Subject Name: **Theory of machines & mechanics**

Subject Code: **ME-3003**

Semester: **3rd**

Unit-II

Motion: Plane motion, Absolute & Relative motion, Displacement, Velocity and Acceleration of a point, Velocity and Acceleration Analysis by Graphical & Analytical methods, Velocity image, Velocity of rubbing, Kennedy's Theorem, Acceleration image, Acceleration polygon, Coriolis acceleration component, Klein's construction, Velocity and Acceleration Analysis using Complex Algebra (Raven's Approach), Numerical problems based on above topics

Plane motion: When the motion of a body is confined to only one plane, the motion is said to be **plane motion.** The plane motion may be either rectilinear or curvilinear

Rectilinear Motion: It is the simplest type of motion and is along a straight line path. Such a motion is also known as **translatory motion.**

Curvilinear Motion: It is the motion along a curved path. Such a motion, when confined to one plane, is called **plane curvilinear motion.**

Absolute Motion: Absolute motion is **motion** that does not depend on anything external to the moving object for its existence or specific nature.

Relative motion: Relative motion is the calculation of the **motion** of an object with regard to some other moving object. Thus, the **motion** is not calculated with reference to the earth, but is the **velocity** of the object in reference to the other moving object as if it were in a static state.

Linear Displacement: It may be defined as the distance moved by a body with respect to a certain fixed point. The displacement may be along a straight or a curved path. In a reciprocating steam engine, all the particles on the piston, piston rod and cross-head trace a straight path, whereas all particles on the crank and crank pin trace circular paths, whose centre lies on the axis of the crank shaft. It will be interesting to know, that all the particles on the connecting rod neither trace a straight path nor a circular one; but trace an oval path, whose radius of curvature changes from time to time.
The displacement of a body is a vector quantity, as it has both magnitude and direction. Linear displacement may, therefore, be represented graphically by a straight line.

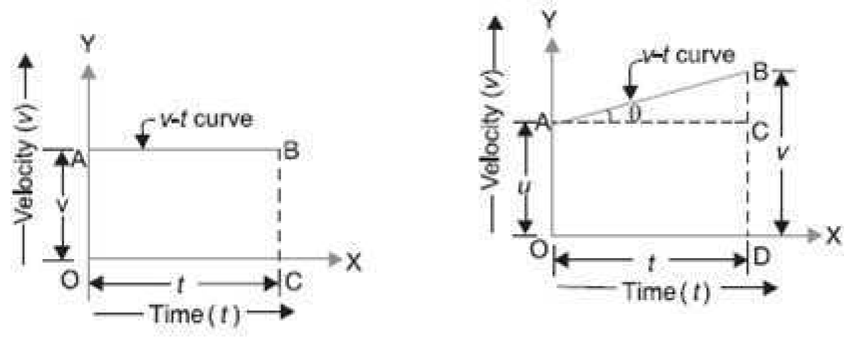
Linear Velocity: It may be defined as the rate of change of linear displacement of a body with respect to the time. Since velocity is always expressed in a particular direction, therefore it is a vector quantity. Mathematically, linear velocity,
$v = ds/dt$

Acceleration of a point: It may be defined as the rate of change of linear velocity of a body with respect to the time. It is also a vector quantity. Mathematically, linear acceleration,
$A = dv/dt = d/dt\,(ds/dt) = d^2s/dt^2$
Velocity and Acceleration Analysis by Graphical
Graphical Representation of Velocity with Respect to Time
We shall consider the following two cases:
1. When the body moves with uniform velocity. When the body moves with zero acceleration, then the body is said to move with a uniform velocity and the velocity-time curve (v -t curve) is represented by a straight line as shown by AB in Fig. 2.1.
We know that distance covered by a body in time t second
= Area under the v-t curve A B
= Area of rectangle OABC
Thus, the distance covered by a body at any interval of time is given by the area under the v-t curve.

2. When the body moves with variable velocity. When the body moves with constant acceleration, the body is said to move with variable velocity. In such a case, there is equal variation of velocity in equal intervals of time and the velocity-time curve will be a straight line AB inclined at an angle θ, as shown in Fig. 2.1. The equations of motion i.e. $v = u + a.\,t$, and
$s = u.\,t + \frac{1}{2}\,a.t^2$ may be verified from this v-t curve.

Let u = Initial velocity of a moving body, and
v = Final velocity of a moving body after time t.

$\tan\theta$ = BC/AC = (v-u) / t = Change in Velocity / Time = Acceleration (a)



(a) Uniform Velocity (b) Variable Velocity

Fig. 2.1

Thus, the slope of the v-t curve represents the acceleration of a moving body

$\tan\theta$ = BC/AC = (v-u) / t Or v=u + at

Since the distance moved by a body is given by the area under the v-t curve, therefore distance moved in time (t),

S = Area OABD = Area OACD + Area ABC

S = u. t + ½ (v-u) t = u. t + ½ a. t^2

Graphical Representation of Acceleration with Respect to Time

We shall consider the following two cases:

1. **When the body moves with uniform acceleration.** When the body moves with uniform acceleration, the acceleration-time curve (a-t curve) is a straight line, as shown in Fig. (a). Since the change in velocity is the product of the acceleration and the time, therefore the area under the a-t curve (i.e. OABC) represents the change in velocity.

2. **When the body moves with variable acceleration**. When the body moves with variable acceleration, the a-t curve may have any shape depending upon the values of acceleration at various instances, as shown in Fig. 2.3(b). Let at any instant of time t, the acceleration of moving body is a.

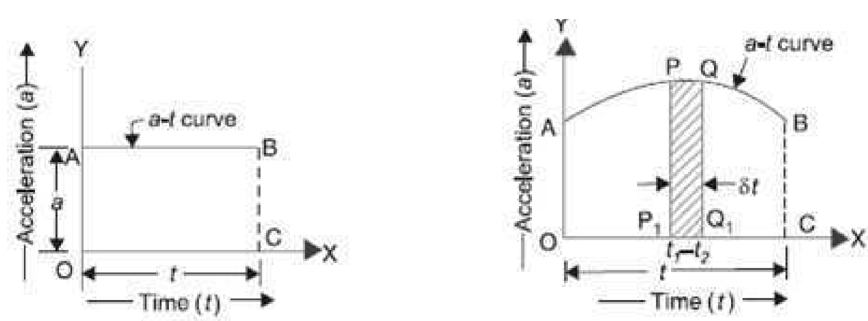
Mathematically, a = dv / dt or dv = a. dt

Integrating both sides,

$\int_{v1}^{V2} dv = \int_{t1}^{t2} a.\,dt$ Or $v2 - v1 = \int_{t1}^{t2} a.\,dt$

Where v_1 and v_2 are the velocities of the moving body at time intervals t_1 and t_2 respectively.

The right hand side of the above expression represents the area (PQQ_1P_1) under the a-t curve between the time intervals t_1 and t_2. Thus the area under the a-t curve between any two ordinates represents the change in velocity of the moving body. If the initial and final velocities of the body are u and v, then the above expression may be written as



(a) Uniform Velocity (b) Variable Velocity

Fig. 2.2

Velocity of a Point on a Link by Relative Velocity Method:

The relative velocity method is based upon the relative velocity of the various points of the link.

Consider two points A and B on a link as shown in Fig. 2.3. Let the absolute velocity of the point A i.e. v_A is known in magnitude and direction and the absolute velocity of the point B i.e. v_B is known in direction only. Then the velocity of B may be determined by drawing the velocity diagram as shown in Fig. 2.3 (b). The velocity diagram is drawn as follows:

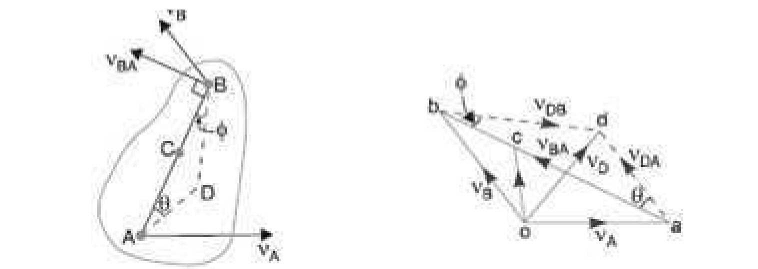
1. Take some convenient point o, known as the pole.

2. Through o, draw oa parallel and equal to v_A, to some suitable scale.

3. Through a, draw a line perpendicular to A B of Fig. 2.3 (a). This line will represent the velocity of B with respect to A, i.e. v_{BA}.

4. Through o, draw a line parallel to v_B intersecting the line of v_{BA} at b.

5. Measure ob, which gives the required velocity of point B (v_B), to the scale.



(a) Motion of points on a link (b) Velocity Diagram

Fig. 2.3

Velocities in Slider Crank Mechanism

In the previous article, we have discussed the relative velocity method for the velocity of any point on a link, whose direction of motion and velocity of some other point on the same link is known. The same method may also be applied for the velocities in a slider crank mechanism.

A slider crank mechanism is shown in Fig. 2.4. The slider A is attached to the connecting rod AB. Let the radius of crank OB be r and let it rotates in a clockwise direction, about the point O with uniform angular velocity ω rad/s. Therefore, the velocity of B i.e. v_B is known in magnitude and direction. The slider reciprocates along the line of stroke AO.

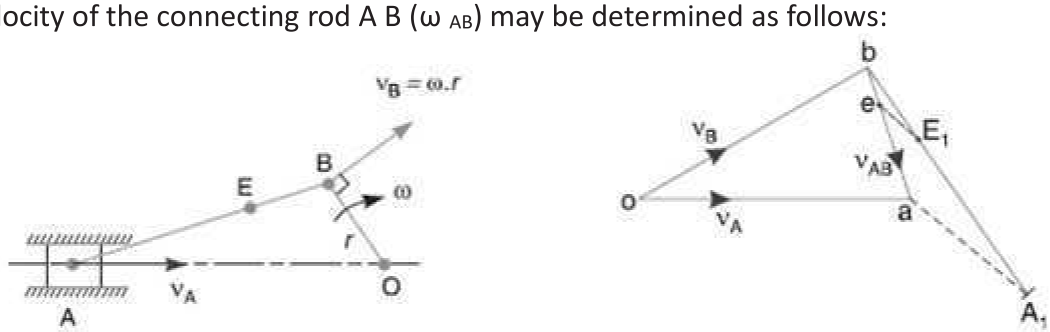
The velocity of the slider A (i.e. v_A) may be determined by relative velocity method as discussed below:

1. From any point o, draw vector ob parallel to the direction of v_B (or perpendicular to OB) such that ob = v_B = ω .r, to some suitable scale, as shown in Fig. 2.4.

2. Since A B is a rigid link, therefore the velocity of A relative to B is perpendicular to A B. Now draw vector ba perpendicular to A B to represent the velocity of A with respect to B i.e. v_{AB}.

3. From point o, draw vector oa parallel to the path of motion of the slider A (which is along AO only). The vectors ba and oa intersect at a. Now oa represents the velocity of the slider A i.e. v_A, to the scale.

The angular velocity of the connecting rod A B (ω_{AB}) may be determined as follows:



(a) Slider Crank Mechanism (b) Velocity Diagram

Fig. 2.4

$\omega_{AB} = v_{BA} / AB = ab / AB$ (anti-clockwise about A)

The direction of vector ab (or ba) determines the sense of ω_{AB} which shows that it is anticlockwise.

Rubbing Velocity at a Pin Joint:

The links in a mechanism are mostly connected by means of pin joints. The rubbing velocity is defined as **the algebraic sum between the angular velocities of the two links which are connected by pin joints, multiplied by the radius of the pin.**

Consider two links OA and OB connected by a pin joint at O as shown in Fig. 2.5.

Let ω1 = Angular velocity of the link OA or the angular velocity of the point A with respect to O.

ω2 = Angular velocity of the link OB or the angular velocity of the point B with respect to O, and

r = Radius of the pin.

According to the definition,

Rubbing velocity at the pin joint O

= (ω1 – ω2) r, if the links move in the same direction

= (ω1 + ω2) r, if the links move in the opposite direction

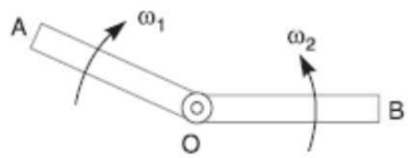


Fig. 2.5

Kennedy's Theorem:

The Aronhold Kennedy's theorem states that **if three bodies move relatively to each other**, **they have three instantaneous centre and lie on a straight line.**

Consider three kinematic links A, B and C having relative plane motion. The number of instantaneous centers (N) is given by

N = n(n-1)/2 = 3(3-1)/2 = 3

where n = Number of links = 3

The two instantaneous centers at the pin joints of B with A, and C with A (i.e. I_{ab} and I_{ac}) are the permanent instantaneous centers. According to Aronhold Kennedy's theorem, the third instantaneous centre I_{bc} must lie on the line joining I_{ab} and I_{ac}. In order to prove this, let us consider that the instantaneous centre I_{bc} lies outside the line joining I_{ab} and I_{ac} as shown in Fig. The point I_{bc} belongs to both the links B and C. Let us consider the point I_{bc} on the link B. Its velocity v_{BC} must be perpendicular to the line joining I_{ab} and I_{bc}. Now consider the point I_{bc} on the link C. Its velocity v_{BC} must be perpendicular to the line joining Iac and Ibc.

The velocity of the instantaneous centre is same whether it is regarded as a point on the first link or as a point on the second link. Therefore, the velocity of the point I_{bc} cannot be perpendicular to both lines I_{ab} I_{bc} and I_{ac} I_{bc} unless the point I_{bc} lies on the line joining the points I_{ab} and I_{ac}. Thus the three instantaneous centres (I_{ab}, I_{ac} and I_{bc}) must lie on the same straight line. The exact location of I_{bc} on line I_{ab} I_{ac} depends upon the directions and magnitudes of the angular velocities of B and C relative to A.

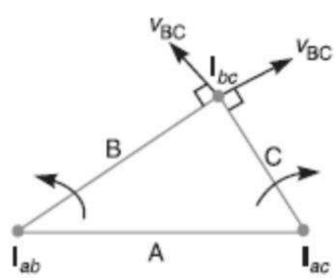


Fig. 2.6

Method of Locating Instantaneous Centers in a Mechanism

Consider a pin jointed four bar mechanism as shown in Fig. 2.7 (a). The following procedure is adopted for locating instantaneous centers.

1. First of all, determine the number of instantaneous centers (N) by using the relation
$N = n(n-1)/2$

2. Make a list of all the instantaneous centers in a mechanism. Since for a four bar mechanism, there are six instantaneous centers, therefore these centers are listed as shown in the following table (known as book-keeping table).

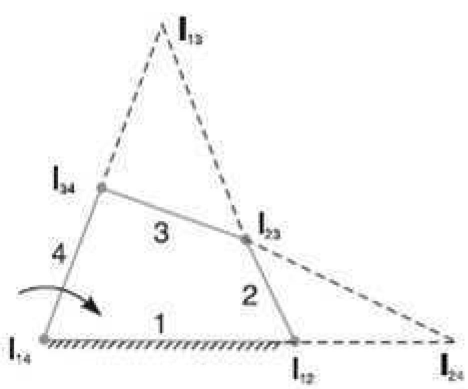
Links	1	2	3	4
Instantaneous Centers	12	23	34	–
(6 in number)	13	24		
	14			

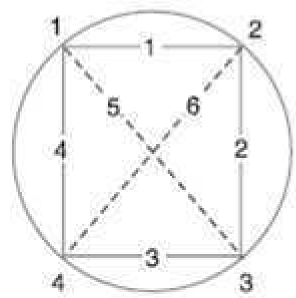
3. Locate the fixed and permanent instantaneous centers by inspection. In Fig. 2.7, I_{12} and I_{14} are fixed instantaneous centers and I_{23} and I_{34} are permanent instantaneous centers.

4. Locate the remaining neither fixed nor permanent instantaneous centers (or secondary centers) by Kennedy's theorem. This is done by circle diagram as shown in Fig. Mark points on a circle equal to the number of links in a mechanism. Mark 1, 2, 3 and 4 on the circle.

5. Join the points by solid lines to show that these centers are already found. In the circle diagram [Fig. 2.7] these lines are 12, 23, 34 and 14 to indicate the centers I_{12}, I_{23}, I_{34} and I_{14}.

6. In order to find the other two instantaneous centers, join two such points that the line joining them forms two adjacent triangles in the circle diagram. The line which is responsible for completing two triangles should be a common side to the two triangles. In Fig. 2.7 (b), join 1 and 3
to form the triangles 123 and 341 and the instantaneous centre I_{13} will lie on the intersection of I_{12} I_{23} and I_{14} I_{34}, produced if necessary, on the mechanism. Thus the instantaneous centre I_{13} is located. Join 1 and 3 by a dotted line on the circle diagram and mark number 5 on it. Similarly the instantaneous centre I_{24} will lie on the intersection of I_{12} I_{14} and I_{23} I_{34}, produced if necessary, on the mechanism. Thus I_{24} is located. Join 2 and 4 by a dotted line on the circle diagram and mark 6 on it. Hence all the six instantaneous centers are located.





(a) Four bar mechanisms (b) Circle Diagram

Fig. 2.7

Acceleration of a Point on a Link:

Consider two points A and B on the rigid link, as shown in Fig. 2.8 (a). Let the acceleration of the point A i.e. a_A is known in magnitude and direction and the direction of path of B is given. The acceleration of the point B is determined in magnitude and direction by drawing the acceleration diagram as discussed below.

1. From any point o', draw vector o'a' parallel to the direction of absolute acceleration at point A i.e. a_A , to some suitable scale, as shown in Fig.

2. We know that the acceleration of B with respect to A i.e. a_{BA} has the following two components:

(i) Radial component of the acceleration of B with respect to A i.e. a_{BA}^r , and

(ii) Tangential component of the acceleration B with respect to A i.e. a_{BA}^t . These two components are mutually perpendicular.

3. Draw vector a'x parallel to the link A B (because radial component of the acceleration of B with respect to A

will pass through AB), such that
Vector a'x = a_{BA}^r = v_{BA}^2 / AB
Where v_{BA} = Velocity of B with respect to A.

4. From point x , draw vector xb' perpendicular to A B or vector a'x (because tangential component of B with respect to A i.e. a_{BA}^t , is perpendicular to radial component a_{BA}^r) and through o' draw a line parallel to the path of B to represent the absolute acceleration of B i.e. a_B. The vectors xb' and o' b' intersect at b'. Now the values of a_B and a_{BA}^t may be measured, to the scale.

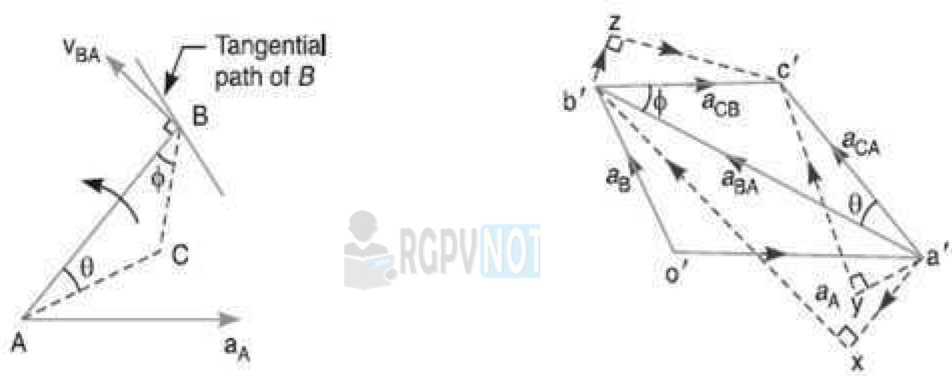
5. By joining the points a' and b' we may determine the total acceleration of B with respect to A i.e. a_{BA}. The vector a' b' is known as **acceleration image** of the link A B.

6. For any other point C on the link, draw triangle a' b' c' similar to triangle ABC. Now vector b' c' represents the acceleration of C with respect to B i.e. a_{CB}, and vector a' c' represents the acceleration of C with respect to A i.e. a_{CA}. As discussed above, a_{CB} and a_{CA} each will have two components as follows:

(i) a_{CB} has two components; a_{CB}^r and a_{CB}^t as shown by triangle b' zc' in Fig. 2.8 (b), in which b' z is parallel to BC and zc' is perpendicular to b' z or BC.

(ii) a_{CA} has two components ; a_{CA}^r and a_{CA}^t as shown by triangle a' yc' in Fig. 2.8 (b), in which a' y is parallel to A C and yc' is perpendicular to a' y or A C.

7. The angular acceleration of the link AB is obtained by dividing the tangential components of the acceleration of B with respect to A (a_{BA}^t) to the length of the link. Mathematically, angular acceleration of the link A B,
ω_{AB} = a_{BA}^t / AB



(a) Points on a link (b) Acceleration Diagram

Fig. 2.8

Acceleration in the Slider Crank Mechanism:

A slider crank mechanism is shown in Fig. 2.9. Let the crank OB makes an angle θ with the inner dead centre (I.D.C) and rotates in a clockwise direction about the fixed point O with uniform angular velocity ω_{BO} rad/s.

∴ Velocity of B with respect to O or velocity of B (because O is a fixed point), v_{BO} = v_B = ω_{BO} × OB, acting tangentially at B

We know that centripetal or radial acceleration of B with respect to O or acceleration of B (because O is a fixed point),

$a^r_{BO} = a_B = \omega^2_{BO} \times OB = v^2_{BO} / OB$

The acceleration diagram, as shown in Fig. may now be drawn as discussed below:

1. Draw vector o' b' parallel to BO and set off equal in magnitude of a_{BO}^r = a_B, to some suitable scale.

2. From point b', draw vector b'x parallel to B A. The vector b'x represents the radial component of the acceleration of A with respect to B whose magnitude is given by:

$a_{AB}^r = v_{AB}^2 / BA$

Since the point B moves with constant angular velocity, therefore there will be no tangential component of the acceleration.

3. From point x, draw vector xa' perpendicular to b'x (or A B). The vector xa' represents the tangential component of the acceleration of A with respect to B i.e. a_{AB}^t.

4. Since the point A reciprocates along A O, therefore the acceleration must be parallel to velocity. Therefore

from o', draw o' a' parallel to A O, intersecting the vector xa' at a'.
Now the acceleration of the piston or the slider A (a_A) and a_{AB}^t may be measured to the scale.

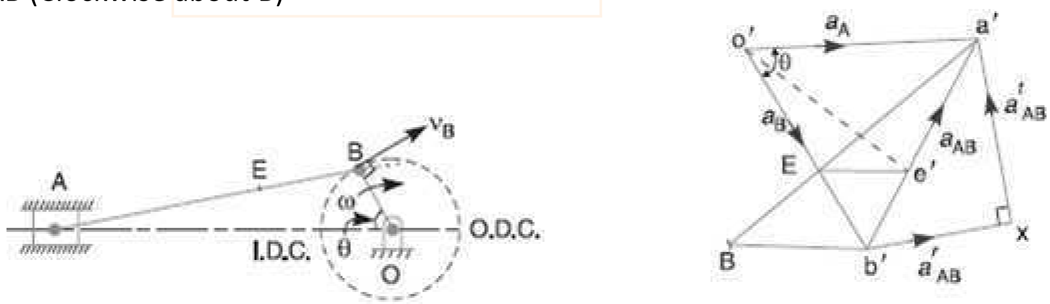
5. The vector b' a', which is the sum of the vectors b' x and x a', represents the total acceleration of A with respect to B i.e. a_{AB}. The vector b' a' represents the acceleration of the connecting rod A B.

6. The acceleration of any other point on A B such as E may be obtained by dividing the vector b' a' at e' in the same ratio as E divides A B in Fig. In other words

a' e' / a' b' = AE / AB

7. The angular acceleration of the connecting rod A B may be obtained by dividing the tangential component of the acceleration of A with respect to B a_{AB}^t to the length of A B. In other words, angular acceleration of AB,

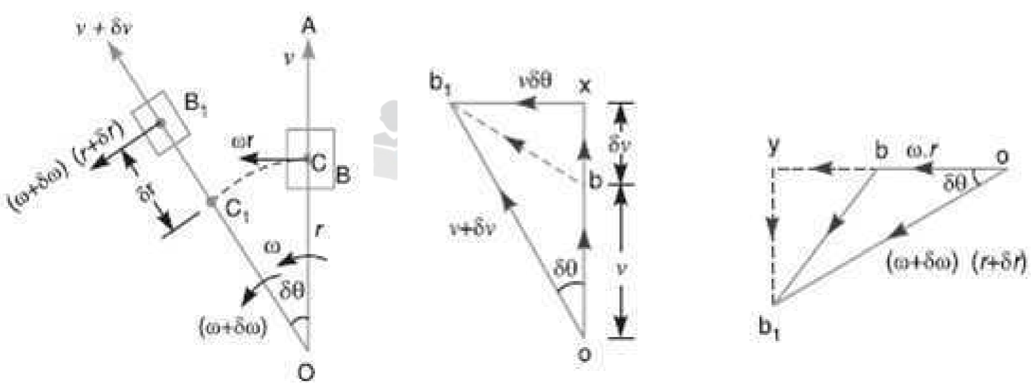
$\alpha_{AB} = a_{AB}^t / AB$ (Clockwise about B)



(a) Slider Crank Mechanism (b) Acceleration Diagram

Fig. 2.9

Coriolis Component of Acceleration



(a) (b) (c)

Fig. 2.10

When a point on one link is sliding along another rotating link, such as in quick return motion mechanism, then the coriolis component of the acceleration must be calculated.

Consider a link O A and a slider B as shown in Fig. 2.10 (a). The slider B moves along the link O A. The point C is the coincident point on the link O A.

Let ω = Angular velocity of the link OA at time t seconds.

v = Velocity of the slider B along the link OA at time t seconds.

ω .r = Velocity of the slider B with respect to O (perpendicular to the link O A) at time t seconds, and (ω + δω), (v + δv) and (ω + δω) (r + δr)

= Corresponding values at time (t + δt) seconds

Let us now find out the acceleration of the slider B with respect to O and with respect to its coincident point C lying on the link OA.

Fig. 2.10 (b) shows the velocity diagram when their velocities v and (v + δv) are considered. In this diagram, the vector bb_1 represents the change in velocity in time δ t sec ; the vector bx represents the component of change of velocity bb_1 along OA (i.e. along radial direction) and vector xb_1 represents the component of change of velocity bb_1 in a direction perpendicular to O A (i.e. in tangential direction). Therefore

$bx = ox – ob = (v + \delta v) \cos \delta\theta - v\uparrow$
Since $\delta\theta$ is very small, therefore substituting;
$\cos \delta\theta = 1$, we have
$bx = (v + \delta v – v)\uparrow = \delta v \uparrow$ ...(Acting radially outwards)
And $xb_1 = (v + \delta v) \sin \delta\theta$
Since $\delta\theta$ is very small, therefore substituting $\sin \delta\theta = \delta\theta$, we have
$xb_1 = (v + \delta v)\, \delta\theta = v.\, \delta\theta + \delta v.\, \delta\theta$
Neglecting
$\delta v.\, \Delta\theta$ being very small, therefore
$xb_1 = v.\, \delta\theta$
Fig. 2.10 (c) shows the velocity diagram when the velocities $\omega .r$ and $(\omega + \delta\omega)\,(r + \delta r)$ are considered. In this diagram, vector bb_1 represents the change in velocity; vector yb_1 represents the component of change of velocity bb_1 along OA (i.e. along radial direction) and vector by represents the component of change of velocity bb_1 in a direction perpendicular to OA (i.e. in a tangential direction). Therefore
$yb_1 = (\omega + \delta\omega)\,(r + \delta r) \sin \delta\theta\downarrow$
$yb_1 = (\omega + \omega\delta r + \delta\omega.\, r + \delta\omega\, \delta r) \sin \delta\theta$
Since $\delta\theta$ is very small, therefore substituting $\sin \delta\theta = \delta\theta$ in the above expression, we have
$yb_1 = \omega.\, r.\, \delta\theta + \omega.\, \delta r.\, \delta\theta + \delta\omega.\, r.\, \delta\theta + \delta\omega.\, \delta r.\, \delta\theta$
$yb_1 = \omega.\, r.\, \delta\theta \downarrow$, acting radially inwards
And $by = oy – ob = (\omega + \delta\omega)\,(r + \delta r) \cos \delta\theta – \omega r$
$by = (\omega.\, r + \omega.\, \delta r + \delta\omega.\, r + \delta\omega.\, \delta r) \cos \delta\theta – \omega r$

This tangential component of acceleration of the slider B with respect to the coincident point C on the link is known as **coriolis component of acceleration** and is always perpendicular to the link.
∴ Coriolis component of the acceleration of B with respect of C,
$a^c_{BC} = a^t_{BC} = 2\omega v$
Where,
ω = Angular velocity of the link OA, and
v = Velocity of slider B with respect to coincident point C.

In the above discussion, the anticlockwise direction for ω and the radially outward direction for v are taken as **positive.** It may be noted that the direction of coriolis component of acceleration changes sign, if either ω or v is reversed in direction. But the direction of coriolis component of acceleration will not be changed in sign if both ω and v are reversed in direction. It is concluded that the direction of coriolis component of acceleration is obtained by rotating v, at 90°, about its origin in the same direction as that of ω.

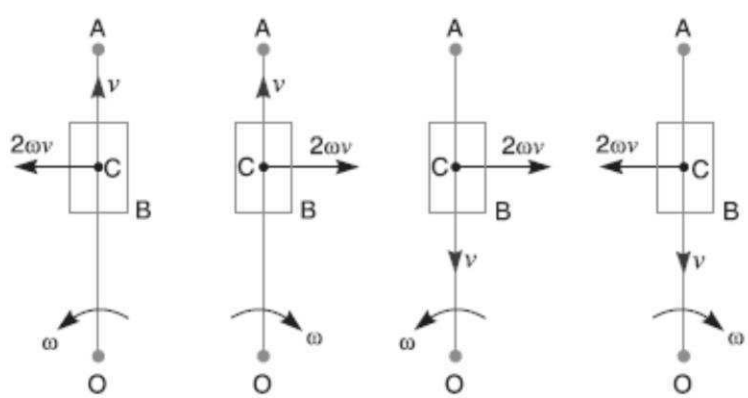
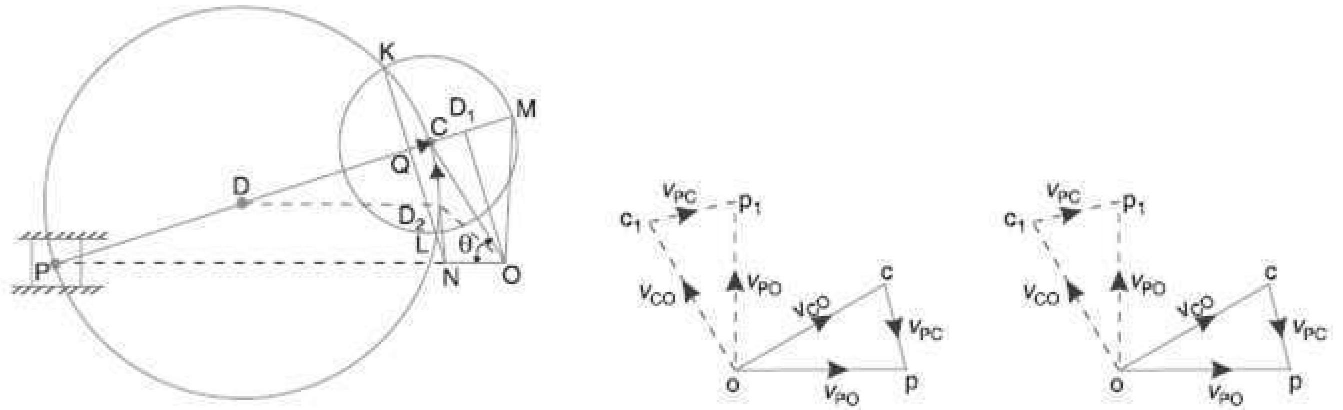


Fig. 2.11 Direction of coriolis component of acceleration

Klein's Construction:
Let OC be the crank and PC the connecting rod of a reciprocating steam engine, as shown in Fig. 2.12 (a). Let the crank makes an angle θ with the line of stroke PO and rotates with uniform angular velocity ω rad/s in a

clockwise direction. The Klein's velocity and acceleration diagrams are drawn as discussed below:



(a) Klein's Construction Diagram (b) Velocity Diagram (c) Acceleration Diagram

Fig. 2.12 Klein's velocity diagram

First of all, draw OM perpendicular to OP; such that it intersects the line PC produced at M. The triangle OCM is known as **Klein's velocity diagram**. In this triangle OCM,
OM may be regarded as a line perpendicular to PO,
CM may be regarded as a line parallel to PC, and ... (Q it is the same line.)
CO may be regarded as a line parallel to CO.
We have already discussed that the velocity diagram for given configuration is a triangle o_{cp}
as shown in Fig. (b). If this triangle revolved through 90°, it will be a triangle oc_1 p_1, in which oc_1 represents v_{CO} (i.e. velocity of C with respect to O or velocity of crank pin C) and is parallel to OC, op_1 represents v_{PO} (i.e. velocity of P with respect to O or velocity of cross-head or piston P) and is perpendicular to OP, and c_1p_1 represents v_{PC} (i.e. velocity of P with respect to C) and is parallel to CP.
A little consideration will show that the triangles oc_1p_1 and OCM are similar. Therefore,
$oc_1/ OC = op_1/OM = c_1p_1/CM = \omega$ (a constant)
$v_{CO}/ OC = v_{PO}/OM = v_{PC}/CM = \omega$
Or $v_{CO} = \omega \times OC$; $v_{PO} = \omega \times OM$ and $v_{PC} = \omega \times CM$
Thus, we see that by drawing the Klien's velocity diagram, the velocities of various points may be obtained without drawing a separate velocity diagram.

Klien's acceleration diagram

The Klien's acceleration diagram is drawn as discussed below:

1. First of all, draw a circle with C as centre and CM as radius.
2. Draw another circle with PC as diameter. Let this circle inter- sect the previous circle at K and L.
3. Join KL and produce it to intersect PO at N. Let KL intersect PC at Q. This forms the quadrilateral CQNO, which is known as **Klien's acceleration diagram.**

We have already discussed that the acceleration diagram for the given configuration is as shown in Fig. 2.12 (c). We know that

(i) o'c' represents a^r_{CO} (i.e. radial component of the acceleration of crank pin C with respect to O) and is parallel to CO;
(ii) c'x represents a^r_{PC} (i.e. radial component of the acceleration of crosshead or piston P with respect to crank pin C) and is parallel to CP or CQ;
(iii) xp' represents a^t_{PC} (i.e. tangential component of the acceleration of P with respect to C) and is parallel to QN (because QN is perpendicular to CQ); and
(iv) o'p' represents a_{PO} (i.e. acceleration of P with respect to O or the acceleration of piston P) and is parallel to PO or NO.
A little consideration will show that the quadrilateral o'c'x p' [Fig. 2.12 (c)] is similar to quadrilateral CQNO [Fig. 2.12 (a)]. Therefore,

$o'c'/OC = c'x'/CQ = xp'/QN = o'p'/NO = \omega^2$ (a constant)

$a^r_{co}/OC = a^r_{PC}/CQ = a^t_{PC}/QN = a_{PO}/NO = \omega^2$

$a^r_{CO} = \omega^2 \text{ X } OC$; $a^r_{PC} = \omega^2 \text{ X } CQ$;

$a^t_{PC} = \omega^2 \text{ X } QN$ and $a_{PO} = \omega^2 \text{ X } NO$

Thus we see that by drawing the Klien's acceleration diagram, the acceleration of various points may be obtained without drawing the separate acceleration diagram.