LECTURE NOTES
ON

THEORY OF MACHINES

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CHAPTER-1SIMPLEMECHANISMS

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THEORYOFMACHINE

It deals with the study of relative motion between the various parts of machineand the forces which act on them. Theory of machine may be sub-divided intothefollowingcategories:

- **Kinematics of Machine:** It deals with the relative motion between thevarious parts neglecting the forces which are responsible for producingthesemotions.
- **Dynamics of Machine:** It deals with the forces act on various parts ofmachines. Dynamics of machine may be sub-divided into following twocategories:
  - **Static:** It dealswith the study of forceswhich act on differentpartsofmachineshavingthepartmustbeinrestposition.
  - **Kinetics:** It deals with the inertia forces due tomass and motionofpartsof machine.

KINEMATICLINK

Each part of machine which moves relative to other is called kinematic link orelement. If a link may consist of number of parts connected in such a way thatthey form one unit and have no relativemotionwitheach other. Examplepiston, piston rod and cross head of engine constitute one unit and behave likesingle link. On the other hand cross head, connecting rod, frame of engine aredifferentlinks.

TypesofLinks

- **Rigid link:** A rigid link is one which does not undergo any deformationwhile transmitting motion.In actual practice, no link is perfectly rigid,butforourconveniencewemaytakeconnectingrod,cranketc.asrigid.
- **Flexible Link:** A flexible link is that which, while transmitting motion ispartlydeformedinsuchamannerthattransmissionisnotaffected.
- **Fluid Link:** It is formed by having fluid in a container and motion istransmitted through fluid by pressure. E.g. hydraulic Jack, hydraulic pressetc.

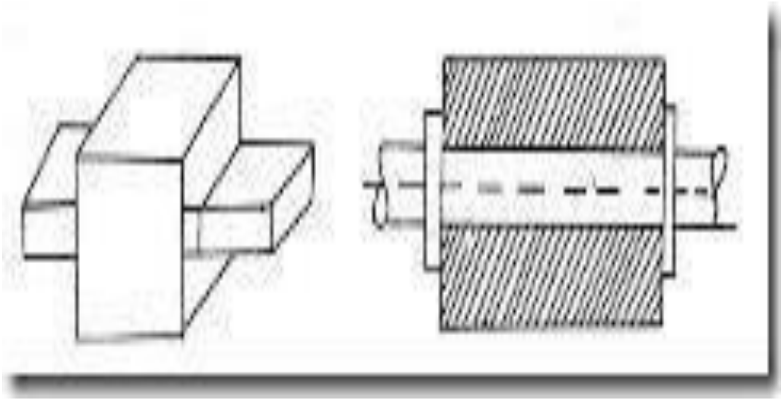
KINEMATICPAIR

A pair isformed when there isa contact between two links of machine, butwhen there is relative motion between the two links, then it is called kinematicpair.Therelativemotionbetweenthetwolinksmustbecompletelyorsuccessfullyconstrainedtomakerequiredpair.ExamplesareCylinderandpiston,pistonandconnectingrodetc.

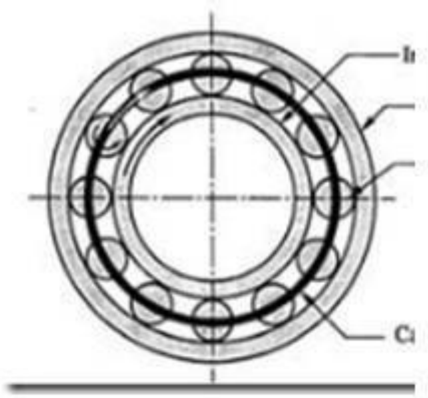
Typesofkinematicpairs:

(i) Basedonnatureofcontactbetweenelements:

(a) **Lowerpair:**Ifthejointbywhichtwomembersareconnectedhassurface contact, the pair is known as lower pair. Eg. pin joints, shaftrotatinginbush,sliderinslider crankmechanism.

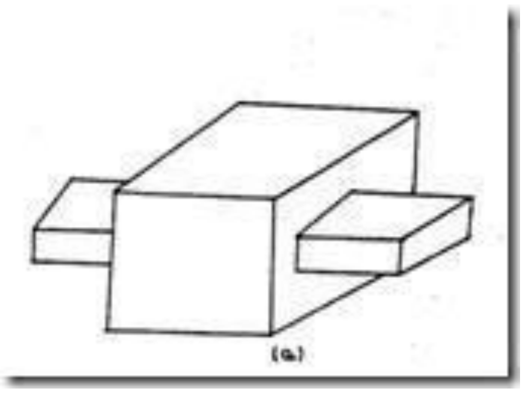


(b) **Higherpair:**Ifthecontactbetweenthepairingelementstakes placeat a point or along a line, such as in a ball bearing or between two gearteethincontact,itisknownasahigherpair.

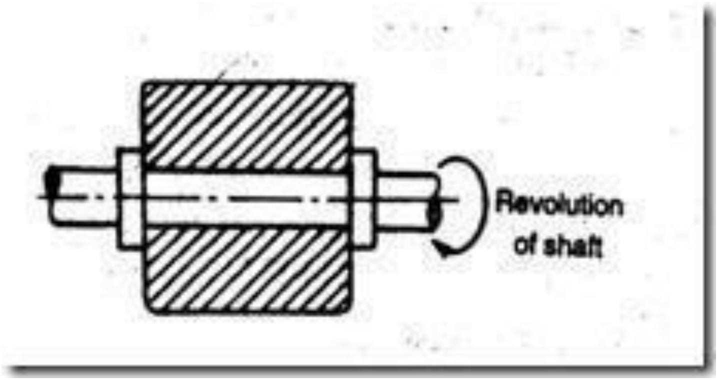


(ii) Basedonrelativemotionbetweenpairingelements:

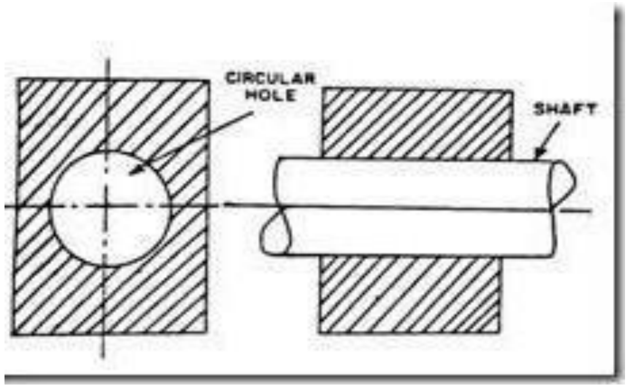
(a) **Sidingpair:**Slidingpair isconstitutedbytwoelementssoconnectedthatoneisconstrainedtohaveas lidingmotionrelativetotheother.



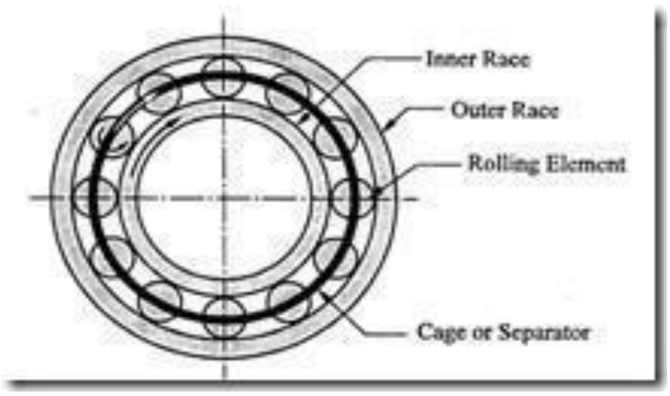
(b) **Turning pair**: When connections of the two elements are such thatonlyaconstrainedmotionofrotationofoneelementwithrespecttothe otherispossible,thepairconstitutesaturningpair.



(c) **Cylindricalpair:**Iftherelativemotionbetweenthepairingelementsis the combination of turning and sliding, then it is called as cylindricalpair.

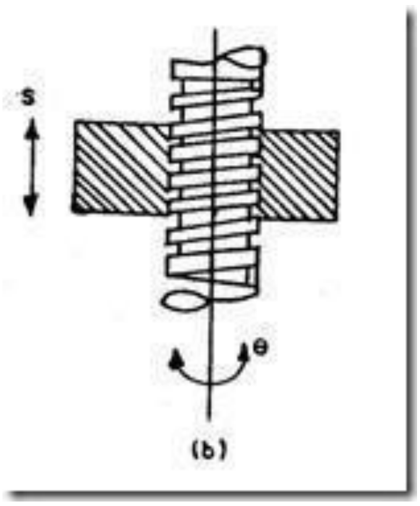


(d) **Rollingpair:**Whenthepairingelementshaverollingcontact,thepairformediscalledrollingpair.E.g.Bearings,Beltandpulley.



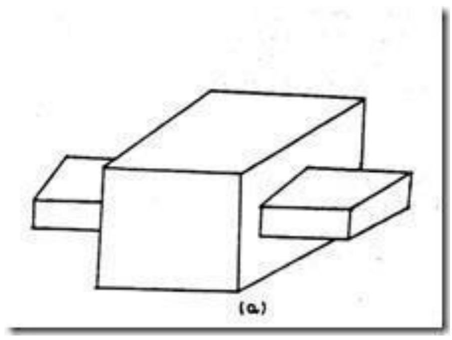
(e) **Sphericalpair:**Asphericalpairwillhavesurfacecontactandthreedegre esoffreedom.Eg.Balland socketjoint.DOF=3

(f) **Helical pair or screw pair:** When the nature of contact between theelementsofa pairissuchthatoneelementcanturnaboutthe otherbyscrewthreads,itisknownasscrewpair.

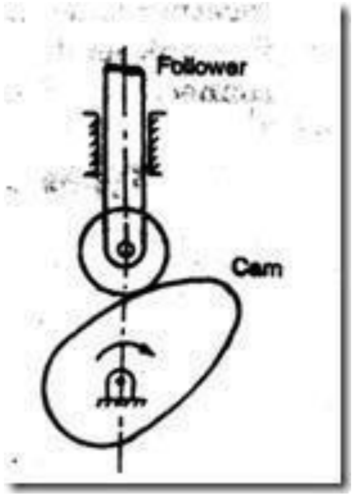


(iii) Basedonthenatureofmechanicalconstraint.

(a) **Closedpair:**Elementsofpairsheldtogethermechanicallyduetotheirgeometry constitute a closed pair. They are also called form-closed or self-closed pair.



(b) **Unclosed or force closed pair**: Elementsof pairsheld together by theaction of external forces constitute unclosed or force closed pair .Eg. Camandfollower.



CONSTRAINEDMOTIONANDITSTYPES

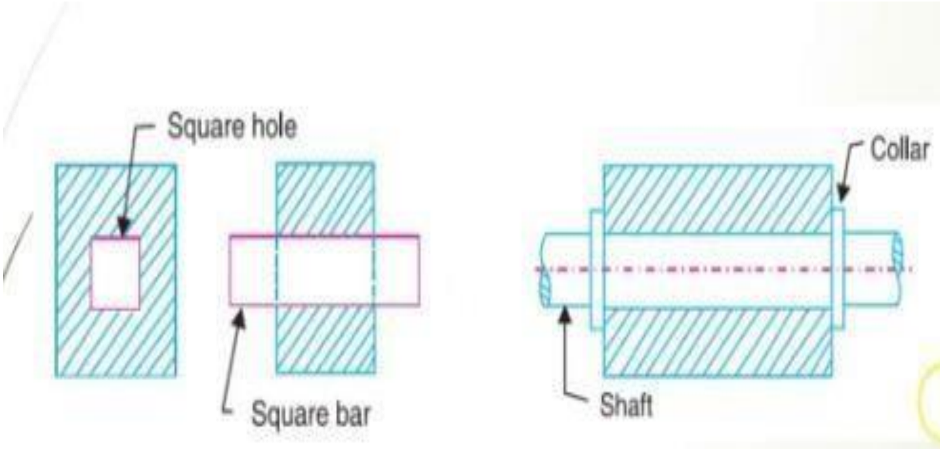
Constrainedmotion resultswhen an objectisforcedtomovein arestrictedwayi.e.movesindefinitedirection.

Constrainedmotion(orrelativemotion)canbebroadlyclassified intothreetypes:

1. Completelyconstrained motion
2. Incompletelyconstrainedmotion
3. Partially(orsuccessfully)constrained motion

1. Completelyconstrainedmotion:

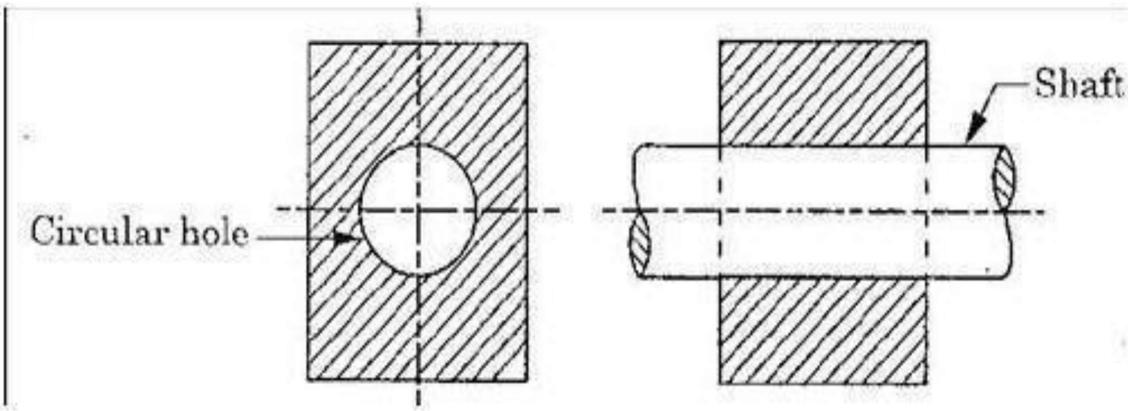
Completely constrainedmotion is a type of constrainedmotion in whichrelative motion between the links of a kinematic pair occurs in a definitedirection by itself, irrespective of the external forces applied. E.g. Square barinasquareholeundergoescompletelyconstrainedmotion



Evenwhenanyexternalforceisapplied,
asquarebaralwaysslidesinsideasquarehole.It doesnot turn.

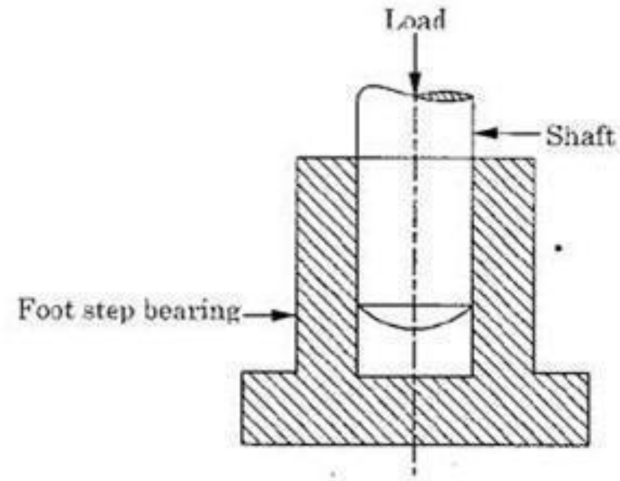
2. Incompletelyconstrainedmotion:

In incompletely constrained motion, the relative motion between the linksdepends on the direction of external forcesacting on them. A good exampleof incompletely constrained motion is the motion of a shaft inside a circularhole. Depending on the direction of external forces applied, the shaft mayslide or turn (or do both) inside the circular hole. Incompletely constrainedmotionisundesirableinanymechanicalsystem.Itleadstoimproperme chanicaloutputs.



3. Partially(orsuccessfully)constrainedmotion:

A kinematic pair is said to be partially or successfully constrained if therelative motion between its links occurs in a definite direction, not by itself,butbysomeothermeans.Agoodexampleofsuccessfullyconstrainedmotion is piston reciprocating inside a cylinder in an internal combustionengine. Normally, when a piston is placed in a cylinder, it may undergoreciprocating motion (upward and downward motion) and turning motion,dependingonthe externalforcesapplied.Itisincompletelyconstrained.



KINEMATICCHAIN:

It is combination of kinematics links in such a way that the relative motionbetween the links is completely or successfully constrained and the last link isconnectedtothefirst link.

Thefollowingrelationshipsholdgood forakinematicchain:

$$l=2p-4$$
$$j=\frac{3}{2}l-2$$

Where,

l= Numberoflinks

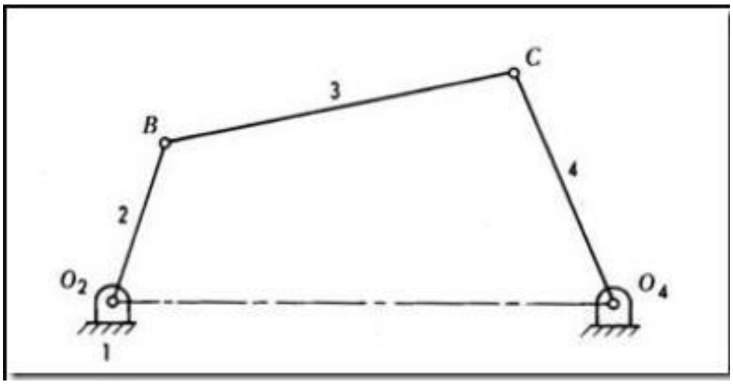
j=Numberofjoints

p=Numberofpairs

TypesofKinematicChain

1) FourBarChain
2) SliderCrankchain
3) DoubleSliderCrankChain

1.)FourBarChain: Itismade offourrigidlinkswhichareconnectedtoformaquadrilateralbyfourpin-joints.

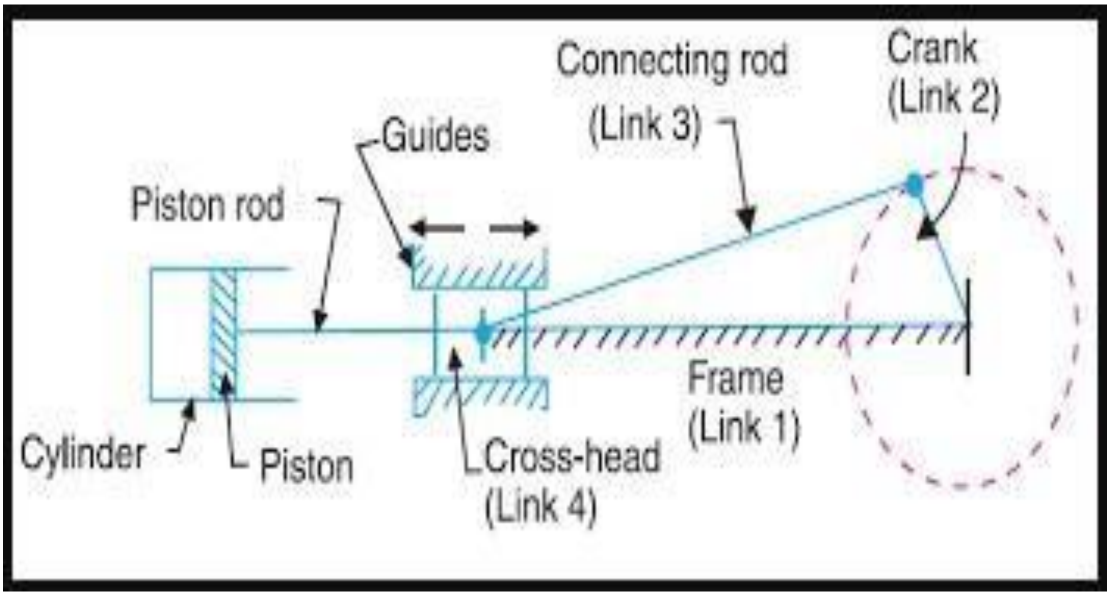


LinkO_2O_4isfixedandknownasframe,linkO_2Brotateandiscalledcrank.ThelinkBC iscalledcouplerandlink CO_4iscalledlever.

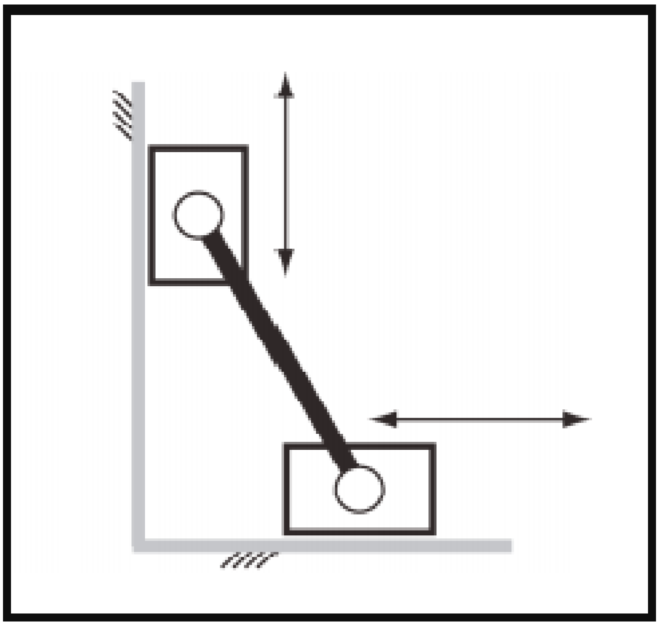
ApplicationsofFourBarChain:

1) BeamEngine
2) CoupledWheeloflocomotive
3) Engineindicator

2.) SliderCrankChain: Itisafourbarchainhavingoneslidingpairandthree turning pairs. This mechanism is used to convert reciprocatingmotionofpistonintorotarymotionofcrank.



3.)DoubleSlider CrankChain: Afourbarchainwithtwoturningpairs andtwoslidingpairsisknownasdoubleslidercrank chain.



MECHANISM

It is an assembly of a number of resistant links which are connected in such awaythattheyhavecompletelyorsuccessfullyconstrainedrelativemotionbetweenthemandmechanismisobtainedbyfixingoneofthelinksofkinematicchain.

A mechanism which has up to four links with lower pairs is called Simplemechanism.

Amechanismwithmorethanfourlinksistermedascompoundmechanism.

MACHINEANDSTRUCTURE

Machine: A machine is a device which receives energy in some available formandusesittodosomework.Thereexistsarelativemotionbetweenitsparts.

E.g.lathe,shaperetc.

Structure: It is an assembly of various parts which having no relative motionbetween them and use to take up loads having straining actions. There exists norelativemotionbetweenitsparts.E.g.roof,trusses,buildingsetc.

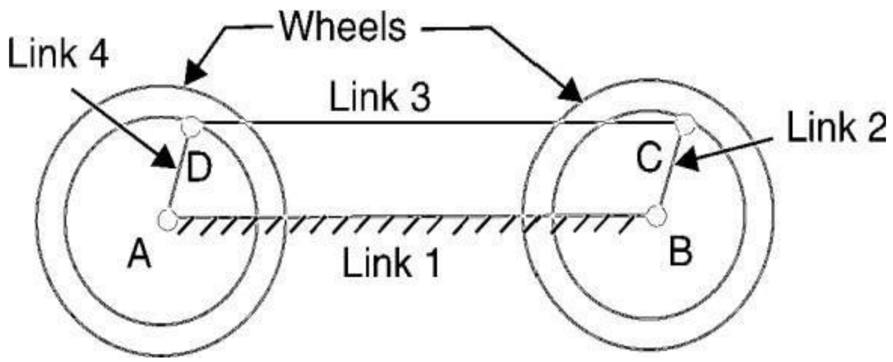
INVERSION:

As a mechanism is obtained by fixing one of the link of kinematic chain. If anyotherlinkofthemechanismisfixedinsteadoftheoriginalone,thenewmechanismobtainediscalledinversionofmechanism.Hence,differentinversions can be obtained by fixing different links rather than original one. e.g.a slider crank chain become an oscillating cylinder mechanism if the connectingrod isfixed and apendulumpumpiftheslderblockisfixed.

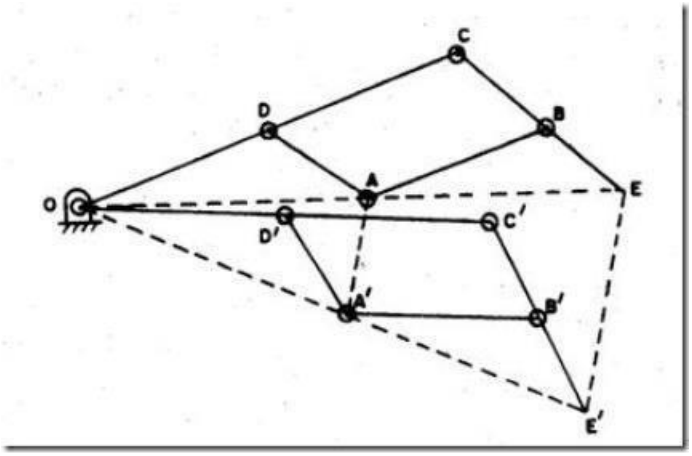
INVERSIONSOFKINEMATICCHAIN:INVERSIONOFFOUR BAR CHAIN, COUPLED WHEELS OF LOCOMOTIVE& PANTOGRAPH. INVERSION OF SINGLE SLIDER CRANKCHAIN- ROTARY I.C. ENGINES MECHANISM, CRANK ANDSLOTTEDLEVERQUICKRETURNMECHANISM.INVERSION OF DOUBLE SLIDER CRANK CHAIN- SCOTCHYOKEMECHANISM&OLDHAM'SCOUPLING.

INVERSIONOFFOURBARCHAIN

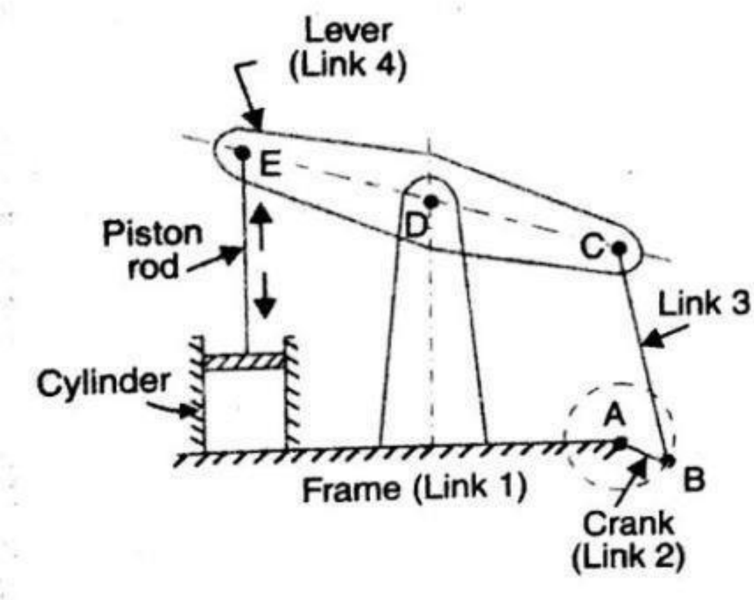
1) **Coupledwheelsoflocomotive:**Thismechanismisusedtotransmitrotary motion of one wheel to another wheel. In this link 1 is fixed andlinks2&4areofequallengthsandactasCrank.Link3actasconnecting rod.



2) **Pantograph:** It is a mechanicallinkage connectedinamannerbasedon parallelograms so that the movement of one pen, in tracing an image,produces identical movements in a second pen. If a line drawing is tracedby the first point, an identical, enlarged, or miniaturized copy will bedrawn by a pen fixed to the other. Using the same principle, differentkinds of pantographs are used for other forms of duplication in areas suchassculpture,minting,engraving,andmilling.



3) **Beam Engine:** It consists of four links. When the link 2 i.e. crank isrotated about point A then link 4 i.e. lever oscillates about point D. Thismechanismis usedtoconvertrotarymotionintoreciprocatingmotion.

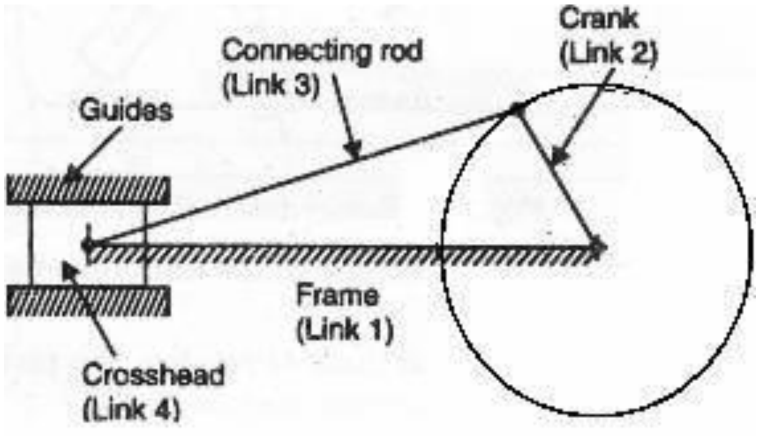


INVERSIONOFSINGLESLIDERCRANKCHAIN

1) RotaryI.C.EnginesMechanism

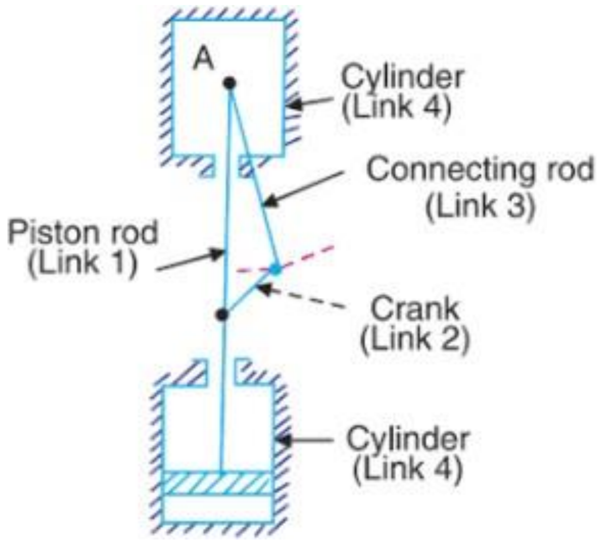
A single slider crank chain is a modification of the basic four-bar chain. Itconsist of one sliding pair and three turning pairs. It is, usually, found inreciprocating steam engine mechanism. This type of mechanism convertsrotarymotionintoreciprocatingmotionandviceversa.Inasingleslider crank chain, as shown the links 1 and 2, links 2 and 3, and links 3 and 4 formthreeturningpairswhilethelinks4 and1formaslidingpair.

Link 1 corresponds to the frame of the engine, which is fixed. The link 2corresponds to the crank; link 3 corresponds to the connecting rod and link 4corresponds to cross-head. As the crankrotates, the cross-head reciprocatesintheguidesandthusthepistonreciprocatesinthecylinder.



2) Bullengineorpendulumengine:

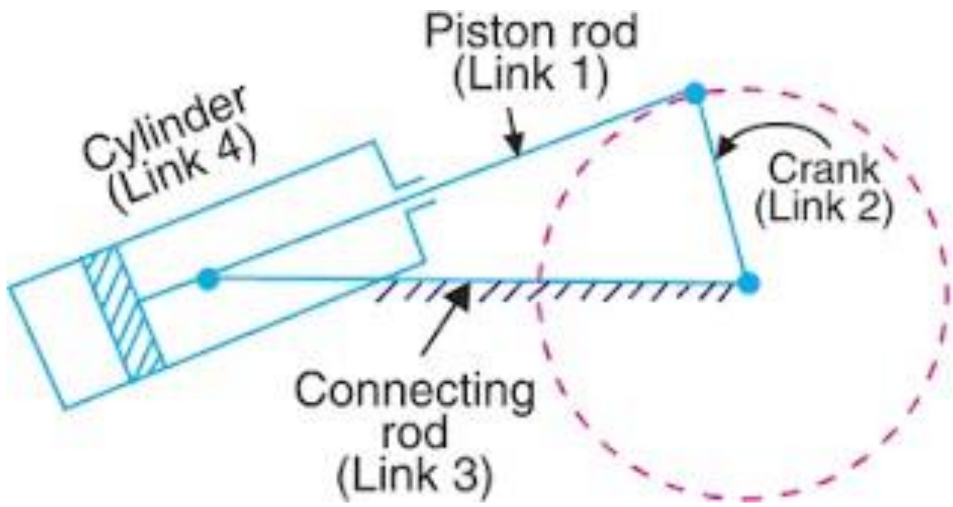
In this mechanism, the inversion is obtained by fixing the cylinder or link 4(i.e. sliding pair), as shown in Fig. In this case, when the crank (link 2)rotates, the connecting rod (link 3) oscillates about a pin pivoted to the fixedlink 4 at A and the piston attached to the piston rod (link 1) reciprocates. Theduplex pump which is used to supply feed water to boilers have two pistonsattachedtolink 1,asshowninFig.



PendulumEngine

3) OscillatingCylinderEngine

The arrangement of oscillating cylinder engine mechanism, as shown in Fig.isusedtoconvertreciprocatingmotionintorotarymotion.Inthismechanism, the link 3 forming the turning pair isfixed.Link 3 correspondsto the connecting rod of a reciprocating steam engine mechanism. When thecrank(link2)rotates,thepistonattachedtothepistonrod(link1)reciprocates and the cylinder (link 4) oscillates about a pin pivoted to thefixedlinkatA.

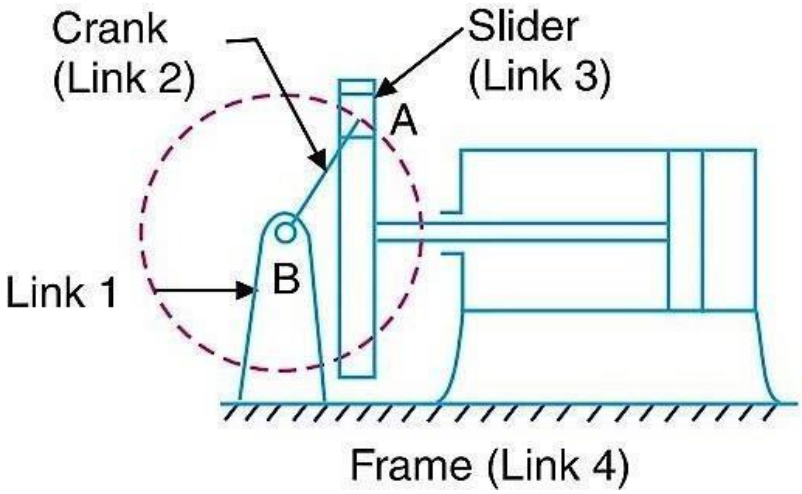


Oscillatoryengine

INVERSIONOFDOUBLESLIDERCRANKCHAIN

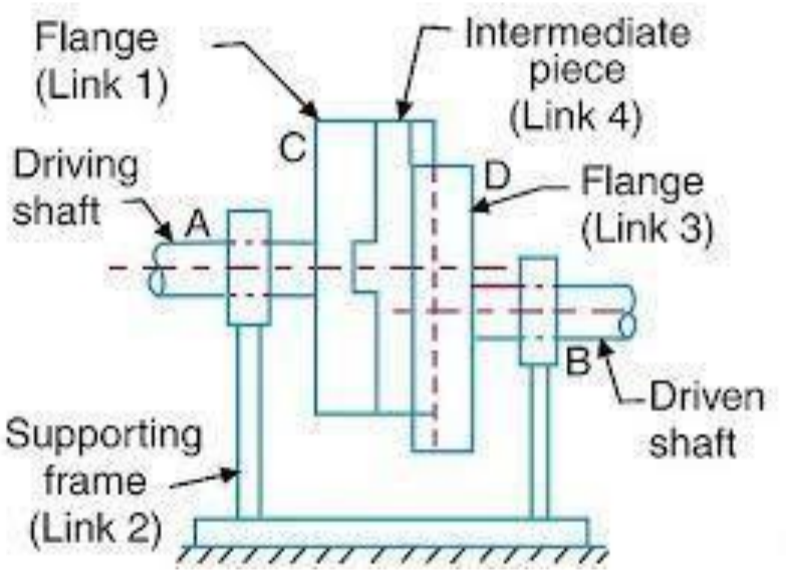
1) ScotchYokeMechanism

In this mechanism, one of the sliding block is fixed. Rotary motion is givento crankaboutthefixedblock.



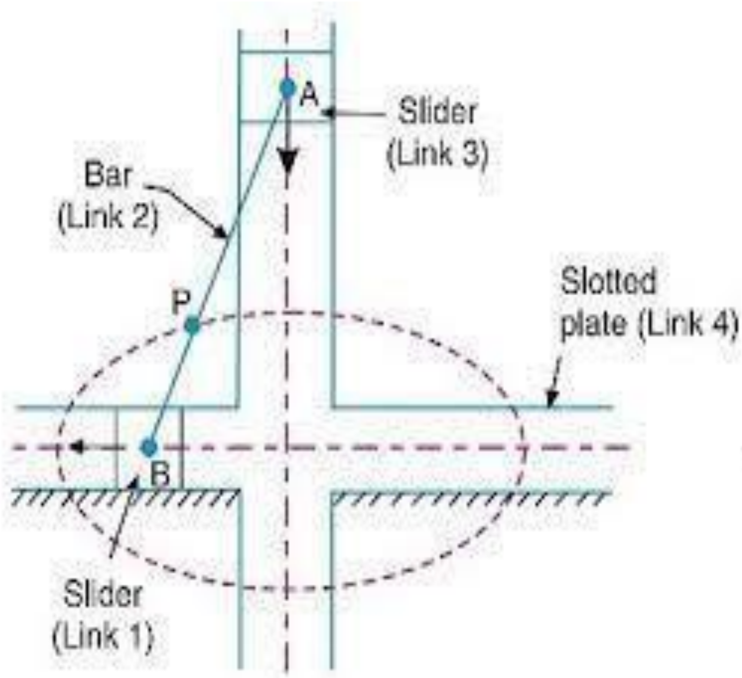
2) Oldham’sCoupling

It meansfor transmissions of power from one shaft to another shaft parallelto each other when the distance between the two axes is small and variable.The shafts are connected in such ways that if one rotate, other shaft rotates atsamespeedandinthesamedirection.



3) EllipticalTrammel

It is a device used for drawing ellipse. It has two grooves cut at right angle ina fixed plate.In the grooves,two sliding blocksare fitted.The link 2 joinstheslidingblocks,oronits extensiontracesoutanellipseonthefixedplate.



CHAPTER-
2POWERTRANSMISSION

INTRODUCTIONTOBELTANDROPEDRIVE

Power is transmitted from one shaft to another shaft by means of ropes, belts,chain and gears. For long distance belts, ropes or chain is used while for smalldistancegearsareused.

Belt: The Flexible wrapping connectors are used to transmit power from oneshaft to another shaft. When the wrapping connector takes the form of band,whosethickness issmallincomparisontowidth iscalledbelt.

Rope: The Flexible wrapping connectors are used to transmit power from oneshaft to another shaft. If the cross section of wrapping connector is circular thenit iscalledRope.

The belt and rope must be kept in tension so that the motion is transmittedwithout any slip. Due to slipping and straining action belt and ropes are notpositivetypesofdrivesastheirvelocityratioisnot constant.
In case of belt drive either flat or grooved pulley are used while in case of ropedrivegroovedpulleyisused.

TYPESOFBELTS

- **Flat Belt:** A belt having rectangular cross section is known as flat belt. Itismostly used for power transmission at a distance not more than 8meters.

- **V- Belt:** A belt having trapezoidal cross section is known as V - belt. It ismostly used for power transmission when two pulleys are close to eachother. To take advantage of wedge cross section grooved pulley is used.Due toitswedgingactionitcantransmitmorepowerthan flatpulley.\

- **Circular Belt:** It is also known as Rope. A belt having circular crosssection is known as flat belt. It is mostly used for power transmission at adistancemorethan8meters

MATERIALSUSEDFORBELTS

Thematerialsusedforbelts mustbestrong,flexibleanddurable.Itshouldhaveahighcoefficient offriction.Thevariousmaterialsusedare:

- **Leather:** The leather may be oak-tanned or mineral salt tanned ex:Chrometanned.Whenthethicknessofthebeltrequired ismorethan,twoor more strips are cemented together. Leather belts require periodiccleaning.

- **Fabric:**Fabricbeltsaremadebyfoldingcanvasorcottonducksisalayer(dependingontherequiredthickness)andstitchingtogether.

- **Rubber:**ThebeltsaremadeofFabricwitharubberlayer.Theseareusedinsawmills,papermills,etc.

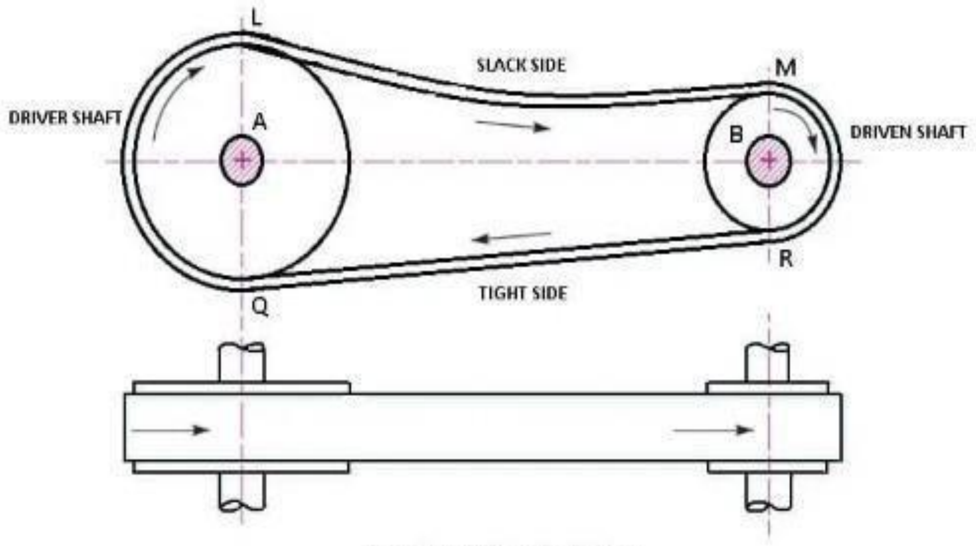
- **Balata:** The belts are made out of these materials are similar to rubberbeltsexpectthatbalatagymisusedinsteadofrubber.Thebeltsofthese materials are acid and waterproof but cannot be used where thetemperatureisabove45°.

TYPESOFBELTDRIVE

Thefollowingarethefivemaintypes ofBeltDrives**:**

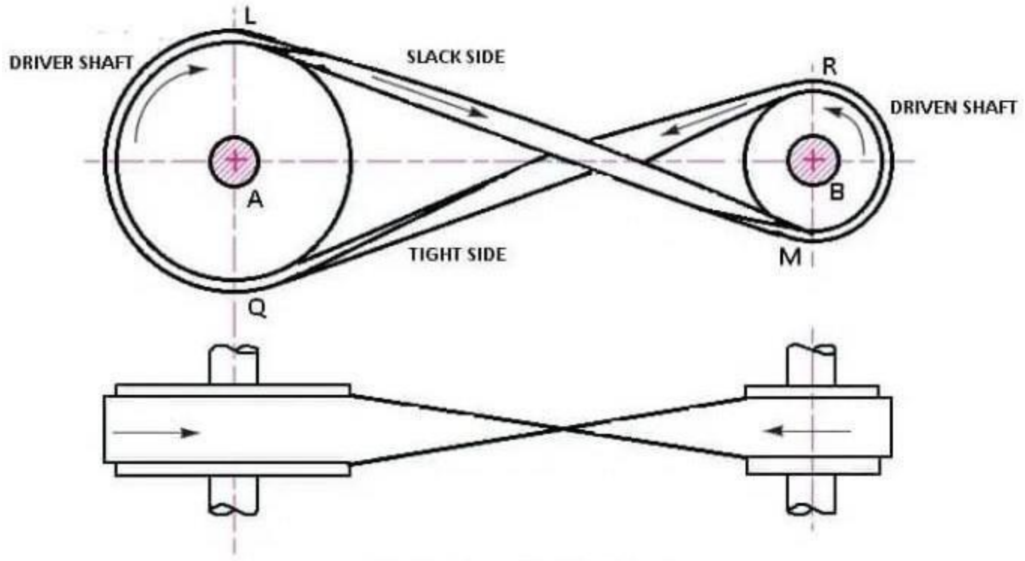
- Openbeltdrive.
- Crossbeltdrive.
- Steppedconepulleyorspeedconedrive.
- Fastandloosepulleys.
- Jockeypulleydrive.

Open Belt drive: In these types of belt drive, the belt is employing when thetwo parallel shafts have to rotate in the same direction. When the shafts are farapart, the lower side of the belt should be the tight side and the upper side mustbe the slack side. . It is mostly used for power transmission at a distance notmorethan8meters



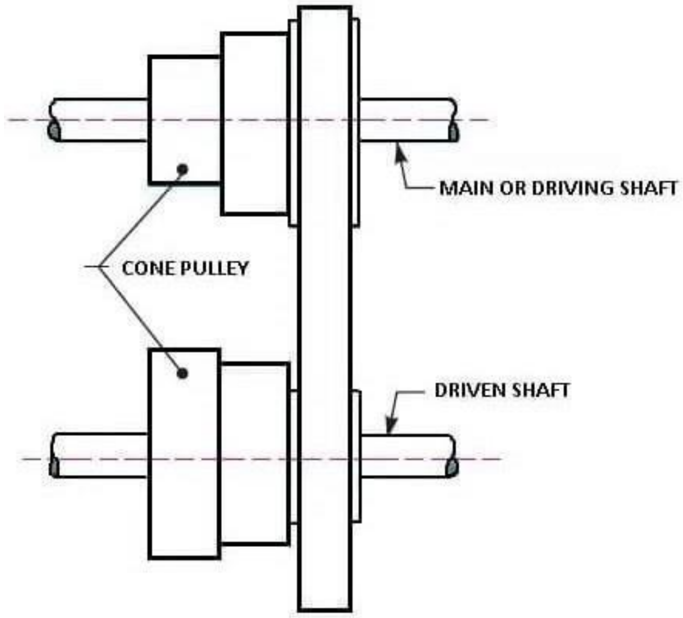
OPEN BELT DRIVE

Crossed belt drive: This type of belt drives, the belt is employing when twoparallel shafts have to rotate in the opposite direction. At the junction where thebelts cross, it rubs against itself and wears off. To avoid excessive wear, theshafts must be placed at a maximum distance from each other and operated atverylowspeeds.



CROSS BELT DRIVE

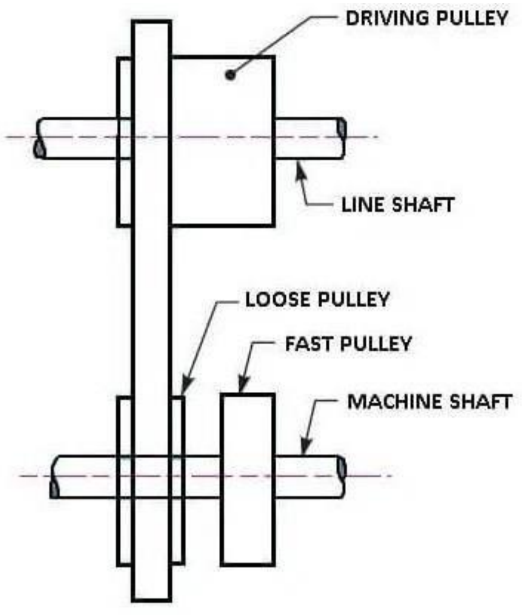
Steeped Cone Pulley or speed cone drive: This type of belt drives are usedwhen the speed of thedriven shaft isto bechanged very frequently asin thecaseofmachinetoolssuchaslathe,drillingmachine,etc.



STEPPED OR SPEED CONE PULLEY

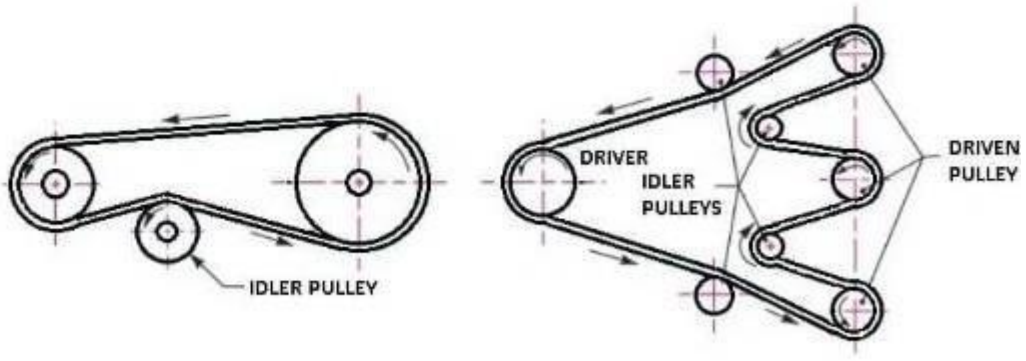
A steppedconepulley isan integral casting having three or numberof pulleysof different sizes one adjacent to the other. One set of stepped cone pulley ismounted in reverse on the driven shaft. An endless belt will be wrapped aroundone pair of pulleys. By shifting the belt from one pair of pulleys to the other, thespeed of the driven shaft can be varied. The diameter of the driving and drivenpulleys is such that the same belt will operate when shifted on different pairs ofpulleys.

Fast and Loose Pulley: This types of belt drives are used when the driven ormachine shaft is to be started or stopped whenever desired without interferingwith the driving shaft. A pulley which is keyed to the machine shaft is called afast pulley and run at the same speed as that of themachine shaft. A loosepulley runs freely over the machine shaft and is incapable of transmitting anypower. When the driven shaft is required to be stopped, the belt is pushed on totheloosepulleybymeansofaslidingbarhavingbeltforks.



FAST AND LOOSE PULLEY DRIVE

Jockey Pulley drive: In an open belt drive arrangement, if the center distance issmall, or if the driven pulleys are very small, then the arc of contact of the beltwith the driven pulley will be very small, which reduces the tensions in the belt,or if the required tension of the belt cannot be obtained by other means, an idlerpulley,calledjockeypulleyisplacedontheslacksideofthebelt.Withincreases the arc of contactand thus the tension which results in increasedpowertransmission.



JOCKEY PULLEY DRIVE

CONCEPTOFVELOCITYRATIO,SLIPANDCREEP;CROWNINGOFPULLEYS(SIMPLE NUMERICALS)

VELOCITYRATIO

Itisthe ratioofspeedofthe drivenpulleytothatofdrivingpulley.Linear Speedofdriver pulley=πD_1N_1

Linear Speedofdrivenpulley=πD_2N_2

Neglectingthicknessofbeltandalsothereisnoslipbetweenbeltandpulley,then

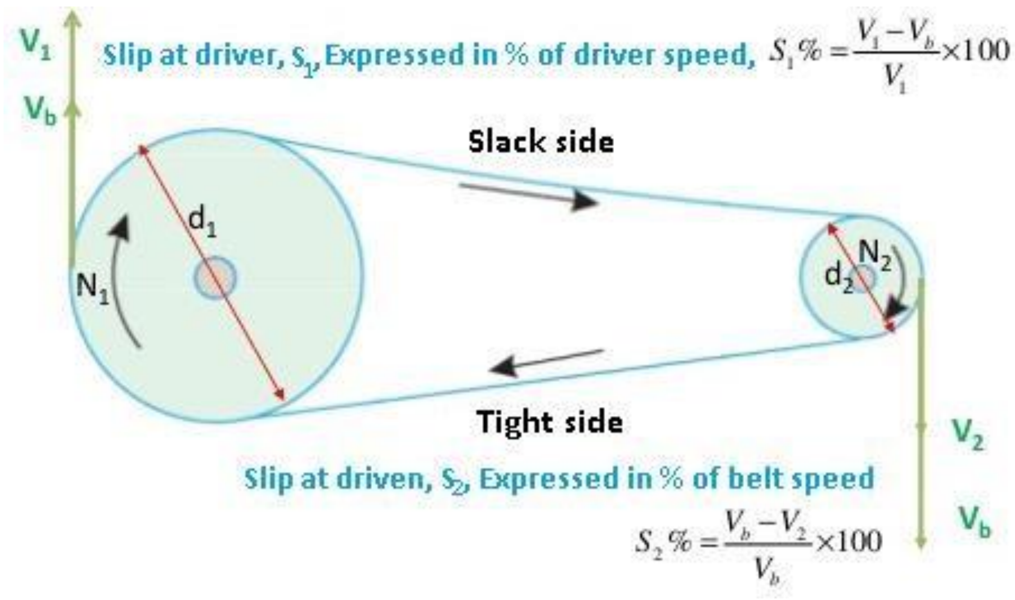
$$\textbf{Velocity Ratio}=\frac{N2}{N1}=\frac{D1}{D2}$$

Ifwe consideringthethicknessofthe belt(t)

$$\textbf{VelocityRatio}=\frac{N2}{N1}=\frac{D1+t}{D2+t}$$

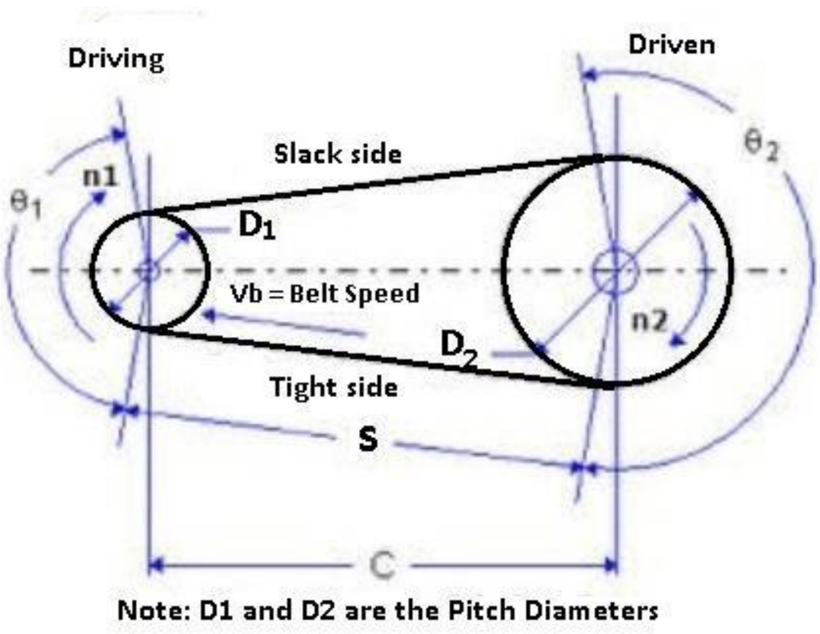
SLIP

If the difference in tension between tight and slack sides if belt is too large to beresisted by friction between the belt and the pulley, then whole portion of beltwhich is in contact with the pulley begins to slide. When this frictional gripbecomesinsufficient,thereisapossibilityofforwardingmotionofdriverwithout pulley with it, this is known as the slip in a belt. Therefore slip may bedefined as the relative motion between the pulley and the belt in it. This reducesthevelocityratioand usuallyexpressedin%and itisdenotedbyS.



CREEPINBELT

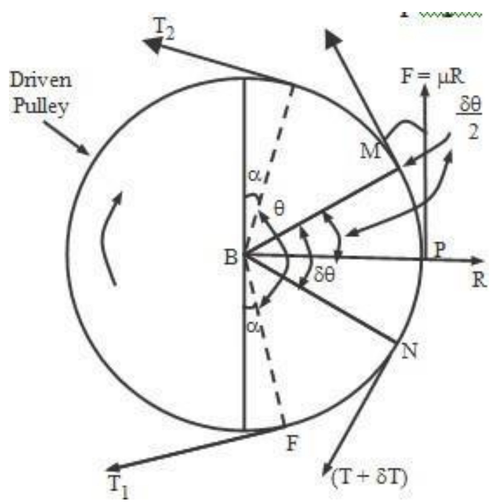
During rotation, there is an expansion of a belt on a tight side and contraction ofthe belt on the slack side. Due to this uneven expansion and contraction of thebelt over the pulleys, there will be a relative movement (motion) of the belt overthepulleysthisphenomenonisknownasCreepinabelt.



FLAT AND V BELT DRIVE: RATIO OF DRIVINGTENSIONS,POWERTRANSMITTED,CENTRIFUGALTENSIONANDCONDITIONFORMAXIMUMHORSEPOWER (SIMPLENUMERICALS)

RATIOOFDRIVINGTENSION

RatioofDrivingTensionforFlatBelt: Letusconsideradrivenpulleyrotatinginclockwisedirectionasshowninfigure:



Let,

T_1= Tension in belt on the tight

sideT_2=Tensioninbeltontheslackside

θ=Angleofcontact

μ=Coefficientoffrictionexistingbetweenbeltandpulley.α=An

gleof Lap

Considerdrivenorfollowerpulley.BeltremainsincontactwiththeEBF.Let$T_1$and

T_2arethetensionsintightsideand slack side.

Angle EBFknownasangle ofcontact= ∏.-

2αConsider drivenorfollower pulley.

Belt remains in contact with the NPM. Let $T_1$and $T_2$are tensions in tightside and slack side. Let T be tension at point M & (T + dT) be the tension atpoint N.

ConsiderequilibriuminhorizontalReaction'R'andverticalreactionμR.Sincethe wholesystemisinequilibrium,thatis

ΣV = 0; Tsin (90 - δq/2) + μR - (T + δT)sin(90 - δθ/2) =

0Tcos(δθ/2)+μR=(T+δT)cos(δθ/2)

Tcos(δθ/2)+μR=Tcos(δq/2)+δTcos(δθ/2)μR=

δTcos(δθ/2)

Since δθ/2 is very small and cos0° = 1, So cos(δθ/2) =

1μR= δT ...(*i*)

ΣH=0;

R-Tcos(90-δq/2)-(T+δT)cos(90-δθ/2)=0

R=Tsin(δθ/2)+(T+δT)sin(δθ/2)Asδθ/2issmallSosin(δθ/2)=δθ/2R=T(δθ/2

)+T(δθ/2)+δT(δθ/2)R=T.δθ+δT(δθ/2)

As δT(δq/2) is very small So δT(δq/2) =

0R= T.δq ...(*ii*)

Puttingvalueof(*ii*)inequation(*i*)μ.T

.δθ=δT

or,$\delta T/T=\mu.\delta\theta$

Integratingboththeside:,Whereθ= Totalangleofcontact

$$\int_{T_2}^{T_1} \delta T/T = \mu \int_0^0 \delta\theta,$$

$\ln(T_1/T_2)=\mu$

$$\frac{T1}{T2}=\mathbf{e}^{\mu.\theta}$$

Thus,Ratio ofbelttension= $\frac{T1}{T2}$ $=\mathbf{e}^{\mu.\theta}$

Ratioof DrivingTensionforV-Belt

Let

RN=Normalreactionbetweenbeltandsides

withagroovedpulley.2α=Angleof groove

μ=Co-

efficientoffrictionbetweenbeltandpulleyR=Totalreac

tionintheplaneofgroove.

Resolvingtheforcesvertically,

We get $R = R_N\sin\alpha + R_N\sin\alpha = 2R_N\sin$

$\alpha R_N=(R/2)\ \mathrm{cosec}\alpha$ ......(i)

Frictionalresistance= $\mu R_N+\mu R_N=2\mu R_N=2\mu(R/2)\mathrm{cosec}\alpha$

$= \mu R\ \mathrm{cosec}\alpha = R\mu\mathrm{cosec}\ \alpha$

So,RatioofTensioninV-Belt: $\frac{T1}{T2}=\mathbf{e}^{\mu.\theta.\mathrm{cosec}\alpha}$

POWERTRANSMITTEDBYABELT

Let,

T_1= Tension on tight side of

BeltT_2=TensiononslacksideofBelt

v=Linearvelocityofbelt

P= Powertransmitted byBelt

$$\mathbf{P=(T_1-T_2)v}\text{ Watt}$$

CENTRIFUGALTENSION

When the belt continuously moves over the pulley, the centrifugal force due toits own weight tends to fit in from the pulley. This centrifugal force produceequal tensions on tight side and slack side of the belt is known as Centrifugaltension.

Considera shortelementofbelt.

Let

m=mass perunitlengthofbelt

T_c=centrifugaltensionontightandslacksides

ofelementF_c=centrifugalforceontheelement

r=radius

ofthepulleyv=

velocityofthe belt

δθ=angleoflapoftheelementoverthepulley

F_c=massofelementxacceleration

=(lengthofelementxmassperunitlength)xacceleration

$=(r\delta\theta \times m)\times\frac{v^2}{r}$

$=mv^2\delta\theta$ (i)

Also,

$$F_c=2T_c\sin\frac{\delta\theta}{2}$$

Asδθissmall,

$$\sin\frac{\delta\theta}{2}\approx\frac{\delta\theta}{2}$$

$$F_c= 2T_c\frac{\delta\theta}{2}$$

$$F_c=T_c\delta\theta \qquad \text{(ii)}$$

From(i)and(ii)

$Tc\ \delta\theta =$

$mv^2\delta\theta$Or **$Tc=mv^2$**

Thuscentrifugaltensionisindependentofthetightandslacksidetensionsanddepends onlyonthevelocityofthebelt over thepulley.

CONDITIONFORMAXIMUMPOWERTRANSMISSION

Ifitisdesiredthatabelttransmitsmaximumpossiblepower,twoconditionsmust befulfilledsimultaneously.Theyare:

1. Largertensionmustreachthemaximumpermissiblevalueforthebelt
2. Thebeltshouldbeonthepointofslipping,i.e.maximumfrictionalforceisdevelope d inthebelt.

Let,

T1 = Tension on tight side of

BeltT_2= Tension on slack side of

Beltv=Linearvelocityofbelt

P=PowertransmittedbyBelt

$$P = (T_1 - T_2).\ V \qquad ...(i)$$

But we know that $T_1/T_2 = e^{\mu\theta}$

Or we can say that $T_2 = T_1/\ e^{\mu\theta}$

Putting the value of T_2 in equation (*i*)

$$P = (T_1 - T_1/\ e^{\mu\theta}).v = T_1(1 - 1/\ e^{\mu\theta}).\ V \qquad ...(ii)$$

Let $(1-1/\ e^{\mu\theta}) = K$, K = any constant

Then the above equation is $P = T_1.K.\ V$ or $KT_1\ V$ ...(*iii*)

Let T_{max} = Maximum tension in the belt

T_c = Centrifugal tension which is equal to $m.v^2$

Then $T_{max} = T_1 + T_c$

$$T_1 = T_{max} - T_c$$

Putting this value in the equation (*iii*)

$$P = K(T_{max} - T_c).V$$
$$= K(T_{max} - m.V^2).V$$
$$= K(T_{max}.v - m.V^3)$$

Powertransmitted willbemaximumifd(P)/dv=0

ThusdifferentiatingequationwithrespecttoVandequatingtozeroformaximumpowe r,weget

$$d(P)/dv = K(T_{max} - 3.m.V^2)=0$$
$$T_{max} - 3mV^2 = 0$$
$$T_{max} = 3mV^2$$
$$V = (T_{max}/3m)^{1/2}$$

Equation(*iv*)

givesvelocityofbeltatwhichmaximumpoweristransmitted.Fromequation(*iv*)

$T_{max}=3T_c$ .... (*v*)

Hencewhenpowertransmittedismaximum,thecentrifugaltensionwouldbearound1 /3rdofthemaximumtension.

Weknow that$T_{max}= T_1+T_c$

$$= T_1 + T_{max}/3$$
$$T_1 = T_{max} - T_{max}/3$$
$$= 2/3.T_{max}$$

Henceconditionfortransmissionofmaximumpoweris:T_c=1/

3T_{max},and

T_1=2/3T_{max}

DIFFERENT TYPES OF CHAINS AND THEIRTERMINOLOGY

CHAINDRIVE

A chain drive consist of an endless chain running over two sprocket, driver anddriven. The velocity ratio is constant. The chains are mostly used to transmitmotion and power from one shaft to another, when the centre distance betweentheshaftsisshort suchasinbicycle,motorcycleetc.

DIFFERENTTYPESOFCHAINS

Therearedifferenttypesofchainsusedinpowertransmission.

- HoistingChains
- ConveyorChains
- PowertransmissionChains.

Hoisting Chains: A hoist is a mechanical device which is used to lift a load orlowering a load, it can be used for shifting of some heavy product from oneplace to another place in a work station. Hoist chains can be classified into twocategories:

a) Oval-LinkChains
b) Stud-LinkChains

a) **Oval-Link Chains**: It is one of the common types of chain used in hoist;itconsistsofmanyovallinksattachedtoeachother.Thesetypesof chains are also called Coil Chains. Links of this type of chain is oval.However, there are square link types of chains that are also available butthe kinking is occurred easily due to high loading. Generally, we usedthesetypesofchainsatlowspeeds only.

b) **Stud-LinkChains:**Thestud-linkchainsusedtominimizethedeformation and link or tangle easily. In this type of chain, a round bar orstud is used to fit inside the oval-link chains to provide more strength tothe chain. It is used in Ship to up and down the anchor of the ships, andsome cranehoistwhereweneedtoliftaveryhighamountofload.

Conveyor Chains: As the name suggests conveyor chains, which means thesetypesofchainsaremostlyusedintheconveyor.Ifyoudon’tknowtheconveyor, it is a mechanical device system that is used to move the materialsfrom one place to another. This type of chain is well shaped that itcan easilyrunover thesprocket.

ConveyorChainsarecategorizedintothreetypes:

a) DetachableorHookJointtypesConveyorchain.
b) Closed-endpintletypeconveyorchain.

a) **Detachable or Hook Joint types Conveyor chain**: Detachable or HookJoint types Conveyor chains are used in a conveyor where the lengthbetween power transmissions is short. Detachable or Hook Joint typesConveyor chains are used in a conveyor where the length between powertransmissionsisshort.
b) **Closed-end pintle type conveyor chain**: This type of chain is consists ofa barrel and link and made in a single casting, and then the chain is heat-treatedtoprovidehigher strength.

PowerTransmission Chains: You can easily findoutby nameof thechainthat it is used to transmit the power. This type of chain is made of steel andsometimes it heats treated to minimize wear and tear. This type of chain hasgreater accuracy and can easily run overthe sprocket. Power TransmissionChainsarecategorizedinto threetypes:

a) BlockChain
b) RollerChain
c) SilentChainorInverted toothChain

a) **Block Chain**: This type of chain is used in low-speed areas and willproduce noise due to the sudden contact between sprocket and chain,however,thisisusedinsomelow-speed conveyormachines.

b) **RollerChain:**This typeofchainis constructedby:

- Abush
- InnerLink
- Apin
- OuterPlate
- Innerplate

In this type of chain, a bush along with the roller is fitted inside both theplates then a pin is passed through both the end of the roller to fasten it.The rollers are free to rotate inside the bush so that when it contactsbetween the sprocket the wear and tear would be minimized. Generally, itis made of steel. It is soundless and wears less as compared to the blockchains and used in any circumstances and this type chains gave muchserviceareaifproper lubrication ismaintained.

c) **Silent Chain or Inverted Tooth Chain:** The operation of this type ofchain is quite silent and can be used in high-speed power transmissionsareas. This type of chain does not have any roller; it is accurately shapedthatitcaneasilysitoverthesprocket.However,lubricationisanimportantfactorforthis typeofchainotherwise itwillwearandtearout.

TERMINOLOGY

- **Sprocket:** The chain is fitted on wheels are called sprockets. Asprockethasprojectedteethwhichfitintothecorrespondingrecessesin thechain.
- **Pitch:** It is the distance between the hinges centre of two adjacentlinks.
- **Pitch Circle:** A circle is drawn through the hinge centre, when thechainiswrappedaroundthesprockets.
- **Pitch CircleDiameter(PCD):** Thediameterof pitch circleiscalledaspitchcirclediameter.

GEARDRIVE-SIMPLE,COMPOUND,REVERTEDANDEPICYCLIC GEARTRAINS (SIMPLENUMERICALS)

GEARSDRIVE

Gears are the tooth wheels used to transmit power between two shafts, when thecentre distance between them is very small. Gears are generally used for one offour differentreasons:

- Toincreaseordecreasethespeedofrotation
- Tochangetheamountofforceortorque;
- Tomoverotationalmotiontoadifferentaxis

- Toreversethedirectionofrotation.

Gears are compact, positive-engagement, power transmission elements capableof changing the amount of force or torque. The gears can be classified accordingto:

- Thepositionofshaftaxes
- Theperipheralvelocity
- Thetypeofgears
- Theteethposition

Accordingtothepositionofshaftaxes:

Gearsmaybeclassifiedaccordingtotherelativepositionoftheaxesofrevolution.Theaxesmaybe:

- Parallelshaftswheretheanglebetweendrivinganddrivenshaftis0 degree. Examples include spur gears, single and double helicalgears.
- Intersecting shafts where there is some angle between driving anddrivenshaft.Examplesincludebeveland mitergear.
- Non-intersecting and non-parallel shafts where the shafts are notcoplanar.Examplesincludethehypoidandwormgear.

Accordingtoperipheralvelocity:

Gearscanbeclassifiedas:

- Lowvelocitytype,iftheirperipheralvelocityliesintherangeof1to3m/sec.
- Mediumvelocitytype,iftheirperipheralvelocityliesintherangeof3to15m/sec.
- Highvelocitytype,iftheirperipheralvelocityexceeds 15m/sec.

Accordingtotype ofgears:

Gearscanbeclassifiedasexternalgears,internalgears,andrackandpinion.

- External gears mesh externally - the bigger one is called “gear” andthesmalleroneiscalled“pinion”.
- Internal gears mesh internally - the larger one is called “annular”gear andthesmalleroneiscalled “pinion”.
- Rack and pinion type – converts rotary to linear motion or viceversa. There is a straight line gear called “rack” on which a smallrotarygearcalled“pinion”moves.

Accordingtoteethposition:

Gearsareclassifiedasstraight,inclinedandcurved.

- Straightgearteetharethosewheretheteethaxisisparalleltotheshaft axis.
- Inclinedgearteetharethosewheretheteethaxisisatsomeangle.
- Curvegearteetharecurvedontherim’ssurface.

TYPE OF

GEARSSPURGE

ARS:

Spur gears are used to transmit power between two parallel shafts. The teeth onthese gears are cut straight and are parallel to the shafts to which they areattached.

SpurGearsCharacteristics:

- Simplestand mosteconomicaltypeofgeartomanufacture.
- Speed ratios of up to 8 (in extreme cases up to 20) for one step (singlereduction) design; up to 45 for two step design; and up to 200 for three-stepdesign.

Limitations:

- Notsuitablewhenadirectionchangebetweenthetwoshaftsisrequired.
- Producenoisebecausethecontactoccursoverthefullfacewidthofthemating teethinstantaneously.

HELICALGEARS

Helical gears resemble spur gears, but the teeth are cut at an angle rather thanparallel to the shaft axis like on spur gears. The angle that the helical gear toothis on is referred to as the helix angle. The angle of helix depends upon thecondition of the shaft design and relative position of the shafts. To ensure thatthe gears run smoothly, the helix angle should be such that one end of the geartooth remains in contact until the opposite end of the following gear tooth hasfoundacontact.Forparallel shafts,thehelix angleshouldnotexceed20degreestoavoidexcessiveendthrust.

Characteristics:

- Thelongerteethcausehelicalgearstohavethefollowingdifferencesfromspurg earsofthesamesize:
- Toothstrengthisgreaterbecausetheteetharelongerthantheteethofspurgearof equivalentpitchdiameter.
- Cancarryhigherloadsthancanspurgearsbecauseofgreatersurfacecontactont heteeth.
- Canbeusedtoconnectparallelshaftsaswellasnon-parallel,non-intersectingshafts.
- Quieterevenathigherspeed andaredurable.
- Limitations:
- Gearsinmeshproducethrust forcesintheaxialdirections.
- Expensivecomparedtospurgears.

BEVELGEARS:

A bevel gear is shaped like a section of a cone and primarily used to transferpower between intersecting shafts at right angles. The teeth of a bevel gear maybe straight or spiral. Straight gear is preferred for peripheral speeds up to 1000feetperminute;abovethattheytend tobenoisy.

Characteristics:

- Designed for the efficient transmission of power and motion betweenintersecting shafts. A good example of bevel gears is seen as the mainmechanism for ahand drill.As thehandle of the drill is turned in avertical direction, the bevel gears change the rotation of the chuck to ahorizontalrotation.
- Permitaminoradjustmentduringassemblyandallowforsomedisplacementduetodeflectionunderoperatingloadswithoutconcentratingtheloadontheendofthetooth.

MITTERGEARS:

Mittergearsareidenticaltobevelgearswiththeexceptionthatbothgearsalwayshavethesamenumber ofteeth.

Characteristics:

- Theyprovideasteadyratio;othercharacteristicsaresimilartobevelgears.
- Theyareusedasimportantpartsofconveyors,elevators andkilns.
- Limitations
- Gearrationisalways1to1andthereforenotusedwhenanapplicationcallsfor achangeofspeed.

WORMGEARS:

Wormgearsareusedtotransmitpowerbetweentwoshaftsthatareatrightanglestoeach other andarenon-intersecting.Wormgearsarespecialgearsthat resemble screws, and can be used to drive spur gears or helical gears. Wormgearing is essentially a special form of helical gearing in which the teeth haveline contact and the axes of the driving and driven shafts are usually at rightanglesanddonot intersect.

Characteristics:

- Inthemeshingoftwoexternalgears,rotationgoesintheoppositedirection. In the meshing of an internal gear with an external gear therotationgoesinthesamedirection.
- The meshing arrangement enables a greater load carrying capacity withimprovedsafety(sincemeshingteethareenclosed)comparedtoequivalent externalgears.
- Shaft axesremain parallel and enablea compact reduction with rotationinthe samesense.Internalgearsare notwidelyavailableas standard.
- When they are used with the pinion, more teeth carry the load that isevenly distributed. The even distribution decreases the pressure intensityandincreasesthelifeofthegear.
- Allows compact design since the center distance is less than for externalgears.Usedinplanetarygearstoproducelargereductionratios.
- Provides good surface endurance due to a convex profile surface workingagainst aconcavesurface.Applications:
- Planetarygeardriveofhighreductionratios,clutches,etc.
- Limitations:
- Housingandbearingsupportsaremorecomplicatedbecausetheexternalgear nestswithintheinternalgear.
- Lowratiosareunsuitableandinmanycasesimpossiblebecauseofinterfe rences.
- Fabricationisdifficultand usuallyspecialtoolingisrequired.

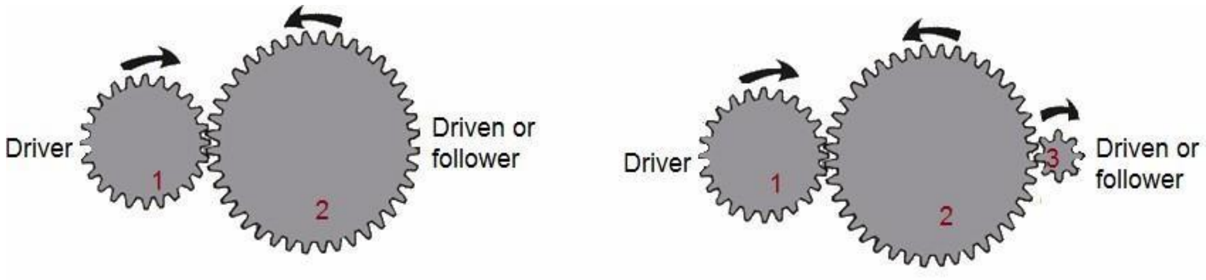
GEARTRAINS

Gear train is a power transmission system made up of two or more gears. Thegear to which the force is first applied is called the driver and the final gear onthe train to which the force is transmitted is called the driven gear. Any gearsbetween the driver and the driven gears are called the idlers. Conventionally, thesmaller gear is the **Pinion** and the larger one is the **Gea**r. In most applications,thepinionisthedriver;thisreducesspeedbutincreasestorque.

Types ofgeartrains:

- Simplegeartrain
- Compoundgeartrain
- Planetarygeartrain

Simple Gear Train - Simple gear trains have only one gear per shaft. Thesimple gear train is used where there is a large distance to be covered betweentheinputshaftandtheoutputshaft.



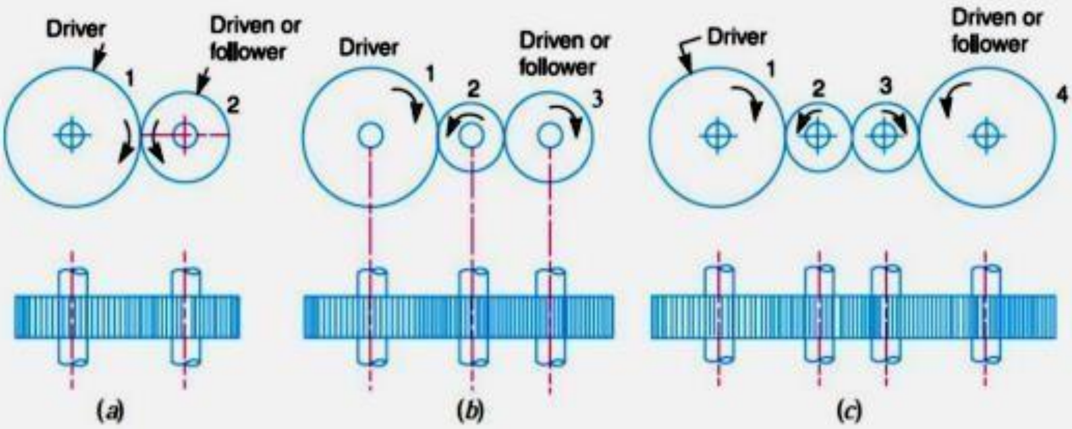


Fig. 13.1. Simple gear train.

Let N_1 = Speed of gear 1(or driver) in r.p.m.,

N_2 = Speed of gear 2 (or driven or follower) in r.p.m.,

T_1 = Number of teeth on gear 1, and

T_2 = Number of teeth on gear 2.

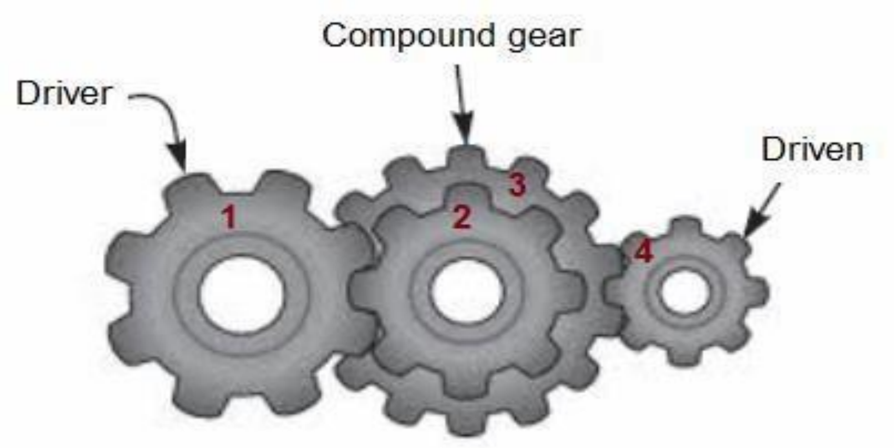
Since the speed ratio (or velocity ratio) of gear train is the ratio of the speed ofthedrivertothespeedofthedrivenorfollowerandratioofspeedsofanypairofgearsin meshistheinverseoftheirnumber ofteeth,therefore

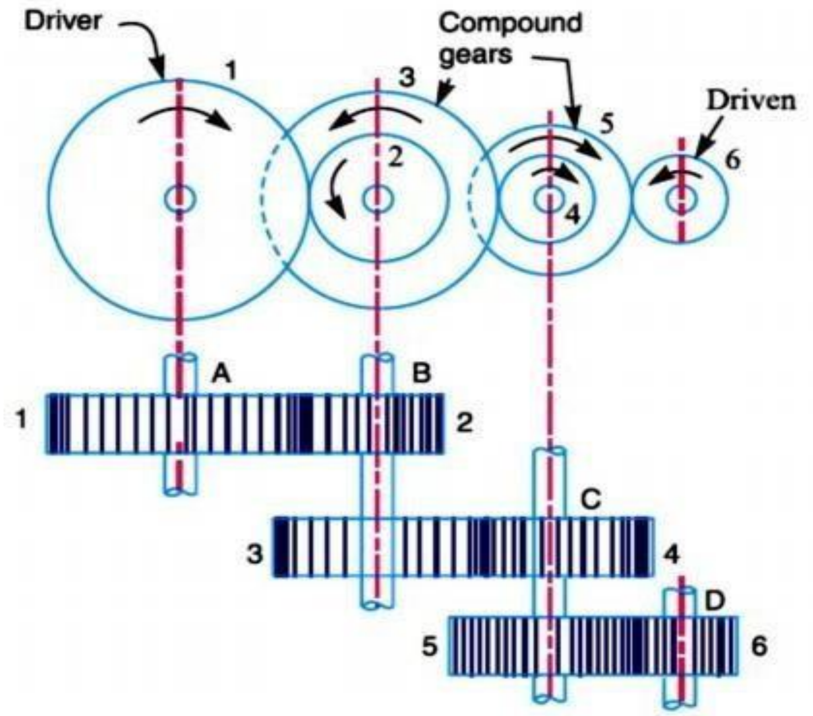
$$\text{Speed ratio} = \frac{N_1}{N_2} = \frac{T_2}{T_1}$$

It may be noted that ratio of the speed of the driven or follower to the speed ofthe driver is known astrain value of the gear train. Mathematically, Fromabove,weseethat the trainvalueisthereciprocalofspeed ratio.

$$\text{Train value} = \frac{N_2}{N_1} = \frac{T_1}{T_2}$$

Compound Gear Train - In a compound gear train at least one of the shafts inthetrainmustholdtwogears.Compoundgeartrainsareusedwhenlarge changes in speed or power output are needed and there is only a small spacebetweentheinputandoutputshafts.





In a compound train of gears, as shown in Fig. 13.2, the gear 1 is the drivinggear mounted on shaft A, gears 2 and 3 are compound gears which are mountedon shaft B. The gears 4 and 5 are also compound gears which are mounted onshaftCand thegear6isthedrivengearmountedonshaftD.

Let

N1= Speedofdrivinggear1,

T1= Numberofteethondrivinggear1,

N2,N3...,N6=Speedofrespective gearsinr.p.m.,and

T2,T3...,T6=Numberofteethonrespectivegears.

Sincegear1isinmeshwithgear2,thereforeitsspeedratiois

$$\frac{N_1}{N_2} = \frac{T_2}{T_1} \quad \ldots\ldots\ldots\ldots(i)$$

Similarly, for gears 3 and 4, speed ratio is

$$\frac{N_3}{N_4} = \frac{T_4}{T_3} \quad \ldots\ldots\ldots\ldots(ii)$$

and for gears 5 and 6, speed ratio is

$$\frac{N_5}{N_6} = \frac{T_6}{T_5} \quad \ldots\ldots\ldots\ldots(iii)$$

The speed ratio of compound gear train is obtained by multiplying the equations (*i*), (*ii*) and (*iii*),

$$\frac{N_1}{N_2} \times \frac{N_3}{N_4} \times \frac{N_5}{N_6} = \frac{T_2}{T_1} \times \frac{T_4}{T_3} \times \frac{T_6}{T_5}$$

Since gears 2 and 3 are mounted on one shaft *B*, therefore $N_2 = N_3$. Similarly gears 4 and 5 are mounted on shaft *C*, therefore $N_4 = N_5$.

$$\frac{N_1}{N_6} = \frac{T_2 \times T_4 \times T_6}{T_1 \times T_3 \times T_5}$$

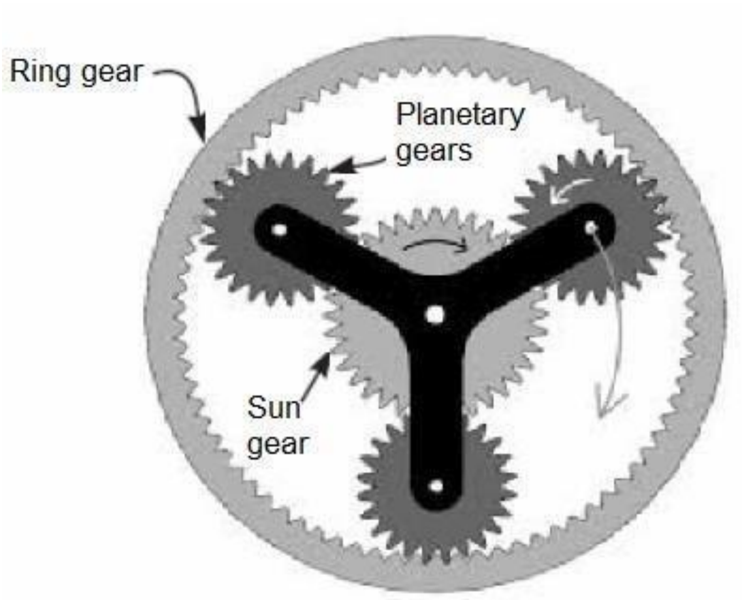
i.e

$$Speed\ ratio = \frac{Speed\ of\ the\ first\ driver}{Speed\ of\ \ last\ driven} = \frac{Product\ of\ the\ number\ of\ teeth\ on\ the\ drivens}{Product\ of\ the\ number\ of\ teeth\ on\ the\ drivers}$$

$$\boldsymbol{and}\ \ Train\ value = \frac{Speed\ of\ \ last\ driven}{Speed\ of\ the\ first\ driver} = \frac{Product\ of\ the\ number\ of\ teeth\ on\ the\ drivers}{Product\ of\ the\ number\ of\ teeth\ on\ the\ drivens}$$

The advantageof a compound train over a simplegear train isthat amuchlarger speed reduction from the first shaft to the last shaft can be obtained withsmall gears. If a simple gear train is used to give a large speed reduction, the lastgear has to be very large. Usually for a speed reduction in excess of 7 to 1, asimple train is not used and a compound train or worm gearing is employed.Note: The gears which mesh must have the same circular pitch or module. Thusgears 1 and 2 must have the same module as they mesh together. Similarly gears3and4,andgears5and6musthavethesamemodule.

Planetary Gear Train - A planetary transmission system or it is also known asepicyclic system. It consists normally of a centrally pivoted sun gear, a ring gearand several planet gears which rotate between these. This assembly conceptexplains the term planetary transmission, as the planet gears rotate around thesungearasintheastronomicalsensetheplanets rotatearoundoursun.



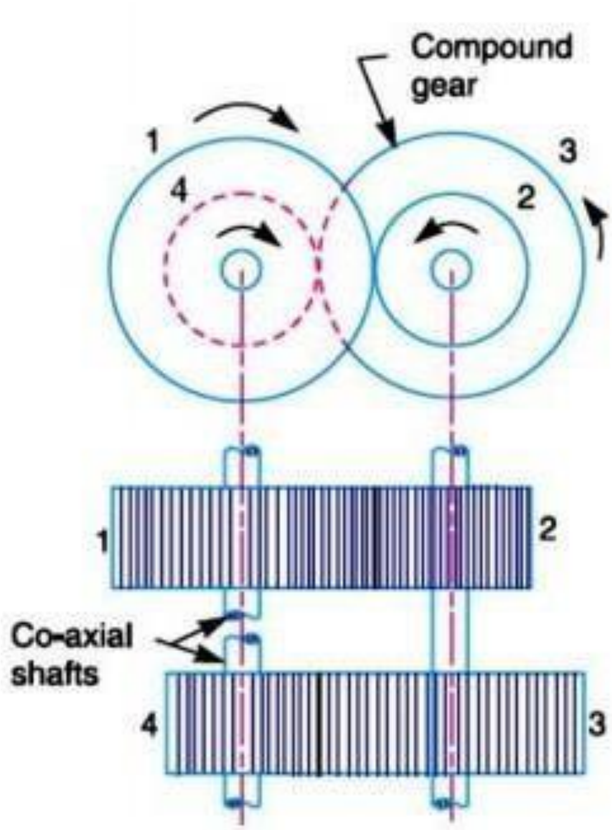
Reverted Gear Train: When the axes of the first gear (i.e. first driver) and thelast gear (i.e. last driven orfollower) are co-axial, then the gear train is knownas reverted gear train. We see that gear 1 (i.e. first driver) drives the gear 2 (i.e.first driven or follower) in the opposite direction. Since the gears 2 and 3 aremounted on the same shaft, therefore they form a compound gear and the gear 3will rotate in the same direction as that of gear 2. The gear 3 (which is now thesecond driver) drives the gear 4 (i.e. the last driven or follower) in the samedirection as that of gear 1. Thus we see that in a reverted gear train, the motionofthefirstgearandthelastgearislike.

Let

T1 = Number of teeth on gear

1,r1=Pitchcircle radiusofgear1,

N1=Speedofgear1inr.p.m.Sim
ilarly,
T2, T3, T4 = Number of teeth on respective
gears,r2,r3,r4=Pitchcircleradiiofrespectivegears,
andN2,N3,N4 =Speedofrespectivegearsinr.p.m.



Since the distance between the centers of the shafts of gears 1 and 2 aswellasgears3and4issame,therefore

r1 +r2 = r3+ r4 ...(i)

Also, the circular pitch or module of all the gears is assumed to be same,thereforenumber of teeth on each gear is directly proportional toitscircumferenceor radius

We know that circular pitch,

$$p_c = \frac{2\pi r}{T} = \pi m \quad \text{or} \quad r = \frac{m.T}{2}, \text{ where } m \text{ is the module.}$$

$$\therefore \quad r_1 = \frac{m.T_1}{2} \; ; \; r_2 = \frac{m.T_2}{2} \; ; \; r_3 = \frac{m.T_3}{2} \; ; \; r_4 = \frac{m.T_4}{2}$$

Now from equation (*i*),

$$\frac{m.T_1}{2} + \frac{m.T_2}{2} = \frac{m.T_3}{2} + \frac{m.T_4}{2}$$

$$\therefore T_1 + T_2 = T_3 + T_4 \qquad \ldots(ii)$$

$$Speed\ Ratio = \frac{Product\ of\ the\ number\ of\ teeth\ on\ the\ drivens}{Product\ of\ the\ number\ of\ teeth\ on\ the\ drivers}$$

or

$$\frac{N_1}{N_4} = \frac{T_2 \times T_4}{T_1 \times T_3} \qquad \ldots(iii)$$

From equations (i), (ii) and (iii), we can determine the number of teeth on eachgearforthegiven centredistance,speedratioandmoduleonly whenthenumber of Gear Trains Page 8 of 23 teeth on one gear is chosen arbitrarily. Thereverted gear trains are used in automotive transmissions, lathe back gears,industrial speed reducers, and in clocks (where the minute and hour hand shaftsareco-axial).

GEARRATIO

Theratioofnumberofteethongeartothatonthepinion iscalledgear ratio.

$$\textbf{GearRatio} = \frac{T}{t}$$

Where,

T= Numberofteethongear

t=Number ofteethonpinion

RELATIVE ADVANTAGES AND DISADVANTAGES OFVARIOUSDRIVES

ADVANTAGESANDDISADVANTAGESOFBELTDRIVE

Advantages:

- Beltdrivesaresimpleareeconomical.
- Theydon’tneedparallelshafts.
- Beltsdrivesareprovidedwithoverloadandjamprotection.
- Noiseandvibrationaredampedout.
- Machinerylifeisincreasedbecauseloadfluctuationsareshock-absorbed.
- Theyarelubrication-free.
- Theyrequirelessmaintenancecost.
- Beltdrives arehighlyefficientinuse(upto98%,usually95%).
- Theyareveryeconomicalwhenthedistancebetweenshaftsisverylarge.

Disadvantages:

- InBeltdrives,angularvelocityratioisnotnecessarilyconstantorequaltotheratioofpulleydiameters,becauseofslippingandstretching.
- Heatbuildupoccurs.Speedislimitedtousually35meterspersecond.Power transmission islimitedto370 kilowatts.
- Operatingtemperaturesareusuallyrestrictedto–35to85°C.
- Someadjustmentofcenterdistanceoruseofanidlerpulleyisnecessaryforwearingandstretching ofbeltdrivecompensation.

ADVANTAGESANDDISADVANTAGESOFCHAINDRIVE

Advantages:

- Theycanbe used forbothlongandshortdistances
- Anumberofshaftsandbedrivenfroma single chain
- Theyarecompactandhavesmalloveralldimensions

- Theydonotpresent firehazard
- Temperatureandenvironmentalconditionsdonotaffecttheirworking
- Theydonotrequire initialtension
- Theyhaveveryhighefficiency(upto96%)
- Theydonotslip
- Theyareeasiertoinstall
- Theycanwithstandabrasiveconditions
- Theycanoperateinwetconditions

Disadvantages:

- Theycan'tbeusedwhereslipisthesystemrequirement
- Theyrequireprecisealignmentcomparedtobeltdrives
- Theyrequirefrequentlubrication
- Theyhavelessloadcapacitycomparedwithgeardrives
- Theiroperationisnoisyandcancausevibrations
- Theyarenotsuitablefornon-parallelshafts
- Theyrequirehousing
- Theyrequireadjustments forslackliketensioningdevice

ADVANTAGESANDDISADVANTAGESOFGEARDRIVE

Advantages:

- Byusinggeartrains,largevelocityratiocanbeobtainedwithminimumspace.
- Gearsaremechanicallystrong,sohigherloadscanbelifted.
- GearsareusedfortransmissionoflargeH.F.
- Theyareusedfortransmittingmotionsmallcentredistanceofshafts
- Theyareusedforlargereductioninspeedandfortransmissionoftorque.
- Gearsrequireonlylubrication,hencelessmaintenanceisrequired.

- Usinggearsystems,wecantransmitmotionbetweennon-parallelintersectingshafts.
- Theyareusedforpositivedrive,soitsvelocityratioremainsconstant.
- Theyhavelonglife, sothegearsystemis verycompact.

Disadvantages:

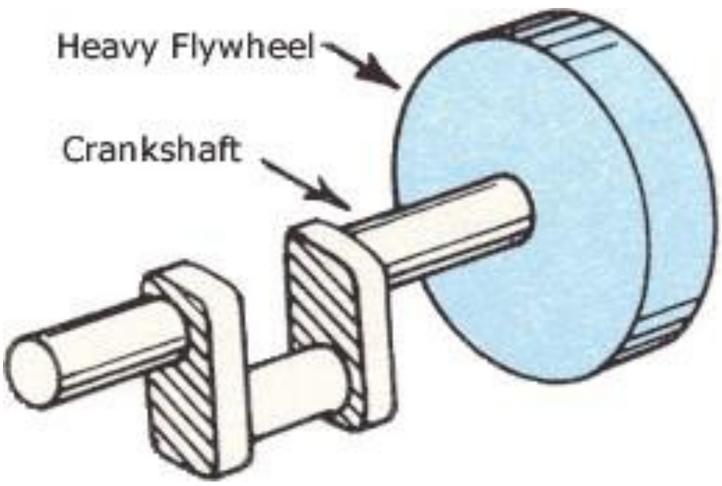
- Theyarenotsuitableforlargevelocities.
- Theyarenotsuitablefortransmittingmotionoveralargedistance.
- Duetotheengagementoftoothedwheelofgears,somepartofmachinemayget permanentlydamaged incaseofexcessiveloading.
- Theyhavenoflexibility.
- Gearoperationisnoisy.

CHAPTER-3FLYWHEEL

PRINCIPLE&APPLICATIONSOFFLYWHEEL

PRINCIPALOFFLYWHEEL

A flywheel isamechanicaldevice specifically designed to efficientlystore rotationalenergy.Flywheelsresistchangesinrotationalspeed bytheir moment of inertia. A flywheel is fitted on the crank shaft of engine. As theflywheel rotates with the crank shaft, it absorbs and releases energy which isproportional to the square of its rotational speed. Flywheel acts as an energyreservoir. Whenever the energy available is in excess than the required one, itabsorbs the energy an when the available energy is less than the required one, itreleases the energy. When the flywheel absorbs energy its speed increases andwhen it releases energy its speed decreases, this occurs at least once during acycle.



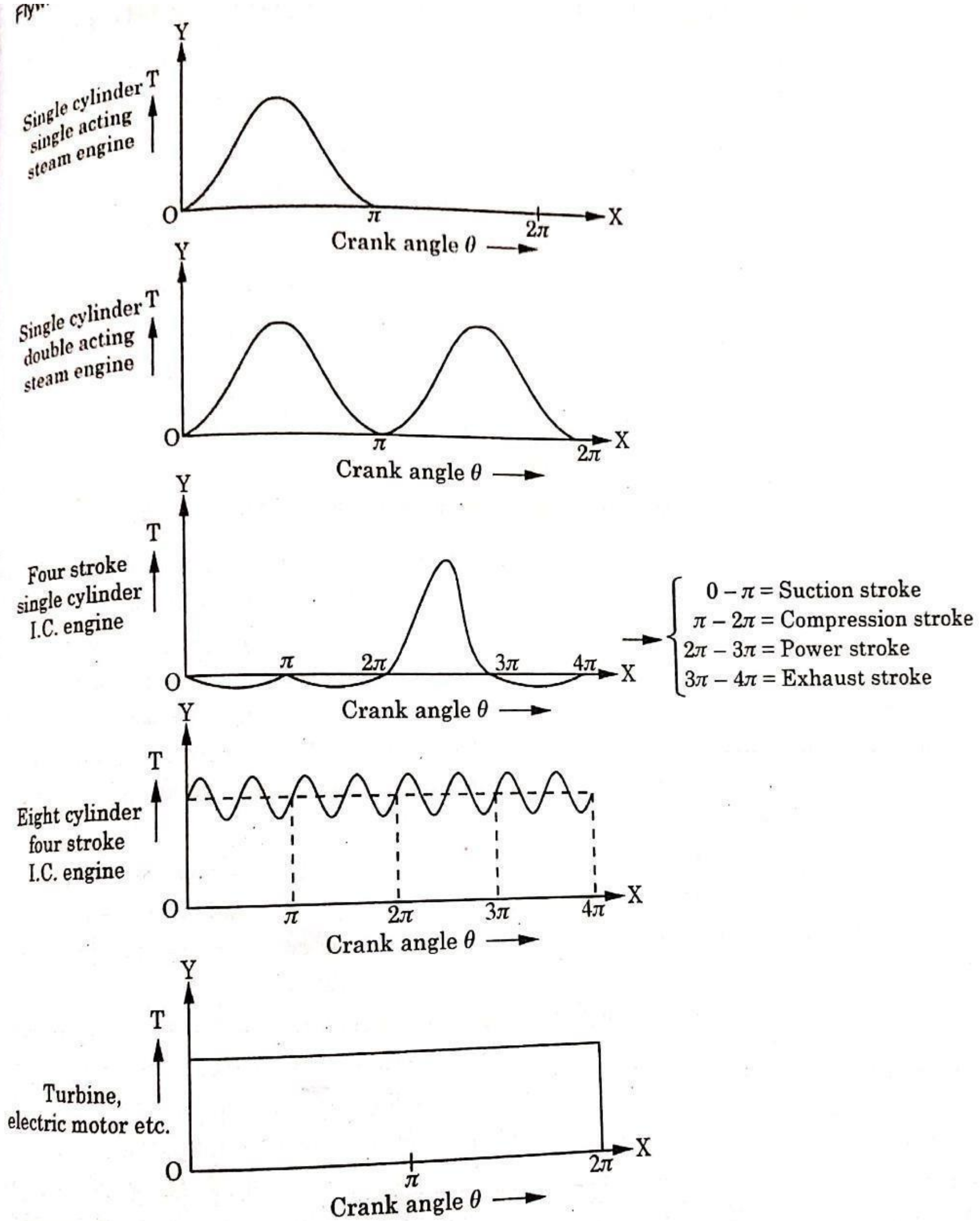
APPLICATIONOFFLYWHEEL

Flywheels are often used to provide continuous power output in systems wherethe energy source is not continuous. For example, a flywheel is used to smoothfast angular velocity fluctuations of the crankshaft in a reciprocating engine. Inthis case, a crankshaft flywheel stores energy when torque is exerted on it by afiring piston, and returns it to the piston to compress a fresh charge of air andfuel. A flywheel may also be used to supply intermittent pulses of energy atpower levels that exceed the abilities of its energy source. This is achieved byaccumulating energy in the flywheel over a period of time, at a rate that iscompatible with the energy source, and then releasing energy at a much higherrate over a relatively short time when it is needed. For example, flywheels areusedinpowerhammersandrivetingmachines.

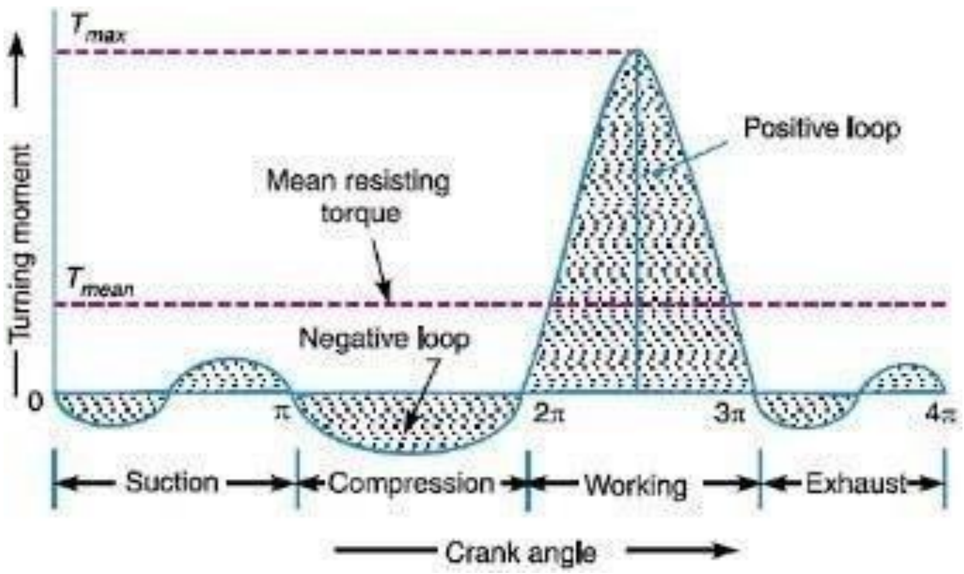
TURNING – MOMENT DIAGRAM OF FLYWHEEL FORDIFFERENTENGINES

It isthegraphical representation of the turningmoment or crank-effortforvarious positions of the crank. It is plotted on Cartesian co-ordinates, in whichthe turning moment is taken as the ordinate and crank angle as abscissa. Theturning moment diagram (also known as crank- effort diagram) is the graphicalrepresentation of the turning moment or crank-effort for various positions of thecrank. It is plotted on Cartesian co-ordinates, in which the turning moment istakenastheordinateandcrankangleasabscissa.

Followingfiguresshowtheturningmomentdiagramsofdifferentengines.



Single cylinder single acting steam engine
Y
T
O
X
π
2π
Crank angle θ
Single cylinder double acting steam engine
Y
T
O
X
π
2π
Crank angle θ
Four stroke single cylinder I.C. engine
Y
T
O
X
π
2π
3π
4π
Crank angle θ
0 – π = Suction stroke
π – 2π = Compression stroke
2π – 3π = Power stroke
3π – 4π = Exhaust stroke
Eight cylinder four stroke I.C. engine
Y
T
O
X
π
2π
3π
4π
Crank angle θ
Turbine, electric motor etc.
Y
T
O
X
π
2π
Crank angle θ



TurningmomentdiagramforfourstrokesinglecylinderI.C.Engine

FLUCTUATION OF SPEED AND FLUCTUATION OFENERGY

FLUCTUATIONOF SPEED: The differencebetween themaximumand minimum speeds during a cycle is called the maximum fluctuation ofspeed.

Fluctuation of speed = $(N_1 – N_2)$

rpmWhere, N_1-maximumspeed,

N_2-minimumspeed

FLUCTUATIONOFENERGY: Itisthedifferencebetweenthemaximuman dminimumenergyof Flywheel.

Fluctuation ofenergy=I $(\omega_1^2 - \omega_2^2)$ inN-mor

JMaximum energy of Flywheel

$=I\omega_1^2$MinimumenergyofFlywheel$=I\omega_2^2$

I–momentofinertiaofflywheel=mk^2

Where, m–massoftheflywheelinkg

k-radiusofgyrationofflywheel,

ω_1–

MaximumAngularvelocity,rad/secω_2–

MinimumAngular velocity,rad/sec

COEFFICIENT OF FLUCTUATION OF SPEED ANDCOEFFICIENTOFFLUCTUATION OFENERGY

COEFFICIENTOFFLUCTUATIONOFSPEED

Itistheratioofmaximumfluctuationofspeedtothemeanspeed.Themaximum fluctuation of speed is difference between maximum and minimumspeedsduringacycle.

Coefficientoffluctuationofspeed=$\frac{N1-N2}{N}$

Where,

N1andN2 = MaximumandMinimumspeedsinr.p.mduringthe

cycle,N=Meanspeedinr.p.m.=(N1+N2)/2

COEFFICIENTOFFLUCTUATIONOFENERGY

Itistheratioofmaximumfluctuationenergytotheworkdonepercycle.

$$C_e=\Delta E/E$$

$$E=\frac{1}{2}I\omega^2_{mean}$$

ΔE=MaximumFluctuationofenergyasspeed changes fromω_{max}toω_{min}

CHAPTER-4GOVERNOR

FUNCTION OFAGOVERNOR,COMPARISONOFFLYWHEELAND GOVERNOR

FUNCTIONOFAGOVERNOR

The function of the governor is to adjust the fuel supply automatically with thechange of the external load of the diesel engine within the required speed rangeof the diesel engine, so as to keep the diesel engine speed basically stable. Whentheloadonanengineincreases,itsspeeddecreases,thereforeitbecomesnecessary to increases the supply of working fluid. On the other hand, when theload on the engine decreases, its speed increases and thus less working fluid isrequired. One of the types of governor is centrifugal governor which uses effectof centrifugal force on rotating weights driven by the machine output shaft toregulateitsspeedbyalteringtheinput amountoffuel.

TypesofGovernors

Therearebasicallytwotypes ofgovernors:

- Centrifugalgovernors
- Inertiagovernor

Thecentrifugalgovernorscanbefurtherclassifiedasfollows:

1. **Pendulumtype—Wattgovernor**
2. **Loadedtype–**

Therearetwokindsofloadedgovernors:

(a) Deadweighttype

(b) Spring-loadedtype

(a) Deadweighttype:

(i) Portergovernor

(ii) Proellgovernor

(b) Spring-loadedtype

(i) Hartnellgovernor

(ii) Hartunggovernor

(iii) Wilson–Hartnellgovernor

(iv) Pickeringgovernor

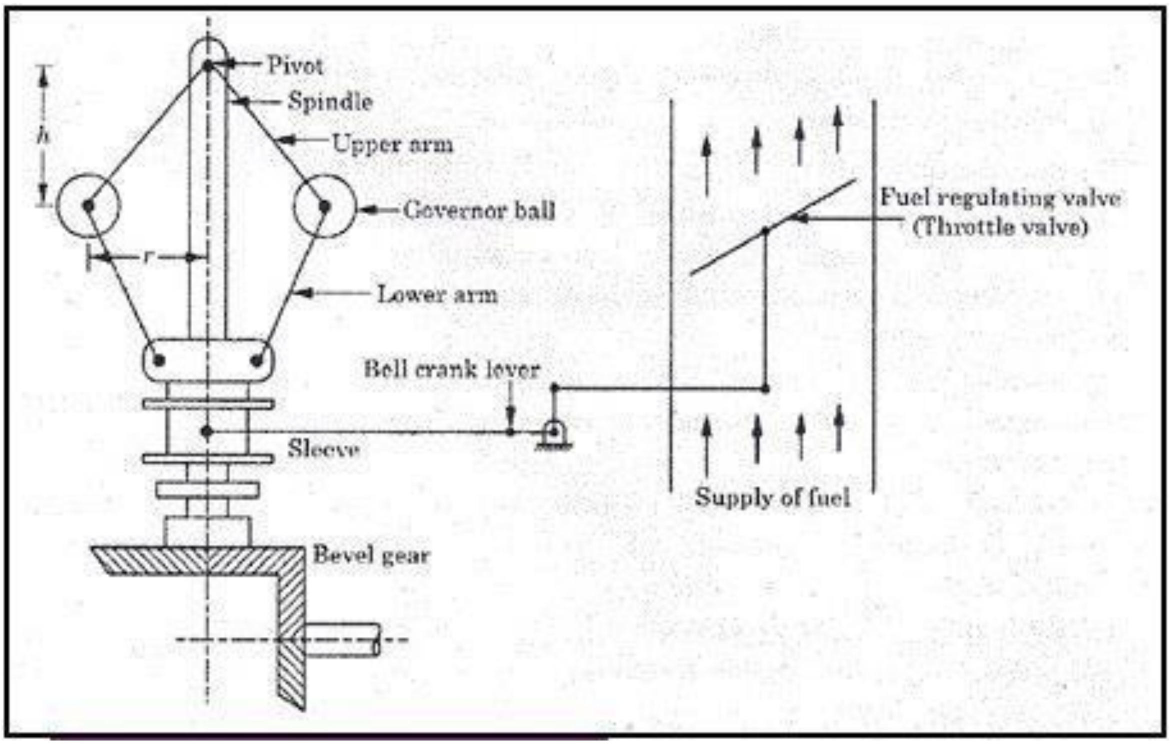
COMPARISONOFFLYWHEEL ANDGOVERNOR

	FLYWHEEL	GOVERNOR
1	Flywheel is used to prevent fluctuation of energy and does not maintain a constant speed.	Governor is used to maintain the constant speed, whenever there are changes in load.
2	Generally, flywheel is a heavy part of the machine.	Governor is a lighter in weight than flywheel.
3	It is a rotating component.	It is a non-rotating component.
4	Energy generated due to flywheel is directly proportional to the square of its angular speed.	There is no such proportionality or equation in a governor.
5	As there are energy variations in engines, a flywheel results in a maintaining a constant speed of crankshaft in each cycle by supply the required energy to the preparatory stokes (other than power stroke).	As the load on engine increases, the speed decreases. This increases the flow of fuel for regulating constant speed.

SIMPLEDESCRIPTIONANDWORKINGOFWATT,PORTERANDHARTNELGOVERNOR(SIMPLENUMERICALBASEDON WATTANDPORTERGOVERNOR)

WATTGOVERNOR

Watt governor is the simplest and gravity controlled form of the centrifugalgovernors. It consists of two fly balls attached to the sleeve of negligible mass.The upper sides of arms are pivoted so that its balls can move upward anddownward as they revolve with a vertical spindle. The engine drives the spindlethrough bevel gears. The lower arms are connected to the sleeves. The sleeve iskeyed to the spindle in such a way that it revolves with the spindle. At the sametime, it can slide up and down according to the spindle speed. Two stoppers areprovided atthebottomandtopofthespindletolimitthemovement sleeve.



When the load on the engine decreases, the speed of the engine and then theangular velocity of the governor spindle increase. The centrifugal force on theball increase; that tends balls move outward and sleeve move upward. Theupward movement of the sleeve actuates a mechanism that operates the throttlevalve at the end of bell crank lever to decreasethe fuel supply. The poweroutput is reduced. When the speed of the engine decreases as the load on theengine increase, the centrifugal force decreases. The result is that the inwardmovement fly-balls and downward movement of the sleeve. The movementcauses a wide opening of the throttle valve. The increase in the fuel supply alsoincreasesenginespeed.

PORTERGOVERNOR

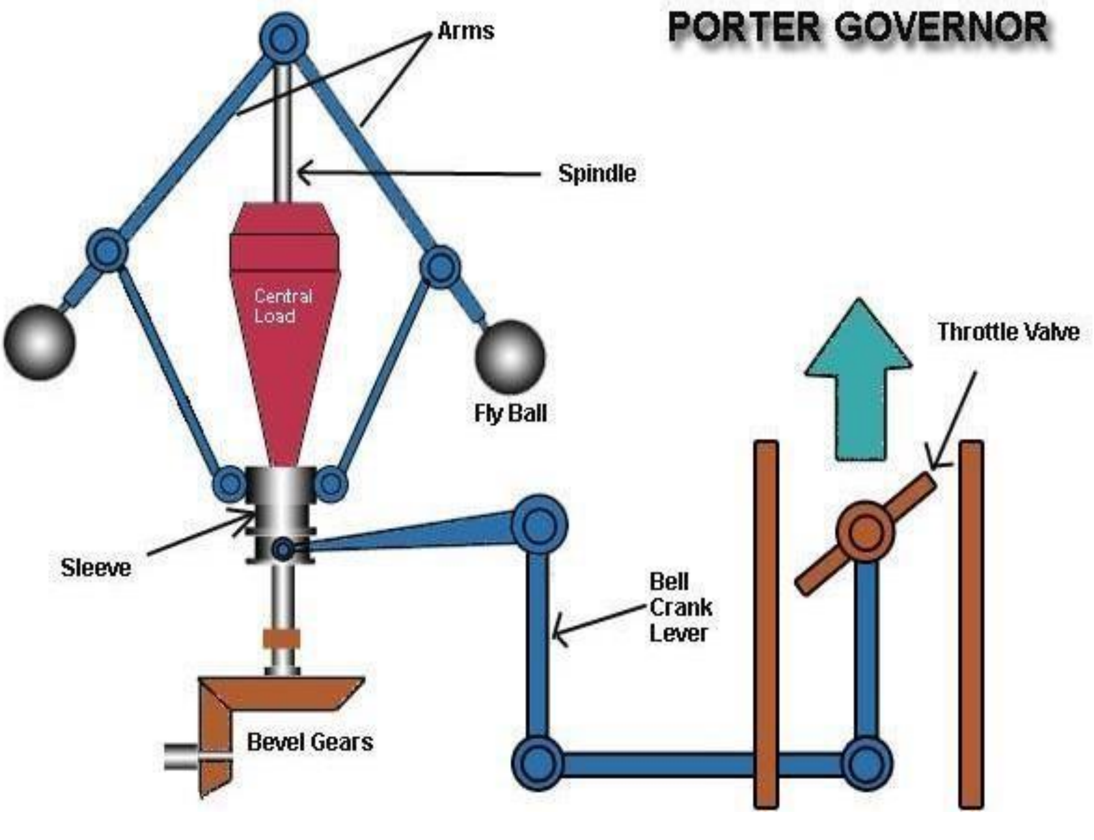
Porter Governor is modification of Watt Governor with central load attached tothe sleeve. This load moves up and down the central spindle. The additionalforce increases the speed of revolution required to enable the balls to rise to anypredeterminedlevel.

Construction:

A Porter governor has two fly balls which are attached to the arms of the portergovernor. These two arms are pivoted to the top of the spindle. This spindle isdrivenbytheengine.Thepartsofthearmsjustabovetheflyballsareconnected to the central sleeve. This sleevemovesup and down according tothe movement of the balls. There are stoppers place in the spindle to limit thevertical movement of the spindle.This sleeve is carriesa heavy central load.Themovementofthesleeve controlsopeningandclosingofthethrottle valve.

Working:

When the load of engine decreases, there will be sudden increase in speed ofengine and spindle speed will also increase. As the spindle speed increases twoflyballsalsostartrotatingaroundthespindlefast.Thecentrifugalforcewill push the balls outward making the ballsmove in upward direction. Since theball movesupward , the arms also moves upward and the sleeve connected tothe lower part of the arm also moves upward. Upward movement of sleeveactuates the throttle valve via a mechanism connected to the sleeve to decreasethe fuel supply to the engine. The decreases in fuel supply decrease the speed.Hence speed is maintained.In the other case, when the load of the engine increases speed of the enginedecreases. As the engine speed decreases, speed of the spindle also decreasesand centrifugal force in the balls. Hence the balls come down with the arms. Asthe arms come down, the sleeve connected to the arm also comes down and itactuates the throttle valve which increases the fuel supply. Due to increase infuelsupply,speedofenginealsoincreases.



HARTNELGOVERNOR

Mr. Hartnell designed his governor circa 1875. It is a Spring-loaded Governor.The function of a governor is to regulate the mean speed of an engine, whenthere are variations in the load e.g. when the load on an engine increases, itsspeeddecreases,thereforeitbecomesnecessarytoincreasethesupplyofworking fluid. On the other hand, when the load on the engine decreases, itsspeedincreases,andthuslessworkingfluidisrequired.Thegovernorautomaticallycontrolsthesupplyofworkingfluidtotheenginewiththevaryingloadconditions andkeeps themeanspeed withincertainlimits.

Construction:

It is a Spring-loaded Governor. It has two bell crank levers carrying the fly ballat one end and roller attached to the other end, the function of spring is toprovide the counterforce which acts against centrifugal force. The spring andshaft are enclosed inside a casing. The sleeve is pressed against the spring whenthe centrifugal force on the balls increases. Due to spring return nature thisgovernorcanbemounded inahorizontal,inverted,(inclined)position.

PartsofHartnellGovernor:

Thefollowingarethemainparts oftheHartnellGovernor.

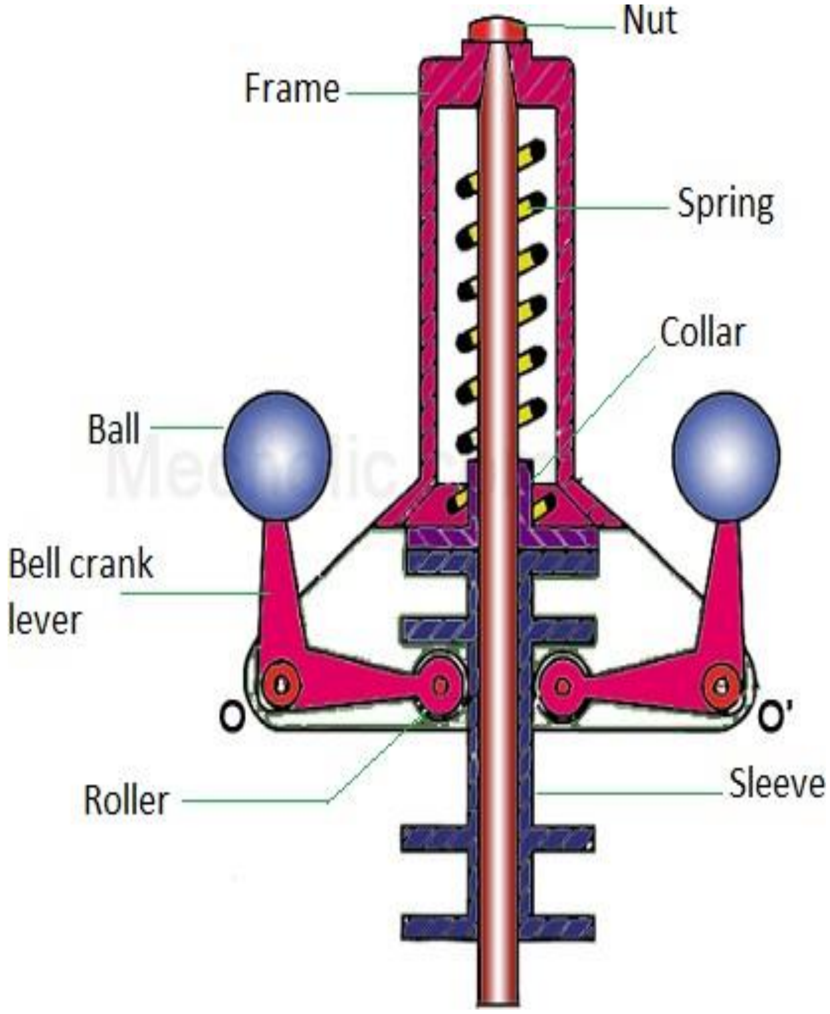
- **Frame:** Thisisprovided with a spring inside which protectsandsupports it and the frame is connected to the bell crank lever whichrotatesalongwiththelever.
- **Balls:** These are placed on the bell crank lever which is done withsomespecifiedweight.
- **Bellcranklever:** Thisisusedtorotatealongwiththeballsprovidedonit anditisconnectedto theframeto rotate it.
- **Nut:** This is proved on the top of the frame, which used to adjust theforceonthesleeve.

- **Spring:** This is used to apply the pressure on the sleeve wheneverrequired and this helps to push the sleeve downwards when it raisedmorethantherequired.
- **Collar:**This provided on the top of the sleeve to support the springonit.
- **Sleeve:** This used to move in an upward and downward directionaccording to the rotation of the bell crank lever attached to it and thishelps to flow the required amount of fluid into the engine when itraisedabovefromthebottompoint.

Working:

Hartnell governor is a spring controlled centrifugal governor, in which a springcontrols the movement of the ball and hence the sleeve. Above fig shows aHartnell governor. It consists of a frame /casing, in which a pre com pressedhelical spring is housed. The casing and spring can rotate about the spindle axis.The spring applies a downward force on the sleeve through an adjustable collar.The spring force can be adjusted by a nut provided. Two bell crank levers arepivoted at O,O' to the frame, each carrying a ball at one end a roller at anotherend.Therollerfitsintothegrooves ofthesleeve.

The sleeve moves up and down depending on the governor's speed. When thespeed of the governor/ engine increases, the ball tends to fly outward from theaxis of the governor, but the ball's movement is constrained. The bell cranklever moves on a pivot, roller end of lever lifts the sleeve upward against thespring force. This movement transferred to the throttle valve through a suitablemechanism, the result is low fuel supply and decreasing speed.When speeddecreases the sleeve moves downward, and throttle opens to more fuel supply;which resultsinincreasingspeed.



AdvantagesofHartnellgovernor:

- Itcanbeoperatedatveryhighspeed
- Smallerinsize
- Verycloseregulation
- Pre-compressioncanbeadjustedtogivetherequiredequilibriumspeed

4.4 TERMINOLOGYUSEDINGOVERNORS:HEIGHT,EQUILIBRIUMSPEED,HUNTING,ISOCHRONISMS,STABILITY,SENSITIVENESSOF AGOVERNOR

Height of Governor: It is the vertical distance from the centre of the ball to apoint where the axes of the arms (or arms produced) intersect on the spindleaxis.Itisusuallydenotedbyh.

Equilibrium Speed: It isthe speed at which the governor balls,armsetc., arein completeequilibrium andthesleevedoesnot tendtomoveupwardsordownwards.

Mean equilibrium speed: It is the speed at the mean position of the balls or thesleeve.

Maximum and minimum equilibrium speeds: The speeds at themaximumand minimum radius of rotation of the balls, without tending to move either wayareknownasmaximumandminimumequilibriumspeedsrespectively.

Sleeve lift: It is the vertical distance which the sleeve travels due to change inequilibriumspeed.

Hunting: It is a condition in which the speed of the engine controlled by thegovernor fluctuates continuously above and below the mean speed. It is causedbyagovernor whichistoosensitive.

Isochronisms: A governor is said to be isochronous, when the equilibriumspeed is constant for all radii of rotation of the balls, within the working range.Anisochronousgovernor willbeinfinitelysensitive.

Stability: A governor is said to be stable if it brings the speed of engine to therequired value and there is not much hunting. The ball masses occupy a definitepositionforeachspeed oftheenginewithintheworking range.

Sensitiveness: A governor is said to be sensitive when it readily respond to asmall variation in speed. It may also be defined as the ratio of mean speed to therangeofspeedofgovernor.

$$Sensitiveness=\frac{Meanspeed}{Rangeofspeed}$$

$$Sensitiveness=\frac{N}{\mathrm{N1}-\mathrm{N2}}$$

Thestabilityandsensitiveness ofagovernoraretwooppositecharacteristics.

CHAPTER-5CAMS

DEFINITION AND FUNCTION OF CAM, DESCRIPTION OFDIFFERENTTYPESOFCAMSANDFOLLOWERSWITHSIMPLELINEDIAGRAM.

DEFINITIONANDFUNCTIONOFACAM

Cam is amechanical element which is used to deliver the reciprocating oroscillating motion to another machine element known as follower. Cam andfollower is a type of assembly, both works together in any machine element.Cam andfollowersaretheexampleof higherpairduetothelinecontactbetween them. Some complicatedmotions are easily achieved by using camsand followers which are difficult to achieve. We can say that the cam andfollowersarethemostimportantpartofthemechanisms.Thecamsandfollowercombinationismostlyusedininternalcombustionenginesforoperating inlet and exhaust valves,machine tools, printing controlmechanismso on. They are generally manufactured by using die casting, milling and bypunching. A cam is a rotating or sliding piece in a mechanicallinkage thatdrives a mating component known as a follower. From a functional viewpoint, acam-and-follower arrangement is very similar to the linkages. The cam acceptsan input motion (rotary motion or linear motion) and imparts a resultant motion(linearmotionor rotarymotion)to afollower.

A cam andfollowerareamethodof convertingrotarymotionintolinearmotion.Themostwell-knownapplicationisinaninternalcombustionengine, where the cam and follower combination determines the opening times anddurationofthevalves.(viathepushrodandrocker arm).

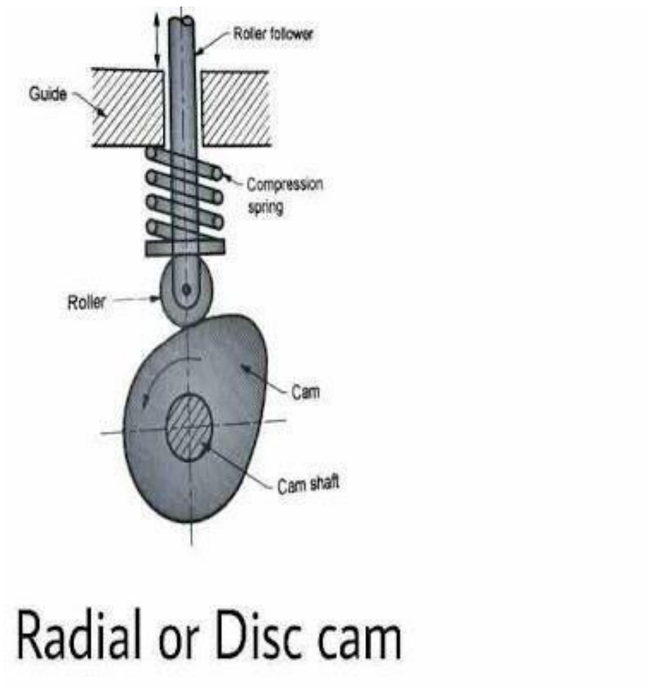
Other applications might be on industrial machinery, regulating opening andclosingofequipmentforfillingbottlesorcontainers,toys(forexamplea“quacking duck” toy, where a cam can be used to move the duck’s beak andmake the quack noise), in fact, any application where you want a fairly shortlinear motion at a regular repeated interval. Change of circular motion to thetranslatory (linear) motion of simple harmonic type and vice-versa and can bedone by slider-crank mechanism as discussed previously. But now the questionarises, what to do when circular or rotary motion is to be changed into linearmotion of complex nature or oscillatory motion. This job is well accomplishedbyamachinepart ofamechanicalmember,knownascam.

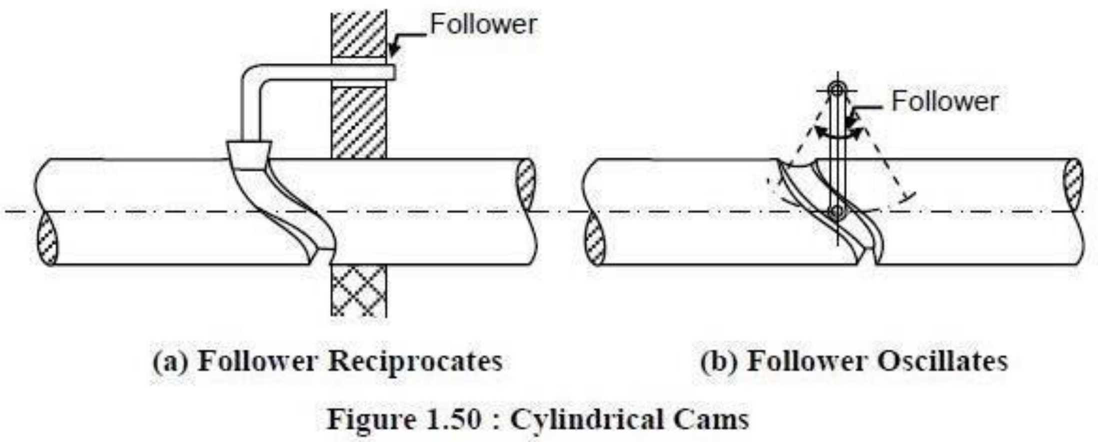
DIFFERENTTYPESOFCAMANDFOLLOWER

TypesofCam:

There aretwotypes ofcams:

- **Radial or Disc cam**: In radial cam, cam profile (shape of cam) is designin such way by which follower move as per the shape of cam or camprofileinperpendiculardirectiontothecam axis.Thereisalwayssurface contact between cam profile and follower by spring force orgravityforce.
- **Cylindrical cam:** In cylindrical cam, follower axis and cam axis areparallel to each other.Cylindrical cam iscylindrical shafton whichprofile made on cylindrical surface by machining. This profile is in thegrooveform andfollowerhassurfacecontactwiththisgroove.Ascylindricalshaftorcylindricalcamisrotatesfollowermoveandmovementoffollowermaybereciprocatingoroscillating.





cylindrical cam

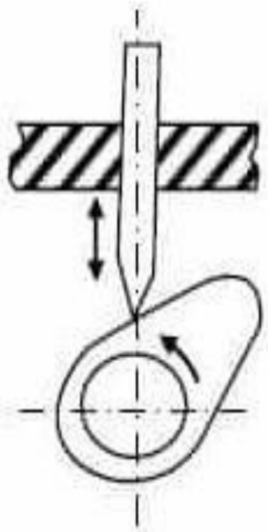
TypesofFollowers:

Followersmaybeclassifiedinthreedifferentways:

a) Dependinguponthetypeofmotion, i.e.reciprocatingoroscillating
b) Dependingupontheaxisofthemotion, i.e.radialoroffset.
c) Dependingupontheshapeoftheircontactingendwiththecam:Underthisclassificationfollowersmaybedividedintothreetypes:

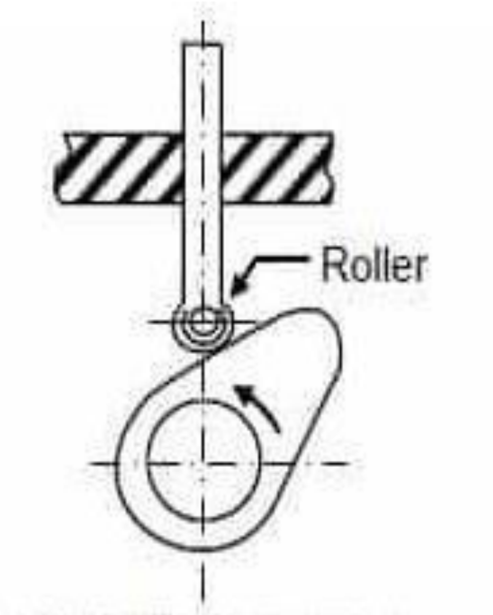
- Knife-edgeFollower
- RollerFollower
- FlatorMushroomFollower

Knife-edge Follower: Knife-edge followers are generally, not used because ofthe obvious high rate of wear at the knife edge. However, cam of any shape canbe worked with it. During working, considerable side thrust exists between thefollower andtheguide.



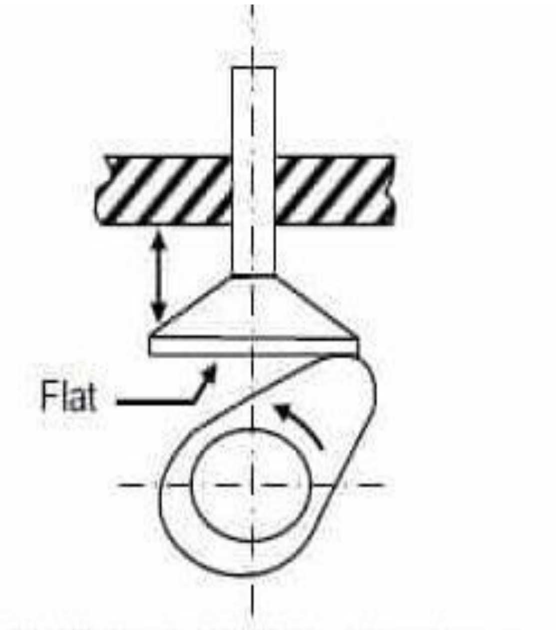
(a) Knife-edge Follower

Roller Follower: In place of a knife-edge, a roller is provided at the contactingend of the follower, hence, the name roller follower. Instead of sliding motionbetween the contacting surface of the follower and the cam, rolling motion takesplace, with the result that the rate of wear is greatly reduced. In roller followersalso, as in knife-edge follower, side thrust is exerted on the follower guide.Roller followers are extensively used in stationary gas and oil engines. They arealso used in aircraft engines due to their limited wear at high cam velocity.While working on the concavesurface of a cam the radius of the surface mustbeatleastequalto theradiusof theroller.



(b) Roller Follower

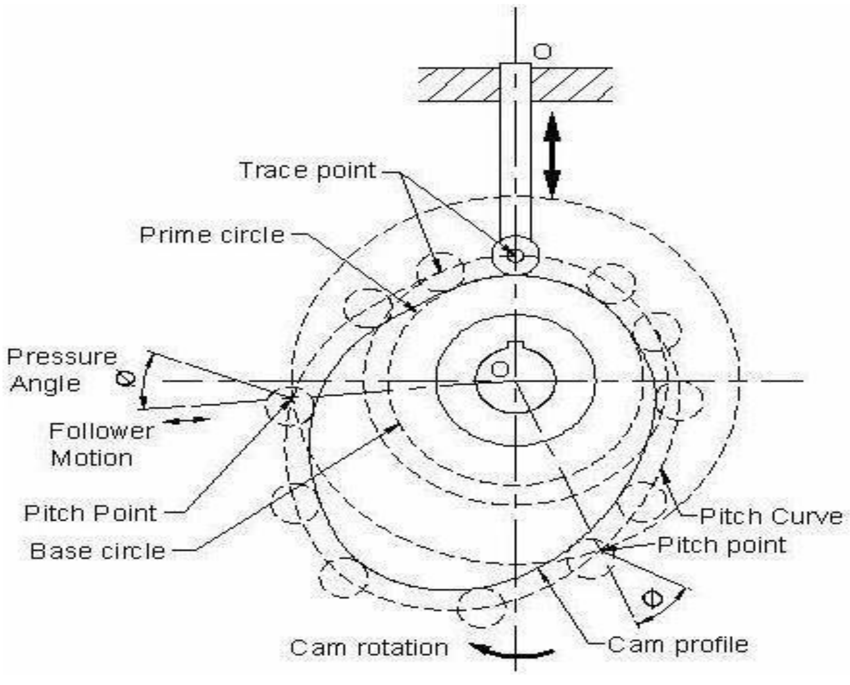
Flat or Mushroom Follower: At the name implies the contacting end of thefollower is flat as shown. In mushroom followers there is no side thrust on theguide except that due to friction at the contact of the cam and the follower. Nodoubt that there will be sliding motion between the contacting surface of thefollowerandthecambutthewearcanbeconsiderablyreducedbyoff-settingthe axis of the followers. The off-setting provided causes the follower to rotateabout its axis when the cam rotates. Flat face follower is used where the space islimited. That is why it is used to operate valves of automobile engines. Wheresufficientspaceisavailableasinstationarygasandoilengines,rollerfolloweris used as mentioned above. The flat-faced follower is generally preferred to theroller follower because of the compulsion of having to use a small diameter ofthe pin in the roller of the roller follower. In flat followers, high surface stressesareproducedintheflatcontactingsurface.Tominimizethesestresses,aspheric alshapeisgiventotheflatend.



(c) Flat or Mushroom Follower

TERMINOLOGYOFCAMPROFILE

- **Camprofile**:Camprofileisoutersurfaceofthedisccam.
- **Basecircle**:Basecircleisthesmallestcircle,drawntangentialtothecampr ofile.



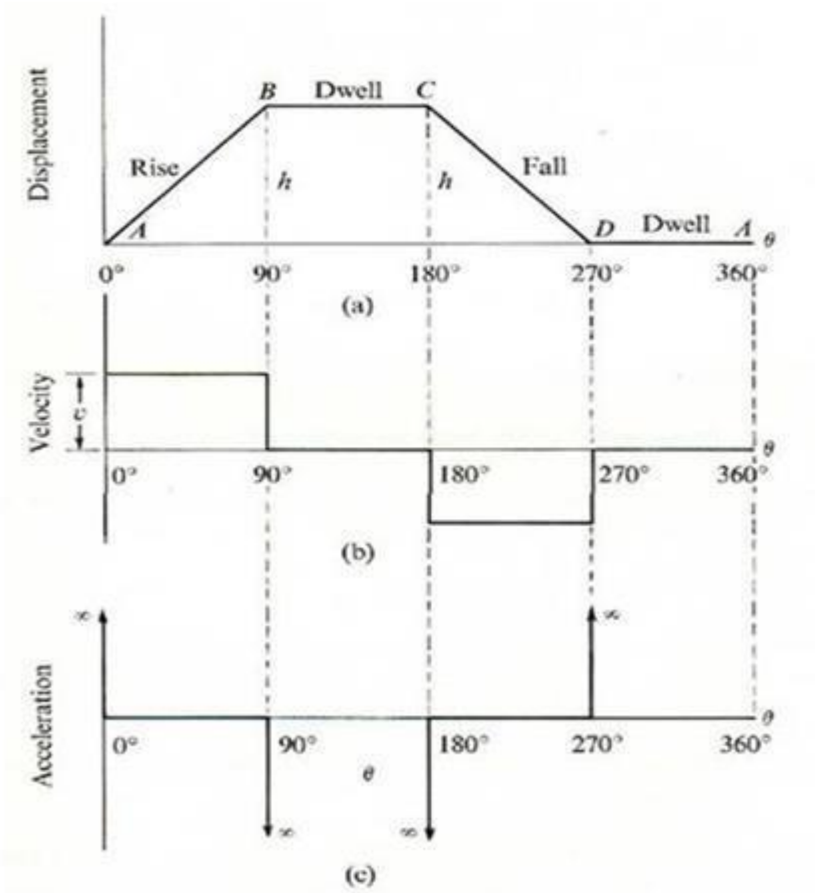
cam nomenclature

- **Tracepoint**:Tracepointisapointonthefollower,tracepointmotiondescribesthemovementofthefollower.
- **Pitchcurve:** Pitchcurveisthepathgeneratedbythetracepointasthefollower isrotatedaboutastationerycam.
- **Primecircle**:Primecircleisthesmallestcirclethatcanbedrawnsoastobe tangentialtothepitchcurve,withitscentreatthecamcentre.
- **Pressureangle:**Thepressureangleistheanglebetweenthedirectionofthefollowermovement andthenormaltothepitchcurve.
- **Pitchpoint:**Pitchpointcorrespondstothe pointofmaximumpressureangle.
- **Pitchcircle:**Acircledrawnfromthecamcenterandpasses throughthepitchpointiscalledPitchcircle
- **Stroke:**Thegreatestdistanceoranglethroughwhichthefollowermovesor rotates.

DISPLACEMENT DIAGRAMFORUNIFORMVELOCITY, S.H.M. AND UNIFORM ACCELERATION ANDDECELERATION.

FOLLOWERMOTIONWITHUNIFORMVELOCITY

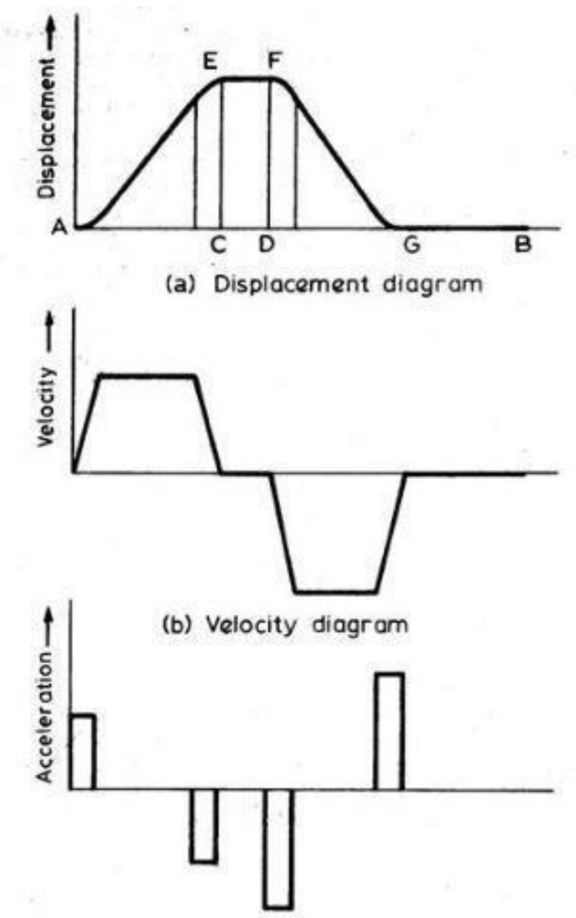
Figure below shows the displacement, velocity and acceleration patterns of afollower having uniform velocity type of motion. Since the follower moves withconstant velocity, during rise and fall, the displacement varies linearly with θ.Also, since the velocity changes from zero to a finite value, within no time,theoretically, the acceleration becomes infinite at the beginning and end of riseandfall.



Follower Motion with Uniform Velocity

FOLLOWERMOTIONWITHMODIFIEDUNIFORMVELOCITY

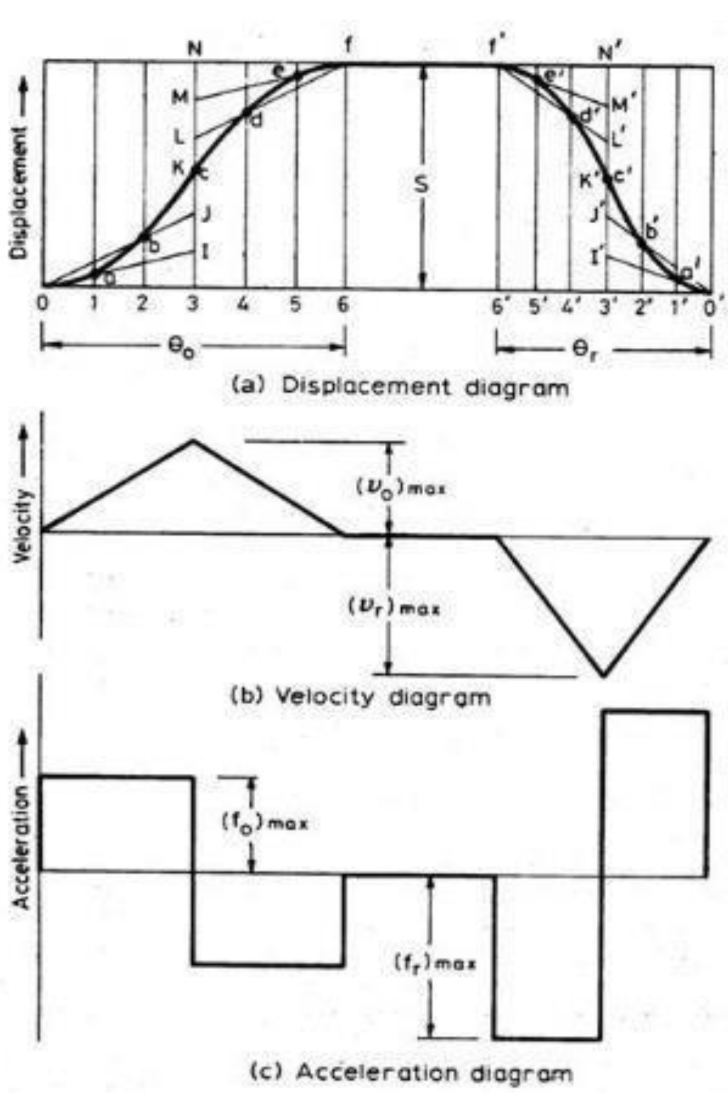
Itisobservedinthedisplacementdiagramsofthefollowerwithuniformvelocity that the acceleration of the follower becomes infinite at the beginningand ending of rise and return strokes. In order to prevent this, the displacementdiagramsareslightlymodified.Inthemodifiedform,thevelocityofthefollowerchangesuniformlyduringthebeginningandendofeachstroke.Accordingly, the displacement of the follower varies parabolically during theseperiods. With this modification, the acceleration becomes constant during theseperiods, instead of being infinite as in the uniform velocity type of motion. Thedisplacement,velocityandaccelerationpatternsareshown infigurebelow.



FollowerMotionwithModifiedUniformVelocity

FOLLOWERMOTIONWITHUNIFORMACCELERATIONANDR ETARDATION(UARM)

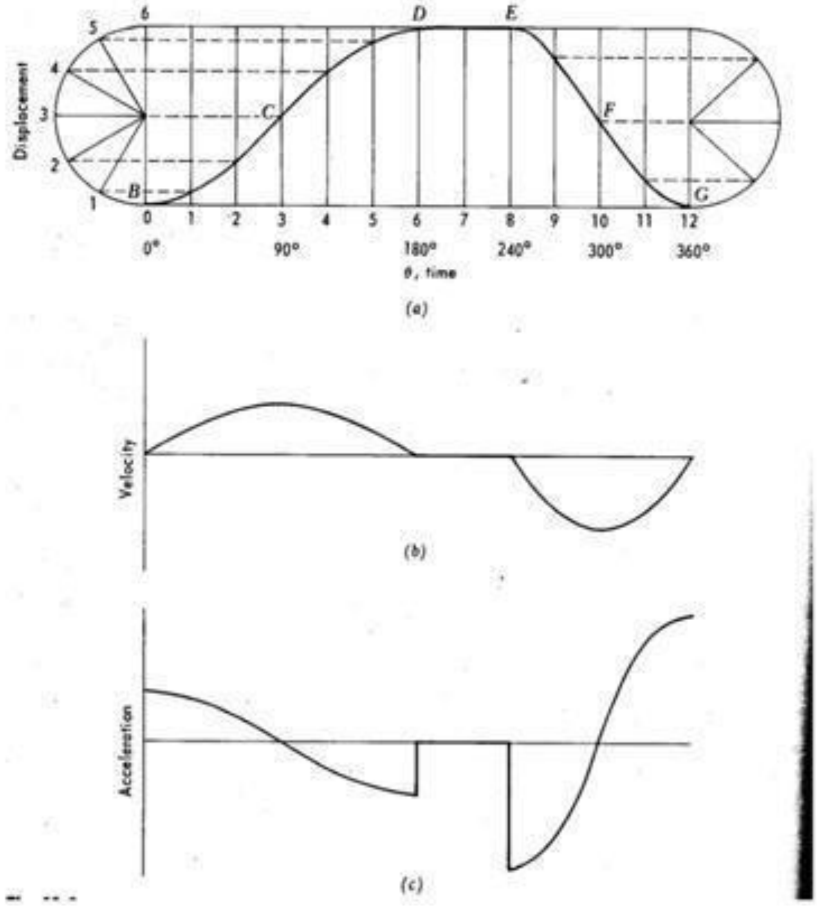
Here,thedisplacementofthefollowervariesparabolicallywithrespecttoangular displacement of cam. Accordingly, the velocity of the follower variesuniformlywithrespecttoangulardisplacementofcam.Theacceleration/retardationofthefollowerbecomesconstantaccordingly.Thedisplacement,velocityandaccelerationpatternsare shown infigurebelow.



Followermotionwithuniformaccelerationandretardation

FOLLOWERWITHSIMPLEHARMONICMOTION(SHM)

In fig.5, the motion executed by point Pl, which is the projection of point P onthe vertical diameter is called simple harmonic motion. Here, P moves withuniformangular velocityωp,alongacircleofradiusr(r=s/2).



FollowerDisplacementDiagramwithSimpleHarmonicMotion

CHAPTER-6BALANCING

NEEDOFBALANCING,CONCEPTOFSTATICANDDYNAMICBALANCING

NEEDOFBALANCING

Thebalancingofrotatingbodiesisimportanttoavoidvibration.Inheavyindustrial machines such as gas turbinesand electric generators, vibration cancause catastrophic failure, as well as noise and discomfort. In the case of anarrow wheel, balancing simply involves moving the center of gravityto thecenter of rotation. For a system to be in complete balancebothforceandcouple polygonsshould be closed in order to prevent the effect of centrifugalforce.Ifproperbalancingisnotdonethenwearandteardonesotoavoidwear & tearandforhighproductionproperbalancingisdone.

CONCEPTOFSTATICANDDYNAMICBALANCING

Static Balancing: Static balance occurs when the center of gravity of an objectis on the axis of rotation. The object can therefore remain stationary, with theaxis horizontal, without the application of any braking force. It has no tendencyto rotate due to the force of gravity. This is seen in bike wheels where thereflective plate is placed opposite the valve to distribute the center ofmass tothecenterofthewheel.

DynamicBalancing:Rotatingshaftunbalancedbytwoidenticalattachedweights, which causes a counterclockwise centrifugal couple Cd that must beresistedbyaclockwisecoupleFℓ=Cdexertedbythebearings.Thefigureis drawnfromtheviewpointofaframerotatingwiththeshaft,hencethecentrifugal forces.

A rotating system of mass is in dynamic balance when the rotation does notproduce any resultant centrifugal force or couple. The system rotates withoutrequiring the application of any external force or couple, other than that requiredto support its weight. If a system is initially unbalanced, to avoid the stress uponthe bearings caused by the centrifugal couple, counterbalancing weights must beadded. This is seen when a bicycle wheel gets buckled. The wheel willnotrotate itself when stationary due to gravity as it is still statically balanced, butwill not rotate smoothly as the centre of mass is to the side of the centre bearing.The spokes on a bike wheel need to be tuned in order to stop this and keep thewheeloperatingasefficientlyaspossible

INTRODUCTION TO BALANCING OF ROTATINGMASSES IN THE SAME PLANE AND DIFFERENT PLANES(SIMPLENUMERICAL)

INTRODUCTIONTOBALANCINGOFROTATINGMASSES

It is paramount to balance a rotating device both statically and dynamically toeliminate common performance problems such as vibrations, noise, and heatwhich maycausesystemfailure.

Thefollowingcasesareimportantfromthe subjectpointofview:

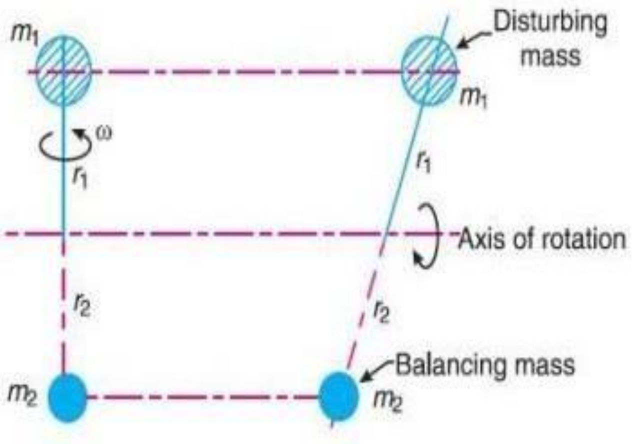
- Balancingofasinglerotatingmassbyasinglemassrotatinginthesamepl ane.
- Balancingofasinglerotatingmassbytwomassesrotatingindiffer entplanes.
- BalancingofSeveralMassesRotatingintheSamePlane.
- Balancingofdifferentmassesrotatingindifferentplanes.

Balancing of a Single Rotating Mass by a Single Mass Rotating in the SamePlane:

Consideradisturbingmassm1attachedtoashaftrotatingatωrad/s.

Let$r_1$betheradiusofrotationofthemassm_1.Weknowthatthecentrifugalforce

exerted by the mass m_1 on the shaft $F_{Cl} = m_1.\ \omega^2.\ r_1$ ....(1)



Thiscentrifugalforceproducesbendingmomentontheshaft.Inordertocounteract the effect of this force, a balancing mass (m_2) may be attached in thesame plane of rotation as that of disturbing mass (m_1) such that the centrifugalforces due to the two masses are equal and opposite. Let r_2= Radius of rotationofthebalancingmassm_2,centrifugalforceduetomassm_2,

$F_{C2}=m_2.\omega^2.\ r_2$ ....(2)

Equatingequations(1)and(2),m

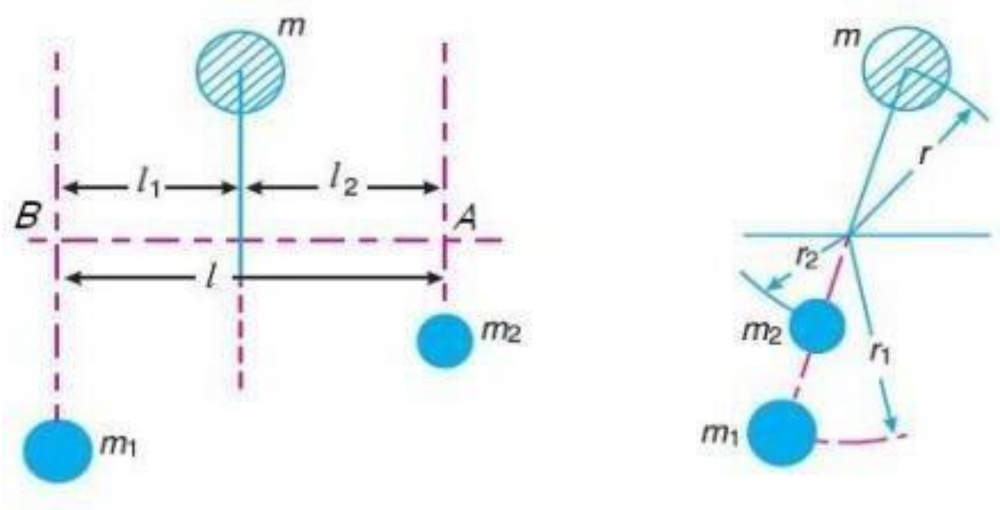
$_1.\omega^2.r_1=m_2.\omega^2.r_2$

or$m_1.r_1=m_2.r_2$

Balancing of a Single Rotating Mass by Two Masses Rotating in DifferentPlanes: In this case plane of disturbing mass lies in between the planes of thetwo balancingmasses.

Consider a disturbing mass m balanced by two rotating masses $m_1$and $m_2$asshowninFigure.

Letr,$r_1$andr$_2$betheradiiofrotationofthemassesm,$m_1$andm$_2$respectively.



ThenetforceactingontheshaftmustbeequaltozeroF$_C$=F$_{Cl}$+

F$_{C2}$

$m.\omega^2.r=m_1.\ \omega^2.\ r_1+m_2.\omega^2.$

r_2Or$m.r=m_1.r_1+m_2.r_2$

Nowinordertofindthemagnitudeofbalancingforceatthe

bearingBofashaft,takemomentsaboutA.Therefore

$F_{C1}\times l=F_C\times l_2$

$m_1.\ \omega^2.\ r_1\times l = m.\ \omega^2.\ r \times$

$l_2 m_1.r_1\times l=m.r\times l_2$

Similarly,inordertofindthebalancingforceatthebearingAofashaft,takemom

entsaboutB.Therefore

$F_{C2}\times l=F_C\times l_1$

$m_2.\ \omega^2.\ r_2\times l = m.\ \omega^2.\ r \times$

$l_1 m_2.r_2\times l=m.r\times l_1$

BalancingofSeveralMassesRotatingintheSamePlane:

Let us consider four masses m_1, m_2, $m_3$and $m_4$rigidly attached to the shaft andrevolving about the axis of the shaft. The corresponding radii of rotation are r_1,r_2, $r_3$and r_4. Let θ_1, θ_2, $\theta_3$and $\theta_4$be the angle of these masses with the horizontallineOX.Letωbetheangularvelocityof theshaftinrad/s.Themagnitudeand positionofthebalancingmassmaybefoundoutbytwomethods;(i)Analyticalmethod and(ii) Graphicalmethodasdiscussedbelow:

1. Analytical method :

(*i*) Find out the centrifugal force exerted by each mass on the rotating shaft.

(*ii*) Resolve each force horizontally and vertically *i.e.* to find ΣH and ΣV.

As ω^2 is same for each mass.

$$\therefore \quad \Sigma H = m_1 r_1 \cos\theta_1 + m_2 r_2 \cos\theta_2 + m_3 r_3 \cos\theta_3 + m_4 r_4 \cos\theta_4$$

Similarly,

$$\Sigma V = m_1 r_1 \sin\theta_1 + m_2 r_2 \sin\theta_2 + m_3 r_3 \sin\theta_3 + m_4 r_4 \sin\theta_4$$

(*iii*) Magnitude of resultant centrifugal force

$$F_c = \sqrt{(\Sigma H)^2 + (\Sigma V)^2}$$

(*iv*) If θ' is the angle, which the resultant force makes with the horizontal, then

$$\tan\theta' = \frac{\Sigma V}{\Sigma H}$$

Therefore the angle of balancing mass with the horizontal, $\theta = 180° + \theta'$

(*v*) The balancing force is equal to the resultant force, but in opposite direction.

(*vi*) Now, find out the magnitude of balancing mass, such as

$$F_c = mr \qquad [\because \omega^2 \text{ is same for each mass}]$$

where, m = balancing mass and r = its radius of rotation.

2. Graphical method :

(*i*) First, draw the space diagram with the position of several masses as shown in Fig.

(*ii*) Find out the centrifugal force exerted by each mass of the rotating shaft.

(*iii*) Now, draw the vector diagram with the obtained centrifugal force such that *ab* represents centrifugal force exerted by mass m_1 in magnitude and direction to some suitable scale. Similarly, draw *bc*, *cd* and *de* representing centrifugal forces of other masses, m_2, m_3 and m_4.

(*iv*) Now, as per polygon law of forces, the closing side *ae* represents the resultant force in magnitude and direction as shown in Fig.

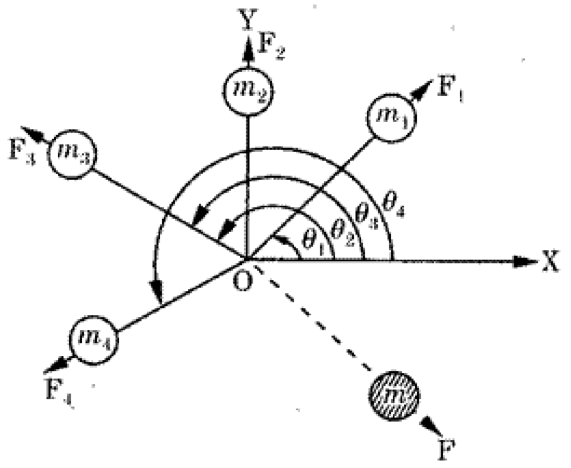
(*v*) The balancing force is then equal to the resultant force, but in opposite direction.

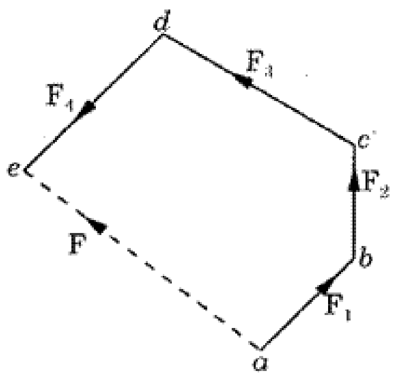
(*vi*) Now, find out the magnitude of balancing mass (m), at a given radius of rotation (r), such that

$$m\omega^2 r = \text{resultant centrifugal force, } F_c$$

or $$mr = \text{resultant of } m_1r_1,\ m_2r_2,\ m_3r_3 \text{ and } m_4r_4$$

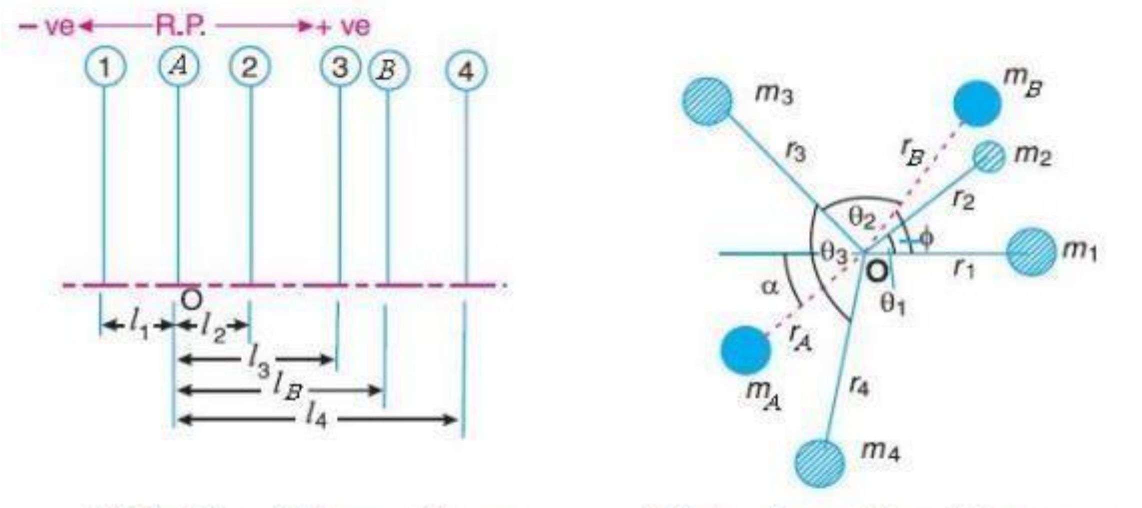
or $$mr = \text{Resultant vector } ae$$



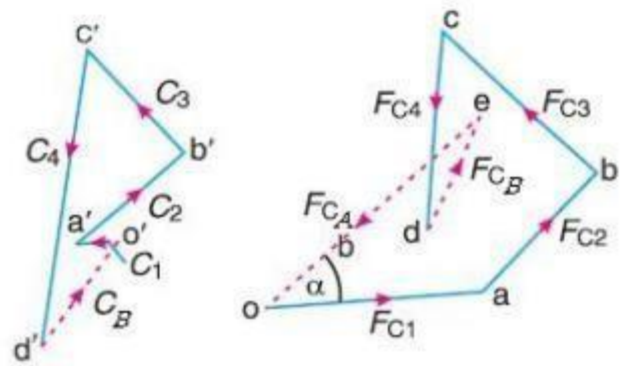


BalancingofSeveralMassesRotatinginDifferentPlanes:

Let us consider four masses m_1, m_2, $m_3$and $m_4$revolving in planes 1, 2, 3 and 4respectively as shown in Figure (a). The relative angular positions of thesemasses are shown in Figure (b). The magnitude of the balancing masses $m_A$and$m_B$inplanesAandBmaybeobtainedasdiscussedbelow:



(*a*) Position of planes of the masses. (*b*) Angular position of the masses.



(*c*) Couple polygon. (*d*) Force polygon.

1. Takeoneoftheplanes;sayAas thereferenceplane(R.P.).
2. Tabulatethedata asshowninTable:2.
3. Thecouplesaboutthereferenceplanemustbalance,i.e.theresultantcouplemust bezero.

$$\sum_{i=1}^{n} m_i\, r_i\, l_i\, \cos\theta_i + m_B\, r_B\, l_B \cos\theta_B = 0$$

$$\sum_{i=1}^{n} m_i\, r_i\, l_i\, \sin\theta_i + m_B\, r_B\, l_B \sin\theta_B = 0$$

Theforcesinthereferenceplanemustbalance,i.e.theresultantforcemustbezero.

$$\sum_{i=1}^{n} m_i\, r_i\, \cos\theta_i + m_A\, r_A\, \cos\theta_A = 0$$

$$\sum_{i=1}^{n} m_i\, r_i\, \sin\theta_i + m_A\, r_A\, \sin\theta_A = 0$$

Example: 1

Four masses m_1, m_2, m_3 and m_4 are 200 kg, 300 kg, 240 kg and 260 kg respectively. The corresponding radii of rotation are 0.2 m, 0.15 m, 0.25 m and 0.3 m respectively and the angles between successive masses are 45°, 75° and 135°. Find the position and magnitude of the balance mass required, if its radius of rotation is 0.2 m.

Solution:

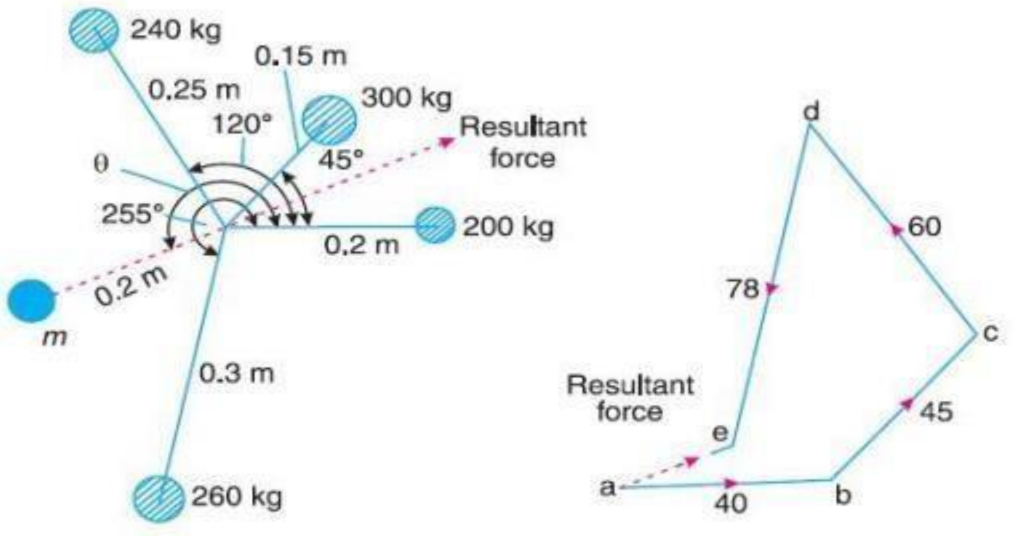
Let m = Balancing mass, and

θ = The angle which the balancing mass makes with m_1.

1. Analytical method

$$\Sigma H = \sum_{i=1}^{n} m_i r_i \cos\theta_i$$

$$\Sigma H = 40\cos 0 + 45\cos 45 + 60\cos 120 + 78\cos 255 = 21.63 \text{ kg.m}$$



(*a*) Space diagram. (*b*) Vector diagram

No. of masses	Mass (kg)	Radius (m)	Angle(deg.)	Centrifugal force ÷ ω^2 (kg.m)
1	200	0.2	0	40
2	300	0.15	45	45
3	240	0.25	120	60
4	260	0.3	255	78
5	m	0.2	θ	$m.r$

$$\Sigma V = \sum_{i=1}^{n} m_i r_i \sin\theta_i$$

$$\Sigma V = 40 \sin 0 + 45 \sin 45 + 60 \sin 120 + 78 \sin 255 = 8.43 \text{ kg.m}$$

$$F_C = \sqrt{(2163.2)^2 + (843.9)^2} = 23.21 \text{ kg.m}$$

$$F_C = m.r, \qquad 23.21 = 0.2 \times m \quad \therefore \quad m = 116 \text{ kg}$$ **Ans.**

$$\tan \acute{\theta} = \frac{\Sigma V}{\Sigma H} = \frac{8.43}{21.63} \qquad \therefore \qquad \acute{\theta} = 21.3°$$

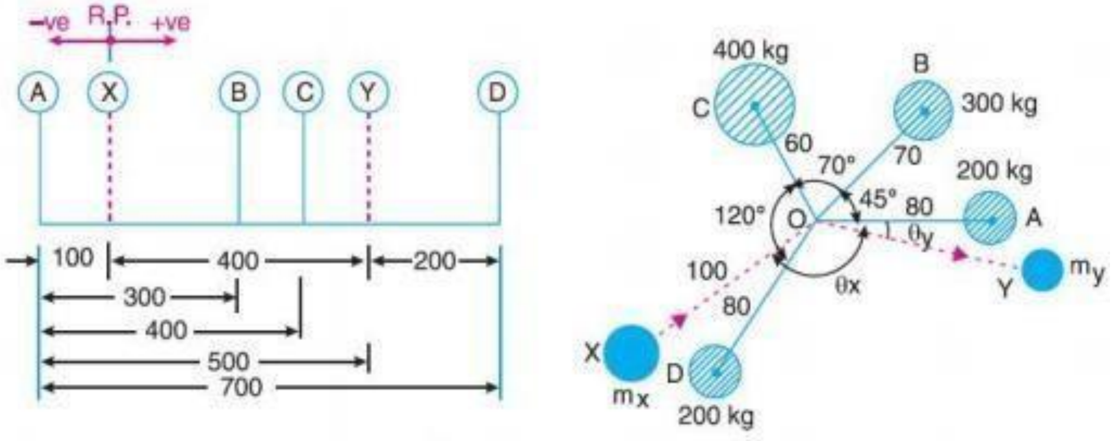
Since $\acute{\theta}$ is the angle of the resultant R from the horizontal mass of 200 kg, therefore the angle of the balancing mass from the horizontal mass of 200 kg,

$$\theta = 180° + 21.48° = 201.48°$$ **Ans.**

Example: 2

A shaft carries four masses A, B, C and D of magnitude 200 kg, 300 kg, 400 kg and 200 kg respectively and revolving at radii 80 mm, 70 mm, 60 mm and 80 mm in planes measured from A at 300 mm, 400 mm and 700 mm. The angles between the cranks measured anticlockwise are A to B 45°, B to C 70° and C to D 120°. The balancing masses are to be placed in planes X and Y. The distance between the planes A and X is 100 mm, between X and Y is 400 mm and between Y and D is 200 mm. If the balancing masses revolve at a radius of 100 mm, find their magnitudes and angular positions.

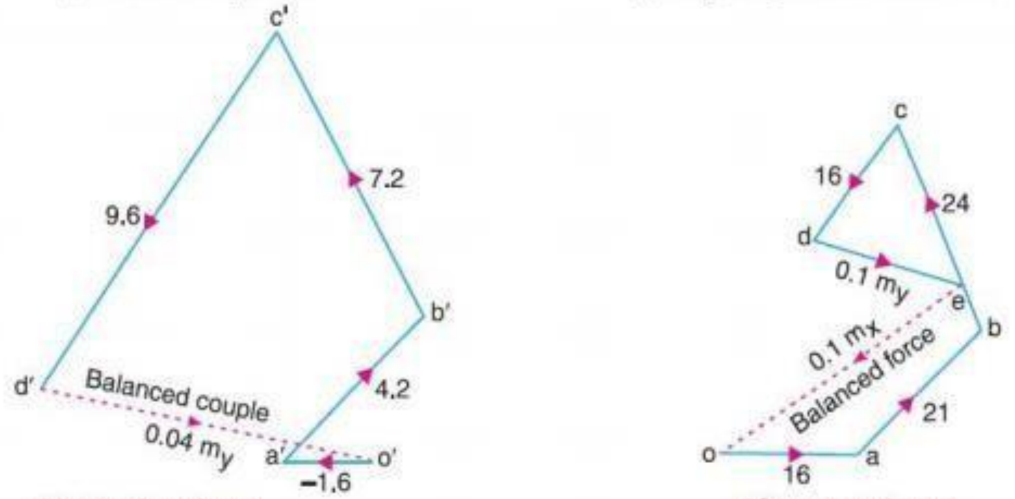
Solution



All dimensions in mm.

(*a*) Position of planes.

(*b*) Angular position of masses.



(*c*) Couple polygon.

(*d*) Force polygon.

Plane (1)	*Mass (m)* kg (2)	*Radius (r)* m (3)	*Cent.force* $\div \omega^2$ (m.r) kg-m (4)	*Distance from Plane x(l)* m (5)	*Couple* $\div \omega^2$ (m.r.l) kg-m^2 (6)
A	200	0.08	16	– 0.1	– 1.6
X(*R.P.*)	m_X	0.1	0.1 m_X	0	0
B	300	0.07	21	0.2	4.2
C	400	0.06	24	0.3	7.2
Y	m_Y	0.1	0.1 m_Y	0.4	0.04 m_Y
D	200	0.08	16	0.6	9.6