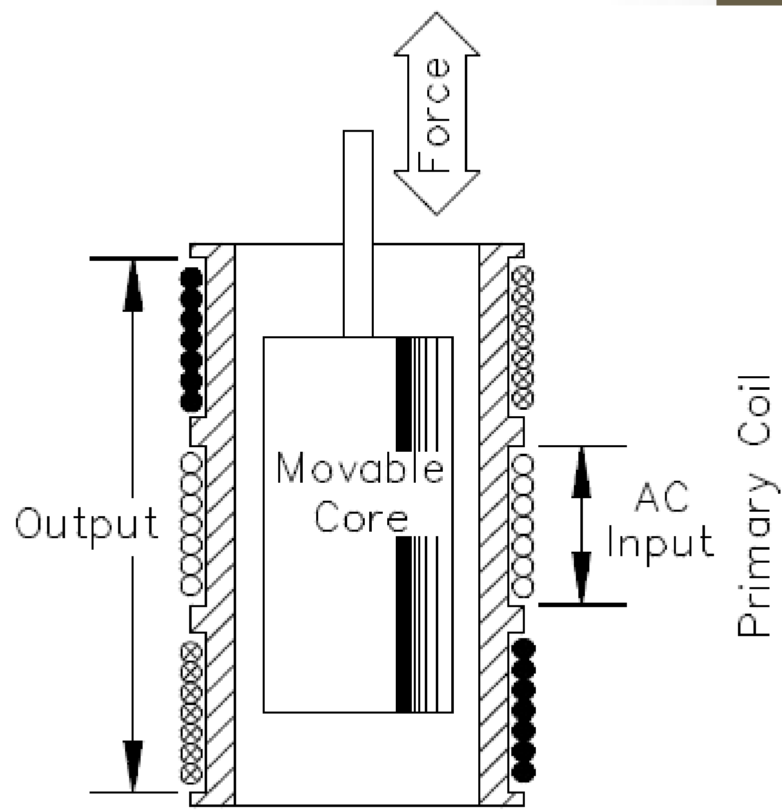


- The inductance-type transducer consists of three parts: a coil, a movable magnetic core, and a pressure sensing element.

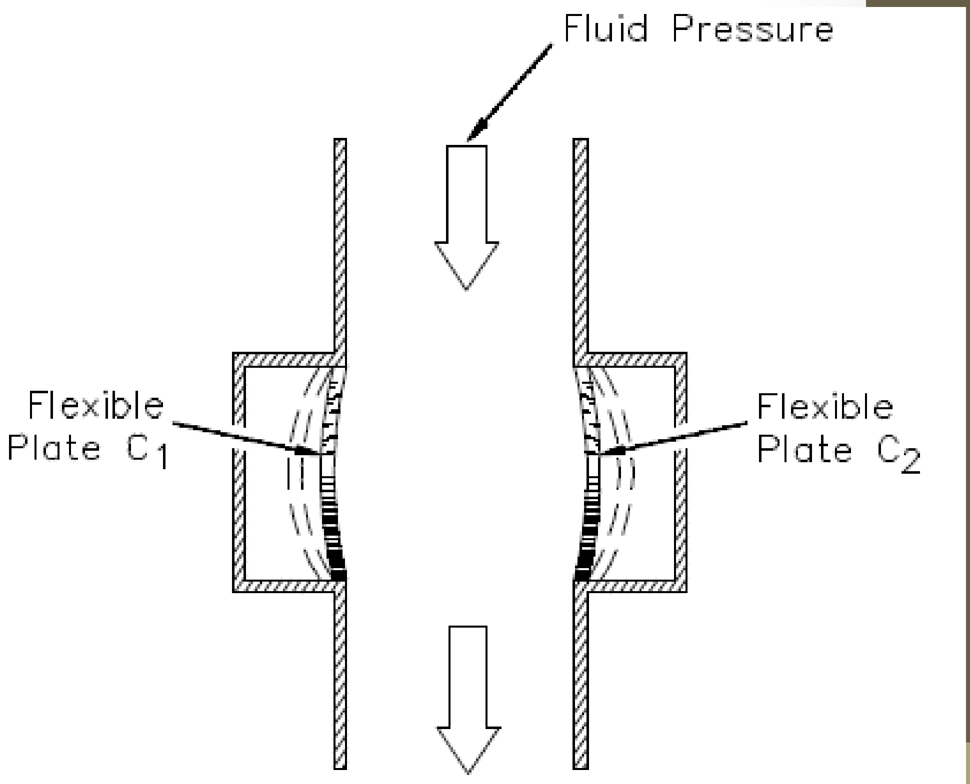
- An AC voltage is applied to the coil, and, as the core moves, the inductance of the coil changes.

LVDT

- Another type of inductance transducer, utilizes two coils wound on a single tube and is commonly referred to as a Differential Transformer or sometimes as a Linear Variable Differential Transformer (LVDT).



Capacitance



Piezoelectric

- When pressure, force or acceleration is applied to a quartz crystal, a charge is developed across the crystal that is proportional to the force applied.
-
- Piezoelectric devices can further be classified according to whether the crystal's electrostatic charge, its resistivity, or its resonant frequency electrostatic charge is measured.
- Depending on which phenomenon is used, the crystal sensor can be called electrostatic, piezoresistive, or resonant.

Electronic Pressure Sensor Range

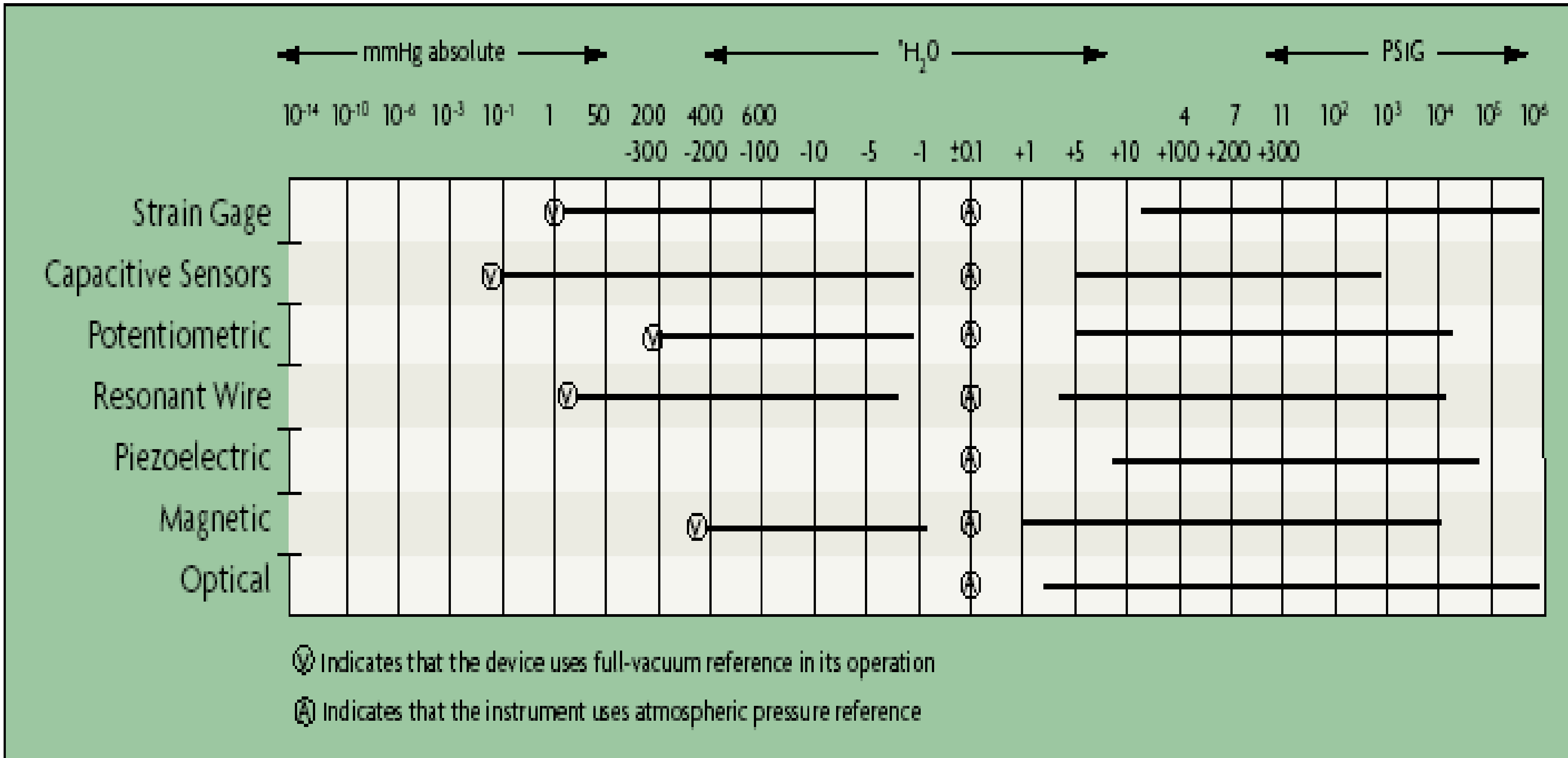


Figure 3-3: Electronic Pressure Sensor Ranges

Principles of Pressure Measurement

Units of Measure

System	Length	Force	Mass	Time	Pressure
MKS	Meter	Newton	Kg	Sec	N/M^2 = Pascal
CGS	CM	Dyne	Gram	Sec	D/CM^2
English	Inch	Pound	Slug	Sec	PSI

How Much is a Pascal (Pa)

- A Newton is the force necessary to accelerate a mass of 1 kg at a rate of 1 meter per second per second.
- The acceleration of gravity is 9.8 m/sec^2
- The force due to gravity on a 1 kg mass is 9.8 N is 1 kg weight.
- 1 Newton is 0.102 kg weight.

How Much is a Pascal (Pa)

- 1 n/m^2 is a very small pressure
- Therefore kilopascal (kPa)
- 1 atmosphere (14.7 psi, 750mmHg) is approximately 100 kPa = 1 bar
- 1 kPa is about 7 mmHg
- 1% of a gas at our altitude is about 7 mmHg

How is pressure generated?

- Collision of molecule with wall
- Momentum is mass x velocity
- Change of momentum is double
- Collision is isothermal = perfectly elastic
- Sum collisions over area to get force

How is pressure measured?

- Absolute v.s. relative pressure
- Manometry
- Bourdon
- Aneroid
- Strain gauge

Manometry

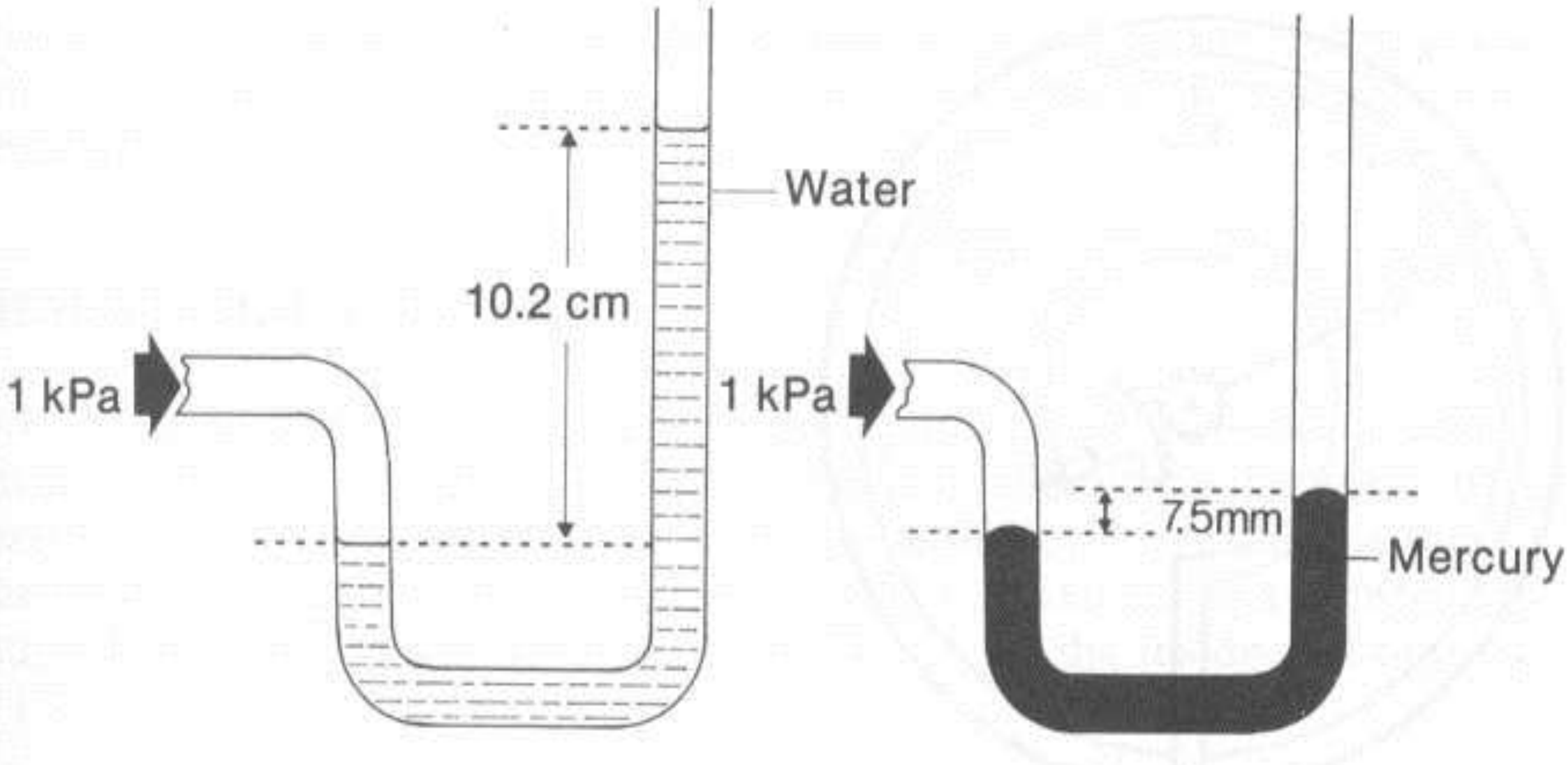


Figure 1.11 Comparison of water and mercury manometers.

Bourdon

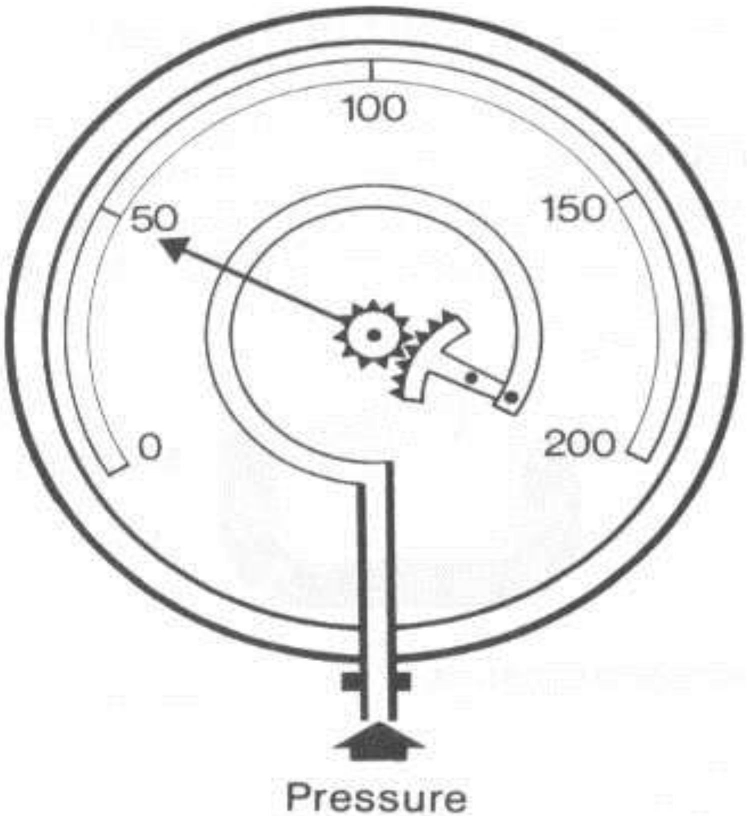


Figure 1.13 Bourdon gauge.

Aneroid

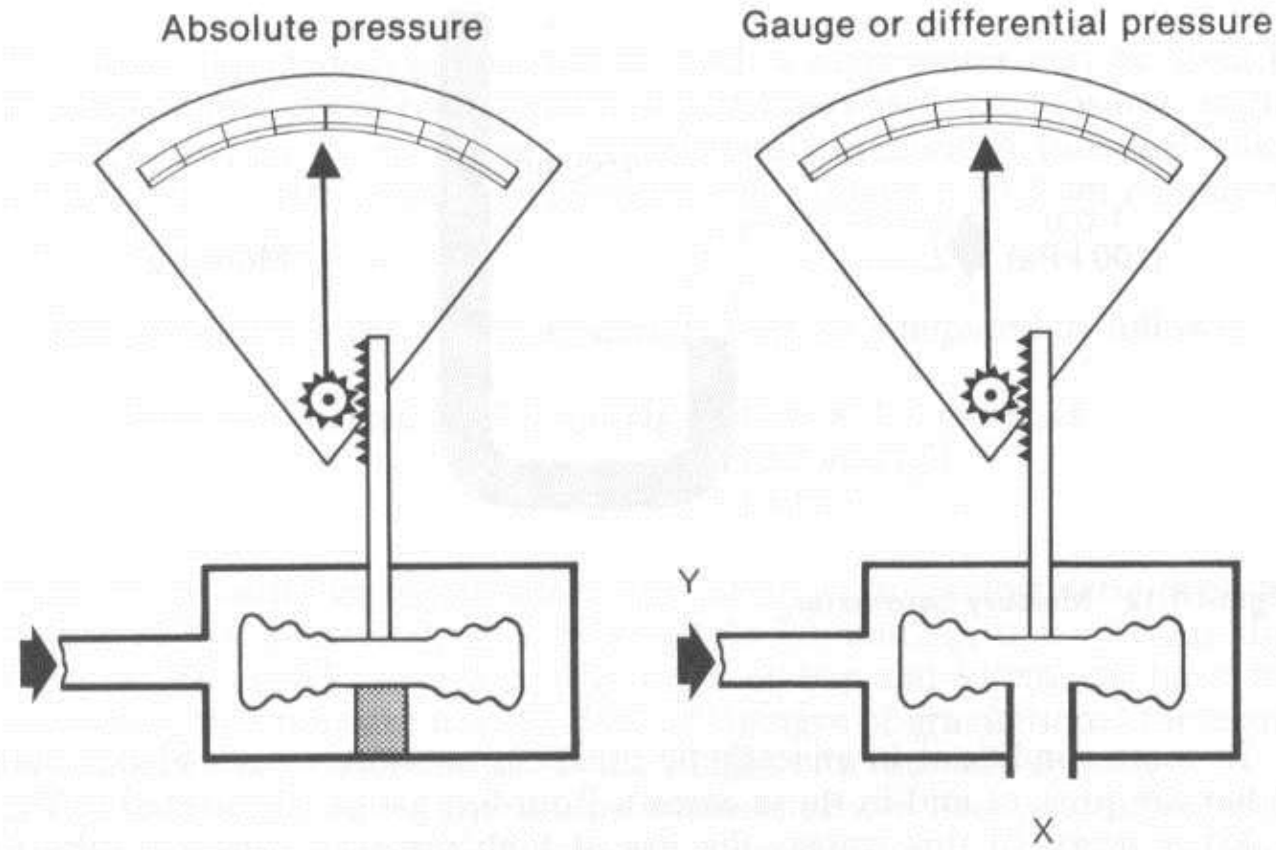


Figure 1.14 Types of bellows aneroid gauges.

Clinical Uses of Pressure Measurement

- Anesthesia gas storage
- Ventilator operation and disconnect
- Cardiovascular management
- Balloon angioplasty
- Nitrogen-powered equipment

Devices to Measure Blood Pressure Clinically

- Mercury manometer
- Aneroid manometer
- Non invasive blood pressure (NIBP)
- Invasive

NIBP

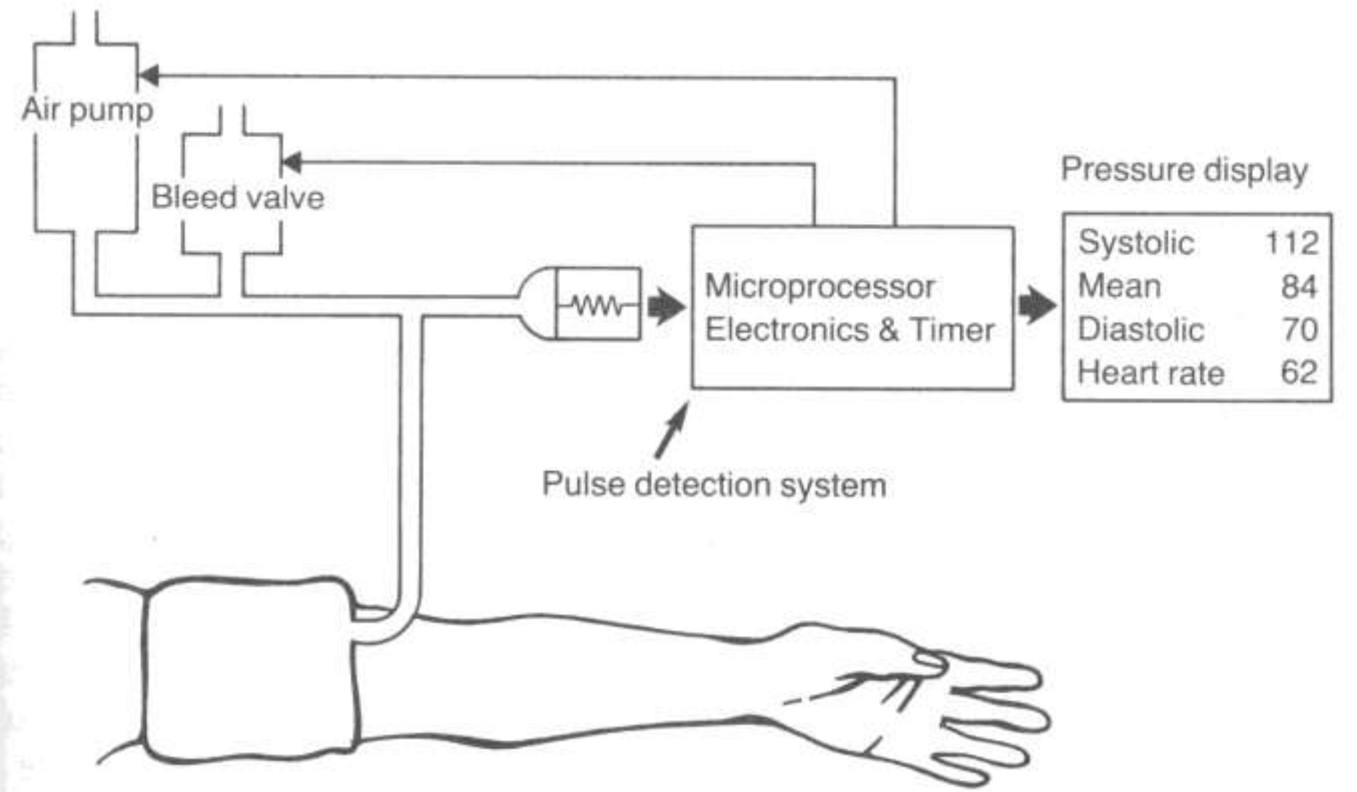
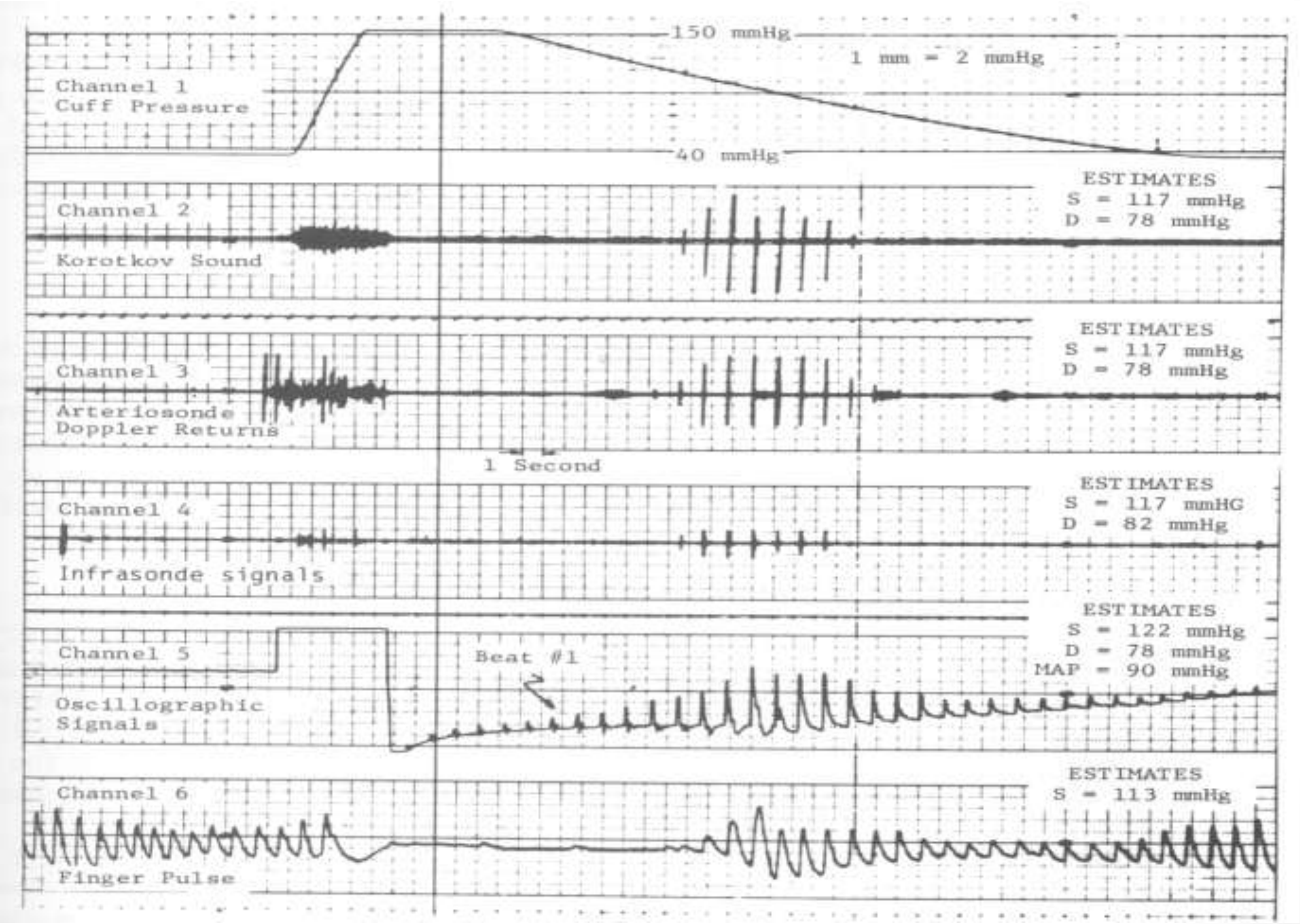
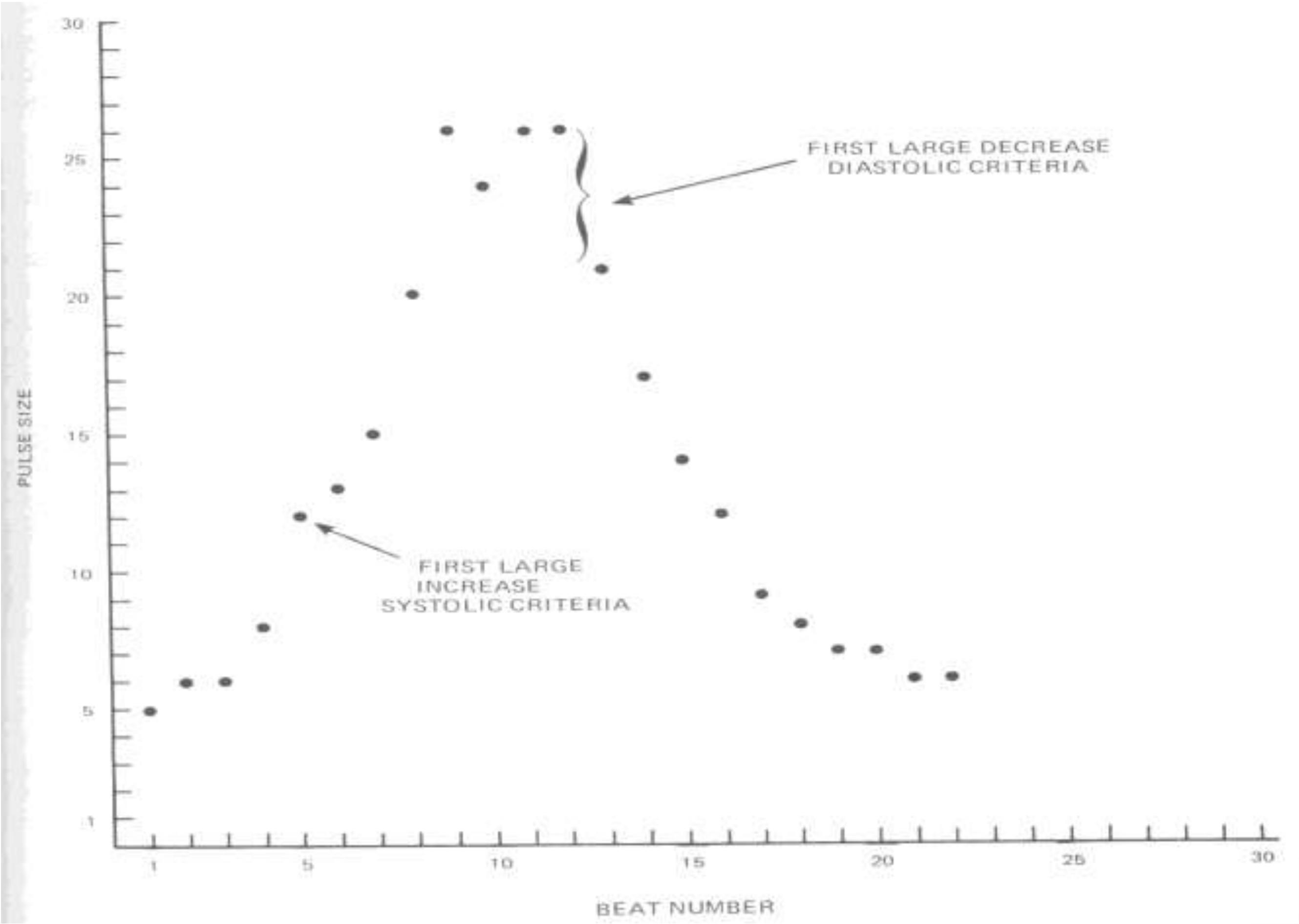


Figure 17.5 Principle of automatic blood pressure measurement.

NIBP


150 mmHg
1 mm = 2 mmHg
Channel 1
Cuff Pressure
40 mmHg
ESTIMATES
S = 117 mmHg
D = 78 mmHg
Channel 2
Korotkov Sound
ESTIMATES
S = 117 mmHg
D = 78 mmHg
Channel 3
Arteriosonde
Doppler Returns
1 Second
ESTIMATES
S = 117 mmHG
D = 82 mmHg
Channel 4
Infrasonde signals
ESTIMATES
S = 122 mmHg
D = 78 mmHg
MAP = 90 mmHg
Channel 5
Beat #1
Oscillographic
Signals
ESTIMATES
S = 113 mmHg
Channel 6
Finger Pulse

NIBP



FIRST LARGE DECREASE
DIASTOLIC CRITERIA
FIRST LARGE
INCREASE
SYSTOLIC CRITERIA
PULSE SIZE
BEAT NUMBER
30
25
20
15
10
5
1
1
5
10
15
20
25
30

Invasive Pressures

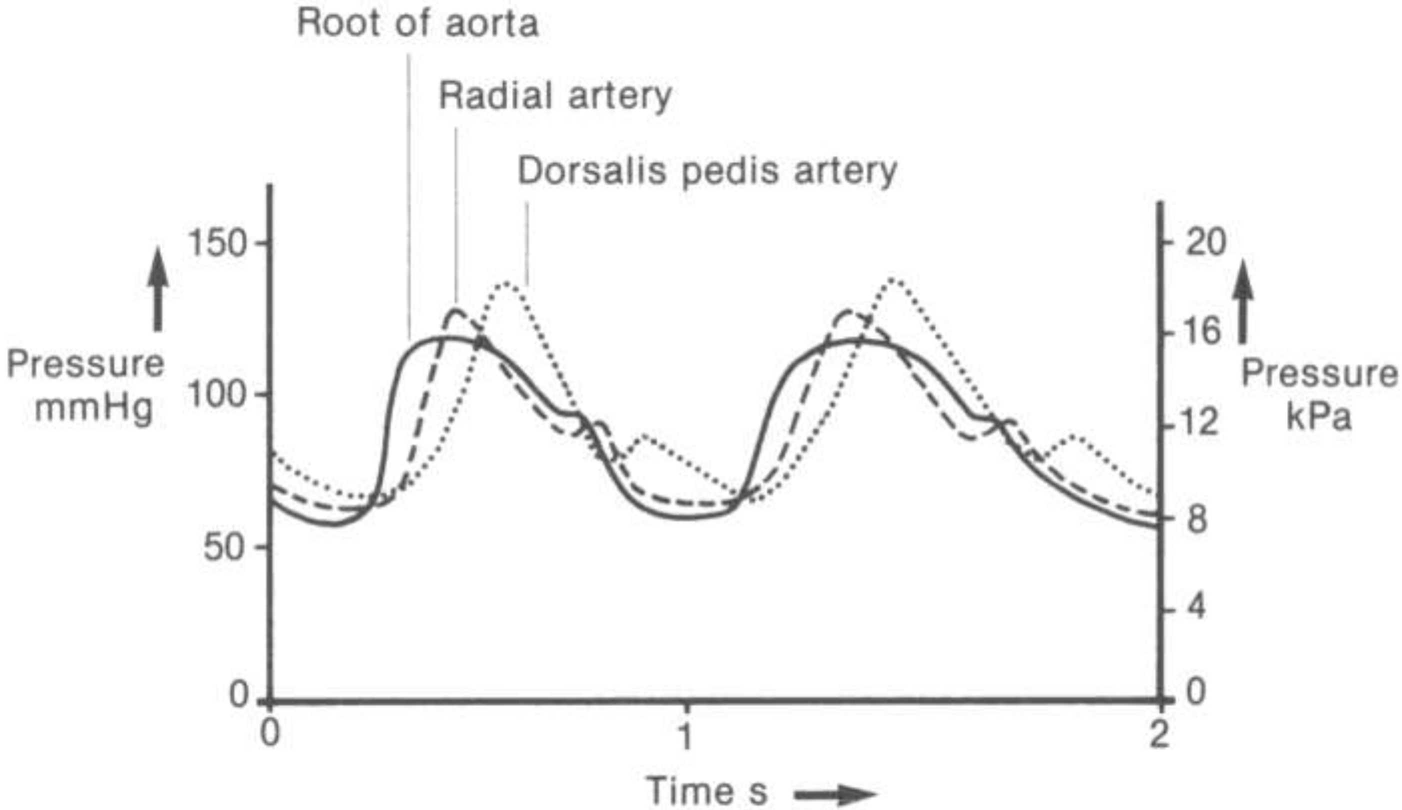


Figure 17.8 Arterial pressure tracings from the aorta, the radial and the dorsalis pedis arteries.

Resonance Limits Physical Devices

- Mass is moving saline column
- Spring is the elastance of the tubing and transducer diaphragm
- Resonant frequency
- Banging the system at its resonant frequency leads to overshoot

Damping

- Removal of energy from a resonant system
- Underdamped: continues to ring
- Overdamped: does not ring at all
- Critically damped: 5% overshoot
- Critical damped system gives best frequency response

Damping

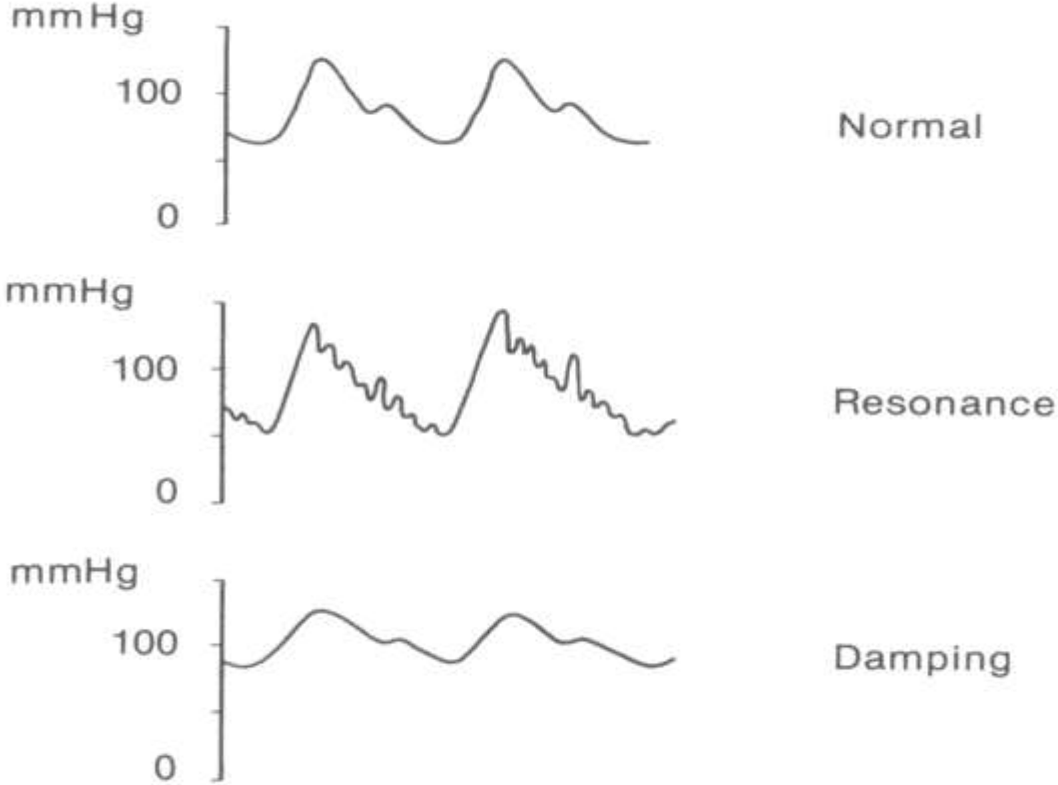


Figure 17.9 Effect of resonance and damping on the arterial pressure trace.

Units of Measure

Unit	MKS	CGS	English
Length meter	cm	inch	
Force newton	dyne	pound	
Mass	kg	gm	slug
Time	sec	sec	sec
Pressure	n/m^2 (pa)	$dyne/cm^2$	psi