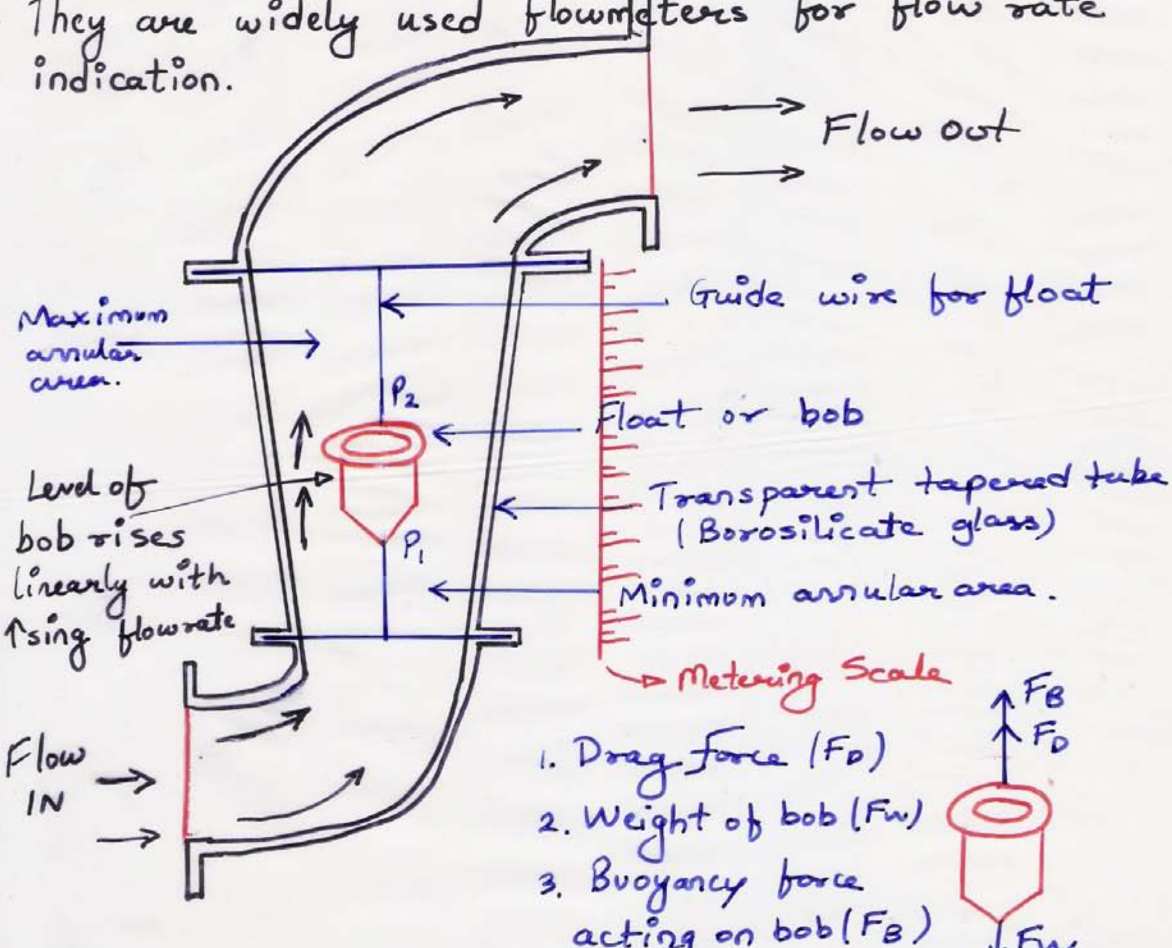
Rotameter (Variable Area Meter - Flowmeter)

- They are widely used flowmeters for flow rate indication.



Forces acting on bob / float.

- Rotameter consists of a transparent tapered vertical glass tube containing a 'float' or 'bob', which rises in the tube with ↑sing flowrate. until a balance is reached between gravitational (F_W), buoyancy (F_B) and drag (F_D) forces on the bob.
- The fluid whose flow is to be measured enters the tube from bottom to top. Fluid flows upwards through the gap between the tube and float.
- The position of the float is calibrated with the float rate.

Rotameter Continue.......

Principle:

- For a given flow rate, the float remains stationary when weight of float is balanced by buoyancy and drag force.
- Annular area between float & vertical tube, varies continuously with vertical displacement of float/bob.
- Since area of cross-section of float is constant, pressure drop across it should be constant.
- When float is in particular position for a flow rate the differential pressure (ΔP) varies with square of flow rate.

∴ To keep ΔP constant, for some other flow rate annular area between float & vertical tube must change.

- Variable Area is provided by vertical tube.
- When fluid enters in, the float starts moving up there is variation in annular area (ie it ↑ses) causing a pressure drop ∝nal to flow area and hence flow rate.
- Float is pushed upwards till the F_D and F_B forces produced due to difference in pressure equals to weight of float (F_W).
- Similar action follows if there is ↓se in flowrate.
- Thus every position of float in tube is (∝nal) to flow rate.

+ Advantages:-

- Simple in construction, easy to install
- Flow rate can be directly seen on calibrated scale without any help of any other device.

Rotameter Continue - - -

Volume flow rate in case of Rotameter is

$$Q = \frac{C_d (A_t - A_b)}{\sqrt{1 - \left(\frac{A_t - A_b}{A_t}\right)^2}} \sqrt{2 g V_b \left(\frac{\rho_b - \rho_f}{A_b \times \rho_f}\right)} \quad \text{— (1)}$$

where, Q - Volume flow rate

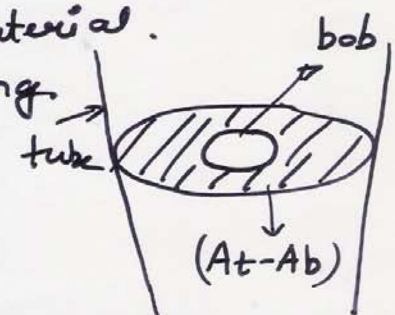
A_t, A_b - Area of cross-section of tube and bob.

C_d - Discharge co-eff

V_b - Volume of float/bob.

ρ_b - density of float/bob material.

ρ_f - density of fluid flowing.



if we assume, $\left(\frac{A_t - A_b}{A_t}\right)^2 << 1$

Eqn (1) becomes,

$$\boxed{Q = K (A_t - A_b)} \; ; \; K = C_d \sqrt{2 g V_b \left(\frac{\rho_b - \rho_f}{A_b \rho_f}\right)}$$

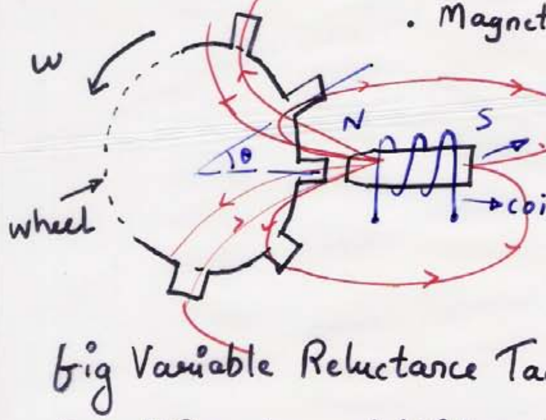
. Remember, Rotameter based on Variable Area principle is used for only Monitoring or Indicating Purposes.

Applications:-

1) For Laboratory use, medical equipment and other applications with small flow rate, glass tube is almost universal.
2) For industrial applications, the metering of corrosive fluids or fluids at high temperature or pressure leads to use of stainless steel rotameter tubes.

Principle of Variable Reluctance Tachogenerator:-

- If time varying flux ϕ linked by a single turn of coil, then back emf developed in coil is $\boxed{e = -\frac{d\phi}{dt}}$



- Magnetomotive force (mmf) → force that causes flux to be established.

The teeth of wheel moves in close proximity to Pole.
∴ Flux linked by coil changes w.r.t time & vtg is developed across the coil.

fig Variable Reluctance Tachogenerator.

- Opposition to establishment of magnetic flux is Reluctance
  $\mathcal{R} = mmf/\phi$ or $mmf = \mathcal{R}\phi$
- Total flux (ϕ_T) linked by a coil of m turns is
  $\phi_T = m\phi = m.\frac{mmf}{\mathcal{R}}.$
- When reluctance is min, flux is max & vice-versa.
- The variation of flux (ϕ_T) with angular position (θ) of wheel will be expressed as,

$$\phi_T(\theta) = \alpha + \beta\cos(n\theta)$$; n - no of teeth of wheel

where, α - mean flux, β - amplitude of time-varying flux

$$\therefore e = -\frac{d\phi_T}{dt} = -\frac{d\phi_T}{d\theta}.\frac{d\theta}{dt}$$

Again, $\frac{d\phi_T}{dt} = -\beta n\sin(n\theta)$ & $\theta = \omega t$, $\frac{d\theta}{dt} = \omega$

ω - rotational velocity of wheel.

$$\therefore \boxed{e = \beta n\omega\sin(n\omega t)}$$ → o/p of V.R tachogenerator

Amplitude $= \beta n\omega$

Freq$^n = \frac{n\omega}{2\pi}$

ω is proportional to ampl and freq^n of e.

This explanat^n required to Understand 'Turbine flowmeter'

Turbine-type Flowmeter :

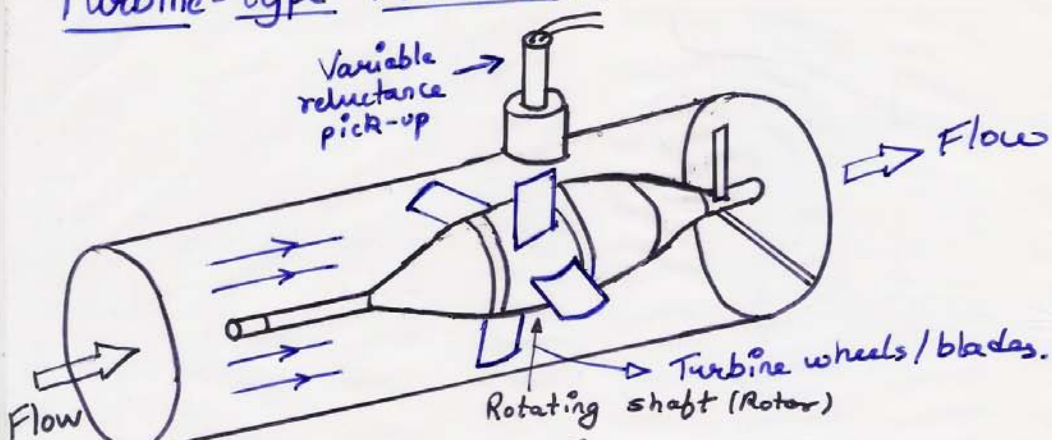


fig Schematic of Turbine type flow meter.

- Turbine flowmeter consists of rotating shaft with turbine type angular blades & it is installed inside the flow pipe.

Principle:- The fluid flowing through pipeline will cause rotation of turbine wheels whose angular speed can be a measure of Flowrate.

Working:-

1. As fluid flows, turbine wheels rotates, its angular velocity depending upon flow rate of clear fluid.
2. The angular velocity of turbine wheel is measured with help of a magnetic pick-up which produces voltage pulses as each blade of turbine moves past it.
3. Either these pulses can be counted by a digital counter over a fixed period of time to determine pulse or pulses can be sensed by V.R pickup & fed to a frequency-to-voltage converter to produce an voltage which can be calibrated in terms of flow rate.

Theory:-

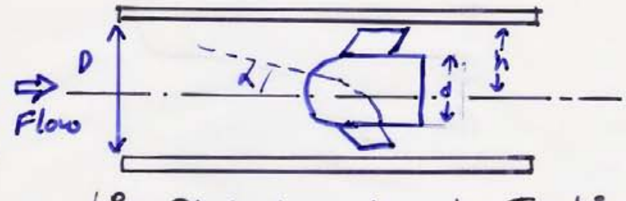


fig Blade Assembly of a Turbine flow meter.

- If no of rotation of blade per second is 'f' and volume flow rate is Q then $f = KQ$.
- Total Volume of Liquid (V_T) flow through pipe over a given time 'T' will be

$$V_T = \int_0^T Q\,dt$$

- Total no of rotation of blade over a time 'T' is

$$N_T = \int_0^T f\,dt = \int_0^T K.Q\,dt = K V_T$$

- let blades makes an angle α with body, then

$$\tan\alpha = \frac{\omega R}{v}$$

where, v = Average velocity of fluid : $v = \frac{Q}{A}$

A = Effective flow area of pipe.

R = radius of blade.

- Angular velocity (ω) is αnal to Volume flow rate (Q)

$$\boxed{\omega = K_1 Q} \quad , \quad K_1 = \frac{\omega}{Q} = \frac{\tan\alpha}{R.A.}$$

- The voltage induced in magnetic pick-up will be periodic in nature and is

$$\boxed{e = \beta n K_1 Q \sin[nK_1 Q]t} \quad — (1)$$

β - amplitude of Angular variation of magnetic flux

Q - Volumetric flow rate.

Eq^n(1) indicates o/p of magnetic pick up is a sinusoidal slg of amplitude = '$\beta n K_1 Q$'

& freq^n $f = \left(\frac{n K_1 Q}{2\pi}\right)$

Applications:-

- Turbine flowmeters are used for a variety of applications in major industries besides water, and natural gas, including oil, petrochemicals, chemical process, milk and beverage, aerospace biomedical and others.

Features:-

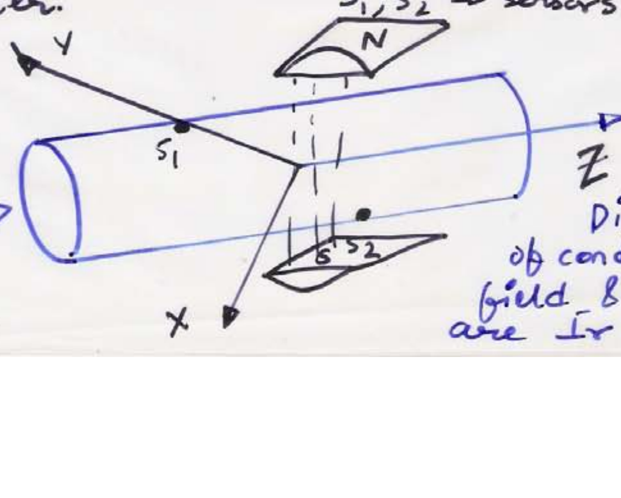
- Turbines type flowmeters performs best when measuring clean, conditioned, steady flow of gases and liquids.
- It is expensive & also imposes permanent pressure loss in measurement system.
- Rate of rotation, can be up to several $\times 10^4$ rpm for smaller meters.
- Measurement accuracy is very high ($\pm 0.1\%$).

→ Faraday's law of Electromagnetic Induction:-

This law states that if a conductor of length l is moving with a velocity v, ⊥r to a magnetic field of flux density B, then induced emf e across end of conductor is $\boxed{e = Blv}$

This principle is utilized to an Electromagnetic Flowmeter.

S_1, S_2 → sensors (Electrode)



Direction of movement of conductor, magnetic field & induced emf are ⊥r to each other

fig Operating Principle.

Electromagnetic Flowmeters

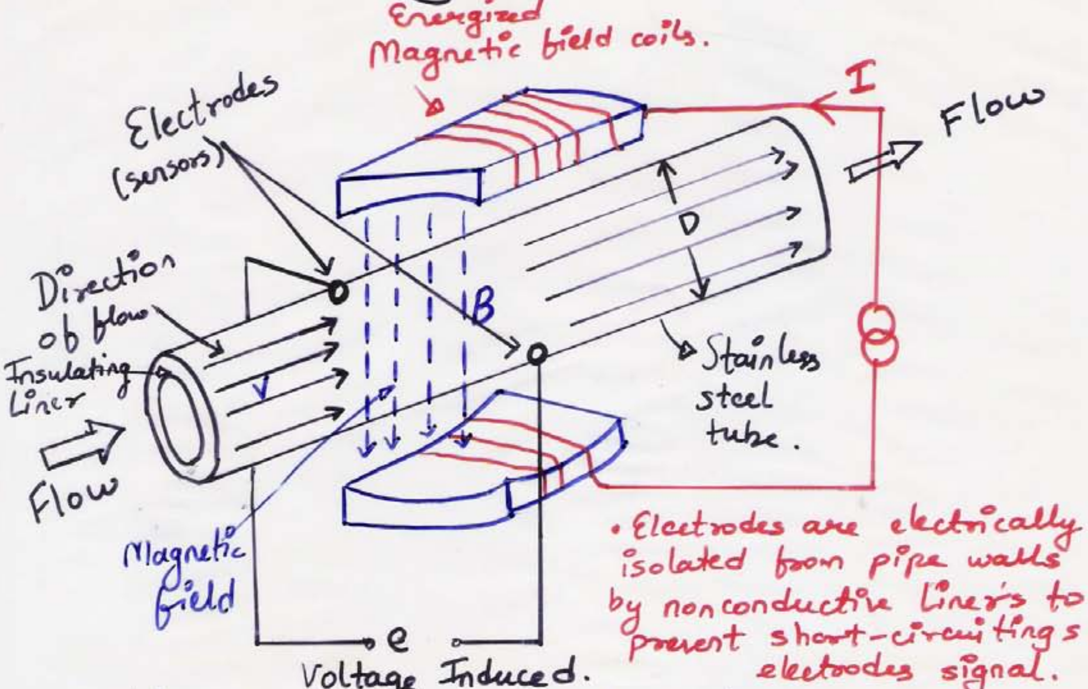


fig Electromagnetic Flowmeters.

- Electromagnetic flowmeters are suitable for measuring volume flow rate of conductive fluids (ie conductivity of fluids should be greater than 10 μmho/cm)
- It works on principle of basic electromagnetic induction ie when a conductor moves along a magnetic field ⊥r to direction of flow, a voltage would be induced ⊥r to direction of movement as also to magnetic field.
- The flowing fluid (liquids) acts like a conductor inside the pipeline. (conductive fluid)
- A magnetic field that is ⊥r to direction of flow is created in the tube by installing energized field coils (magnetic) in diametrically opposite sides.
- The voltage induced is measured by two electrodes inserted on walls of pipeline as shown.

- Ends of electrodes are flush with inner surface of fluid carrying pipe.
- According to faraday's law of induction, the voltage 'e' is induced across the length 'L' of fluid flowing at a velocity 'v' in a magnetic field of flux density 'B' is given by,

$$\boxed{e = BLv} \quad \text{Volts}$$

where, B → Flux density
L → Distance between electrodes or inner diameter of pipe.
v → velocity of fluid flowing in pipe.

Note:- Pipes of electromagnetic flowmeter must be full of liquid at all times for accurate measurements.

Advantages:-

1. It causes no obstruction to flow path.
∴ There is no pressure loss associated with measurement.
2. Absence of any internal part makes it available for measurement of velocity of corrosive and dirty fluids.
3. It gives complete linear o/p in form of voltage.
4. o/p is unaffected by changes in pressure, temperature, fluid density & viscosity of fluid.
5. Flow velocity as low as 10^{-6} m/sec can be measured.
6. No difficulty in measuring either laminar or turbulent flow.
7. Accuracy is around ±1% of indicated flow

Disadvantages:-
- Instrument is expensive as well as installation.
- This flowmeter requires a minimum conductivity of fluids of 10 μmho/cm.
∴ It is not suitable for measurement of flow of gases and liquid hydrocarbon's (oil & petroleum).

- Field excitation for Electromagnetic flowmeters:-

3 possible ways for energizing the magnetic field coils ie a) DC b) AC (50Hz) c) Pulsating DC.

1) DC excitation:-
It will have following difficulties
a) Polarization effect.
b) Electro-chemical effect (small dc current will cause electrolysis ie Oxygen & hydrogen bubbles will be formed & they stick to electrodes surface for some time which will disturb voltage generation process).
c) Thermo-electric effect.
(a), (b) and (c) will affect o/p voltages.

2) AC (50Hz) excitation:-
Field coils can be energized with alternating current of 50Hz.
But disadvantages is o/p is subjected to 50Hz interference voltages.

The problem of DC and AC magnetic field excitation can be solved by energizing the coils with pulsating DC or interrupted DC excitation.

3) Pulsating DC excitation:-
Here, dc field is switched in a square wave fashion between some value and zero at frequency of 3 to 6Hz.

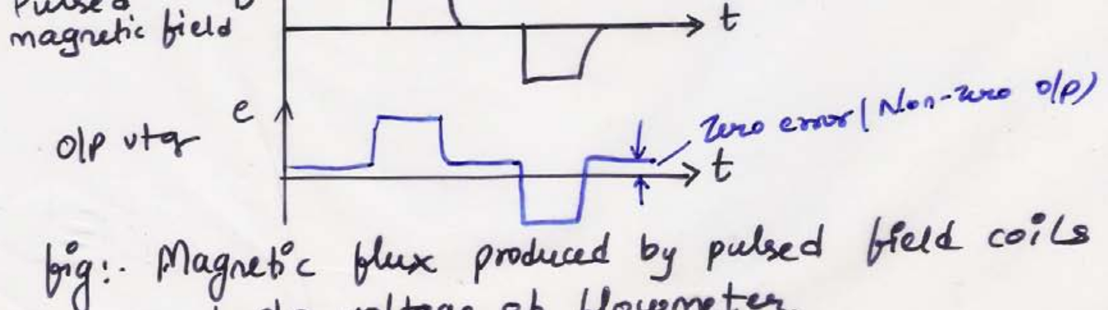


fig:- Magnetic flux produced by pulsed field coils and o/p voltage of flowmeter.

Ultrasonic Flowmeters:

- In markets like waterpower, water sopply, irrigation etc however flow must be measured without any obstructions or any pressure drop.
  This means no moving parts, no secondary devices nor are any restriction's allowed.
- Two types of flowmeters fulfill this requirements Electromagnetic and Ultrasonic flowmeters.
- Whereas, ultrasonic flowmeters can be applied in nearly any kind of flowing liquid, electromagnetic flowmeters requires a minimum electric conductivity of liquid for operation.
- In addition, cost of ultrasonic flowmeters is nearly independent of pipe diameter, whereas price of electromagnetic flowmeter increases drastically with pipe diameter.

Types of Ultrasonic flowmeters:-

Doppler shift — Transit Time

- Both methods depends on transmitting and receiving acoustic (sound waves ie ultrasonic) energy.
- Piezo-electric crystals are used for both T^x & R^x.
- In a T^x, electrical energy in form of short burst of high freq^n voltage is applied to crystal, causing it to vibrate.
- The crystal in contact with fluid, thus vibrations will be communicated (travel) through fluid.

- The vibration finally reaches the receiving crystal which produces electric voltage as an O/P.

⊢ Doppler shift Ultrasonic flowmeters:-

- This type is more popular & less expensive but not as accurate as transit time flowmeters.
- It makes use of Doppler frequency shift caused by sound reflected or scattered from suspensions (suspended particles or bubbles) in the flow path.

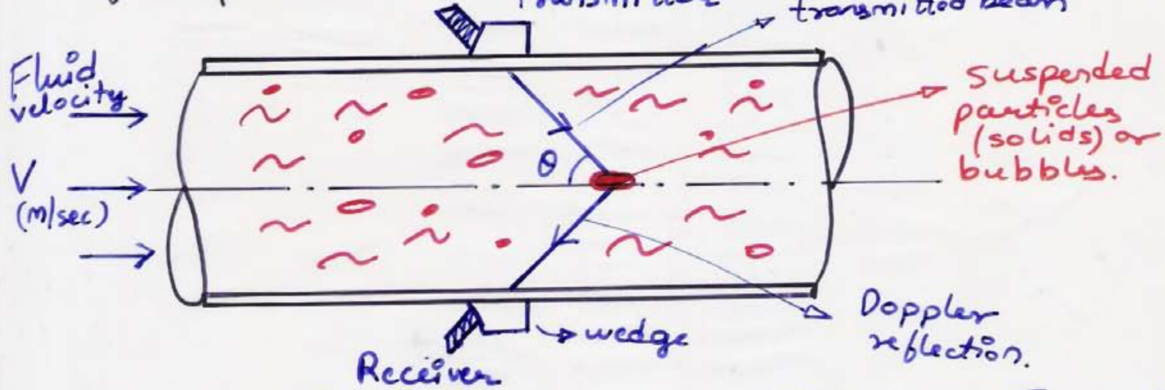


fig:- Doppler frequency shift type Flowmeter

- This instruments are based on Doppler frequency shift phenomena which is used to measure the flow rate of a fluid carrying suspended particles (or air bubbles).
- These flowmeter usually employ clamp on configuration as shown.
- Continuous-wave ultrasonic signal of frequency (0.5 to 10MHz) are generated by piezoelectric crystal oscillator.
- T^{x} propagates these ultrasonic waves in the fluid which is flowing with a uniform velocity V (m/sec).

- The suspended particles or bubbles moving along with fluid flow will reflect these waves. energy to R^x.
- The reflecting elements causes a frequency shift between transmitted and reflected ultrasonic energy waves. which are detected by receiver.
- It can be shown that the frequency shift is proportional to velocity of fluid flow which in turn, is proportional to volume flow rate of the fluid.

Flow velocity (v) is $\boxed{V = \dfrac{c\,(f_t - f_r)}{2 f_t \cos\theta}}$ — (1)

where,

$f_t \rightarrow$ freq^n of transmitted ultrasonic wave.

$f_r \rightarrow$ freq^n of received —"— —"—.

$c \rightarrow$ velocity of sound in fluid being measured.

$\theta \rightarrow$ Angle of incidence and reflected ultrasonic wave with axis of flow in pipe.

- The transmitter T^x and Receiver R^x are made with same piezo-electric oscillator technology.

From eq^n(1), we have $\Delta f = f_t - f_r \rightarrow$ freq^n shift

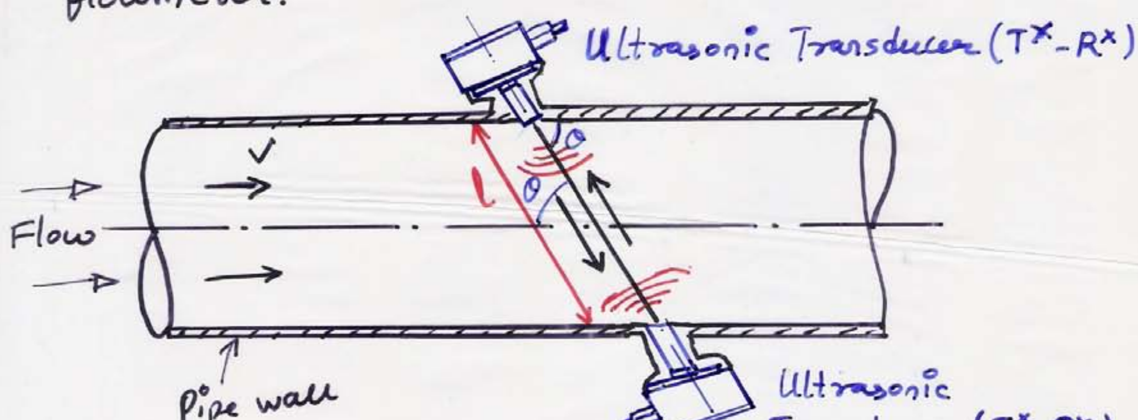
$$\Delta f = f_t - f_r = \frac{2 f_t (\cos\theta)\, v}{c}$$

i.e $\boxed{\Delta f \propto v}$ $\rightarrow$ freq^n shift $\propto$nal to velocity of fluid.

- Measurement accuracy of Doppler type flowmeter depends on flow profile, constancy of pipe wall thickness, no & size of suspended (reflecting) particles and accuracy with which velocity of sound in fluid is known.

Transit Time Ultrasonic flowmeters:-

- It makes use of difference in the time for a ultrasonic pulse to travel a fixed distance, first against the flow and then in the direction of flow. This the principle of transit - time type ultrasonic flowmeter.



- It consists of a pair of ultrasonic transducers mounted at angle 'θ' to pipe wall or fluid flow axis.
- Each transducer consists of Transmitter-Receiver pair.
- When an ultrasonic wave pulses of very short duration are transmitted across the fluid, the velocity of waves ↑ses or ↓ses by fluid velocity depending upon direction of fluid flow (against the flow and in direction of flow).
- Fluid flowing through the pipe causes a time difference between transit times of beams travelling upstream and downstream and measurement of difference in time of travels gives the flow velocity.
- However in actual practice, receipt of ultrasonic pulse is used to trigger the transmission of next ultrasonic energy pulses.

- This type of flowmeter measures the difference in transit times between two ultrasonic pulses transmitted upstream and downstream across the flow.

∴ Forward and reverse transit times of ultrasonic wave pulses across the pipe t_f and t_r are given by,

$$t_f = \frac{l}{c + v\cos\theta}, \quad t_r = \frac{l}{c - v\cos\theta}$$

where, c - velocity of sound in fluid.
v - velocity of fluid.
l - Distance betn 2 ultrasonic transducers.
θ - angle betn ultrasonic beam and axis of fluid flow.

Time difference δt is $\delta t = t_r - t_f = \dfrac{2vl\cos\theta}{c^2 - v^2\cos^2\theta}$

Also, frequencies of forward and return pulses are

$$f_f = \frac{1}{t_f} = \frac{c + v\cos\theta}{l}$$

$$f_r = \frac{1}{t_r} = \frac{c - v\cos\theta}{l}$$

Note: - The transducer comprise the piezo-electric element that converts electric to acoustic (sound) energy.

- $\Delta f = f_f - f_r = \dfrac{2v\cos\theta}{l}$

∴ $v = \dfrac{l\,\Delta f}{2\cos\theta}$ ie $\boxed{v \propto \Delta f}$

∴ measurement is independent of velocity of sound 'c', through fluids

Also, $\boxed{\Delta t = \dfrac{1}{\Delta f} = \dfrac{l}{2v\cos\theta}}$.

- Transit time flowmeter are preferred over Doppler shift for larger pipe diameters.
- Instrument cost is more than a Doppler-shift flowmeter
- Accuracy is good around ± 0.5%

Advantages of Ultrasonic flowmeters:-

- Negligible pressure loss of fluid becoz of very little resistance to fluid flow.
- Provision to clamp on externally on pipe wall without process interruption.
- ∴ They can be installed without pipe cutting or breaking which offers enormous cost advantage.
- Fluid flowing through pipe need not be necessarily conductive fluids.
- It is particularly useful for measuring flow rate of corrosive fluids and slurries.
- It has bi-directional measuring capability, good accuracy, fast response, & wide operating range (-180° to 260°c).
- Has linear calibration curve.
- Suitable for both liquids and gases (streams).
- Measurements are insensitive to viscosity, pressure and temperature variations.
- It's clamp-on mode of operation has significant <u>safety</u> advantage in avoiding the possibility of personnel installing flowmeters coming in contact with hazardous fluids such as toxic, radio-active, flammables ones.

Disadvantages:-

- They are costlier and also are sensitive to velocity profile of flow.