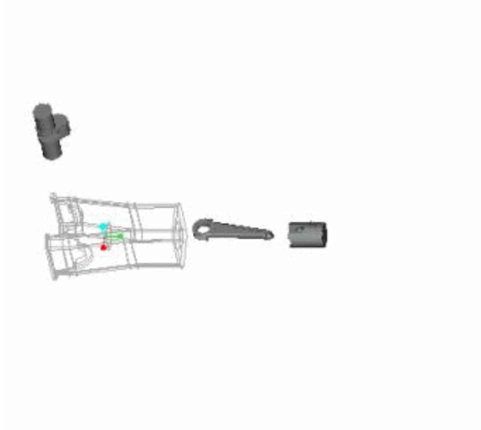
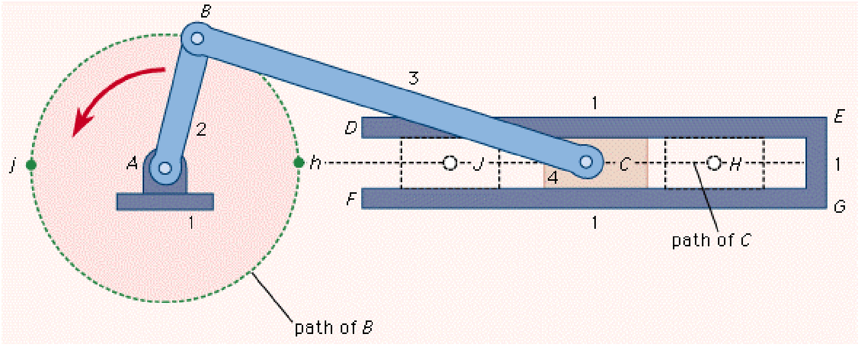
Steps in Design Analysis of Machine or Mechanisms





Static

Kinematics

Kinetics

Stress Analysis

Machine Design

Kinematics Analysis of Plane Mechanisms or Linkages

Aim:

Kinematic analysis establishes the relationship between the motion of the various components or links or elements of a mechanism

Objective

- To determine the kinematic quantities of the links or elements in a mechanism when the input motion is given

- To determine the input motion required to produce a specified motion of another links or elements

Kinematic Parameters

- Position & Displacement
- Velocity
- Acceleration
- Jerks

Steps in Kinematics Analysis of Plane Mechanisms

Configuration &
Kinematic dimensions

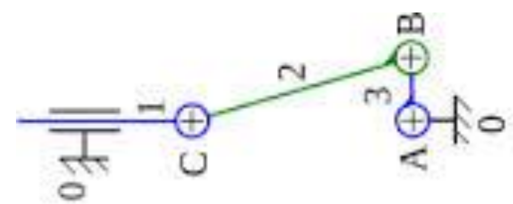
Position / Displacement Analysis

↓

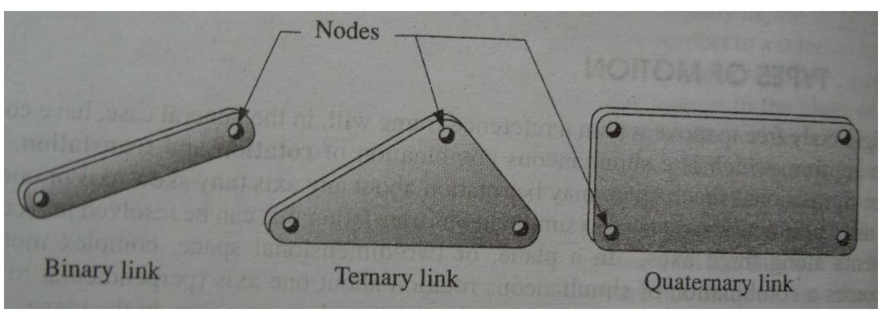
Velocity Analysis

↓

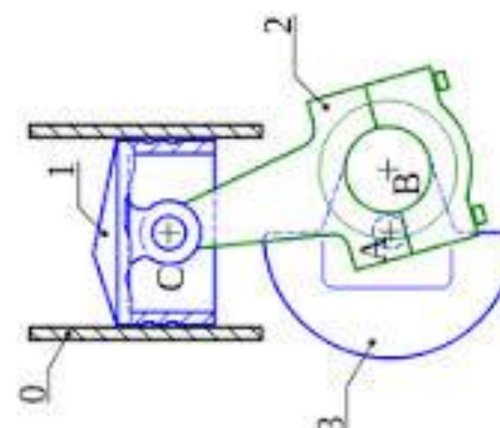
Acceleration Analysis



What is Kinematic dimensions?



Node-node distance
or
joint centre to centre distance etc.



Kinematics

Kinematic Analysis of Plane Mechanisms

Methods

Graphical Methods

Relative Velocity Method

Instantaneous Centre Method

Analytical Methods

Vector Approach by Loop Closure Eq.

Algebraic Approach by Projection

Advantages of Analytical Methods

An Analytical method is preferred whenever

-- A high level of accuracy is desired

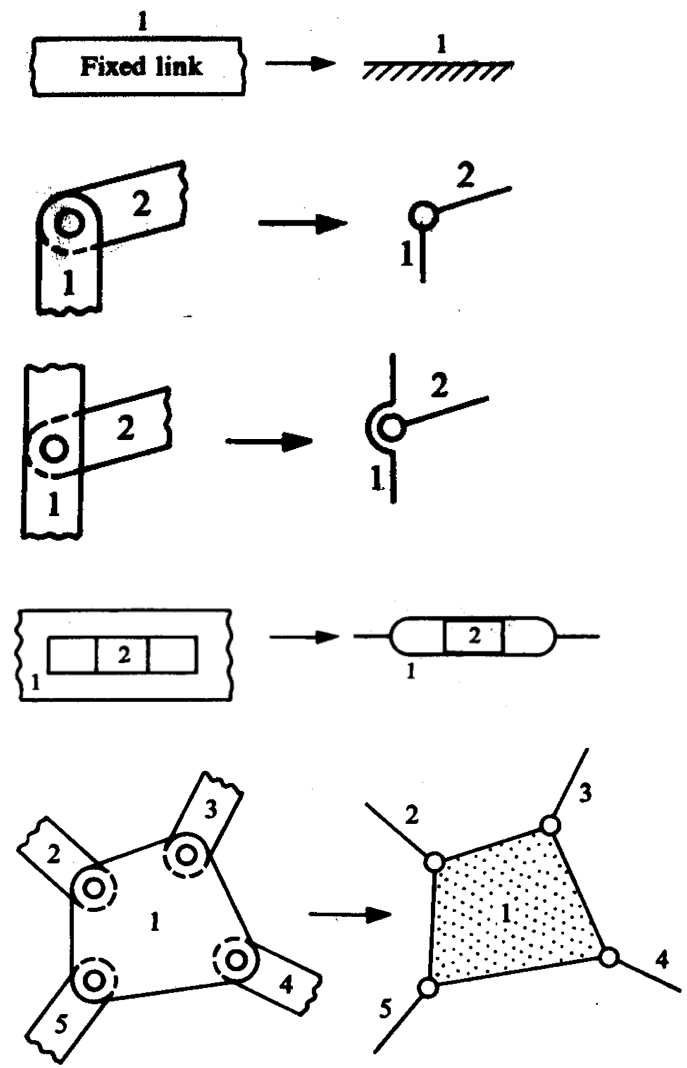
-- analysis has to be carried out for a large nos. of configuration

Analytical Methods are being widely used with the help of CAE tools like ADAMS etc.

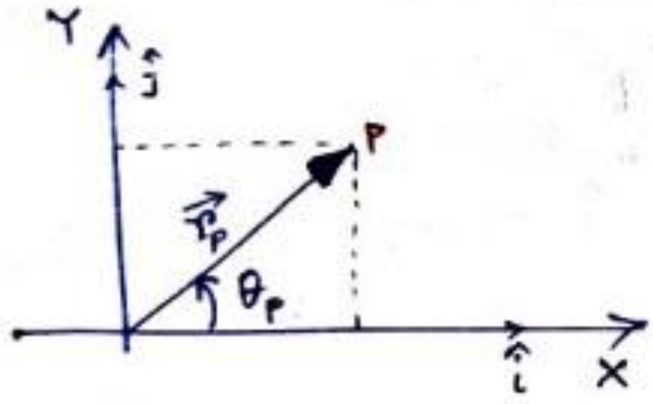
Basics of Mechanism (contd...)

Kinematic Diagram

- As a result of the assumption of rigidity, many of the intricate details of the actual part shapes are irrelevant when studying the kinematics of a mechanism.
- For this reason it is common practice to draw highly simplified schematic diagrams, which contain important features of the shape of each link, such as the relative locations of pair elements, but which completely subdue the real geometry of the manufactured parts. This simplified schematic diagram is known as **KINEMATIC DIAGRAM**. Such a diagram depicts the essential kinematic features of the mechanism.



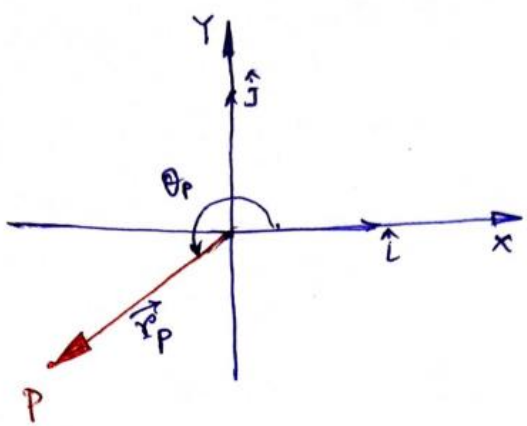
Position Vector

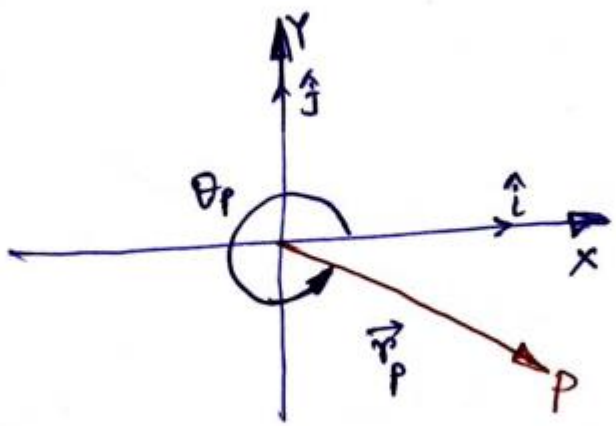


$$\vec{r}_p = \left(r_p\cos\theta_p\,\hat{i} + r_p\sin\theta_p\,\hat{j}\right)$$

$$|\vec{r}_p| = \sqrt{(r_p\cos\theta_p)^2 + (r_p\sin\theta_p)^2}$$

$$|\vec{r}_p| = r_p$$





Convenient Notation to represent the Position Vectors

$\overrightarrow{r_p}$	Polar form	Cartesian form
	$r_p \angle \theta_p$	$r_p \cos\theta_p \hat{i} + r_p \sin\theta_p \hat{j}$
Complex number representation	$r_p e^{j\theta_p}$	$r_p \cos\theta_p + j r_p \sin\theta_p$

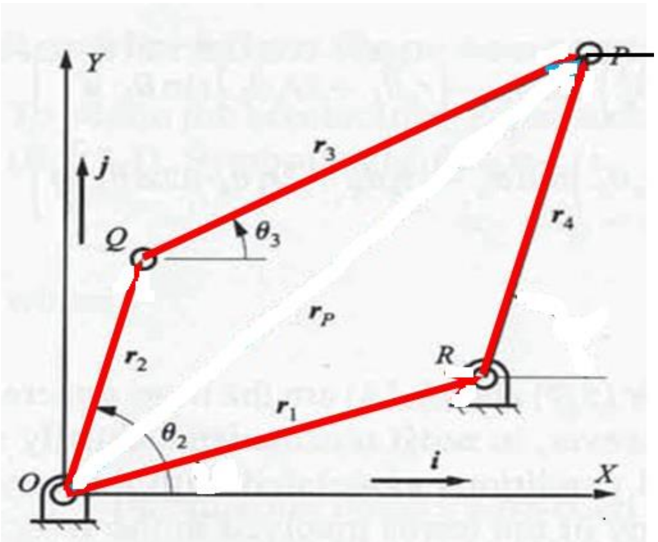
Complex Algebra or Complex polar Algebra

$\overrightarrow{r_p} = r_p \angle \theta_p = r_p \cos\theta_p + j\, r_p \sin\theta_p$ where $j = \sqrt{-1}$ i.e unit imaginary number.

$= r_p e^{j\theta_p}$ where $\left.\begin{array}{l} e^{j\theta_p} = \cos\theta_p + j\sin\theta_p \\ e^{-j\theta_p} = \cos\theta_p - j\sin\theta_p \end{array}\right\}$ Wellknown Euler equation from Trigonometry.

$|\overrightarrow{r_p}| = \sqrt{(r_p\cos\theta_p)^2 + (r_p\sin\theta_p)^2}$

Position Analysis/Displacement Analysis of 4R linkage



Main Steps in Position Analysis

Step 1 - Draw kinematic diagram of the mechanism

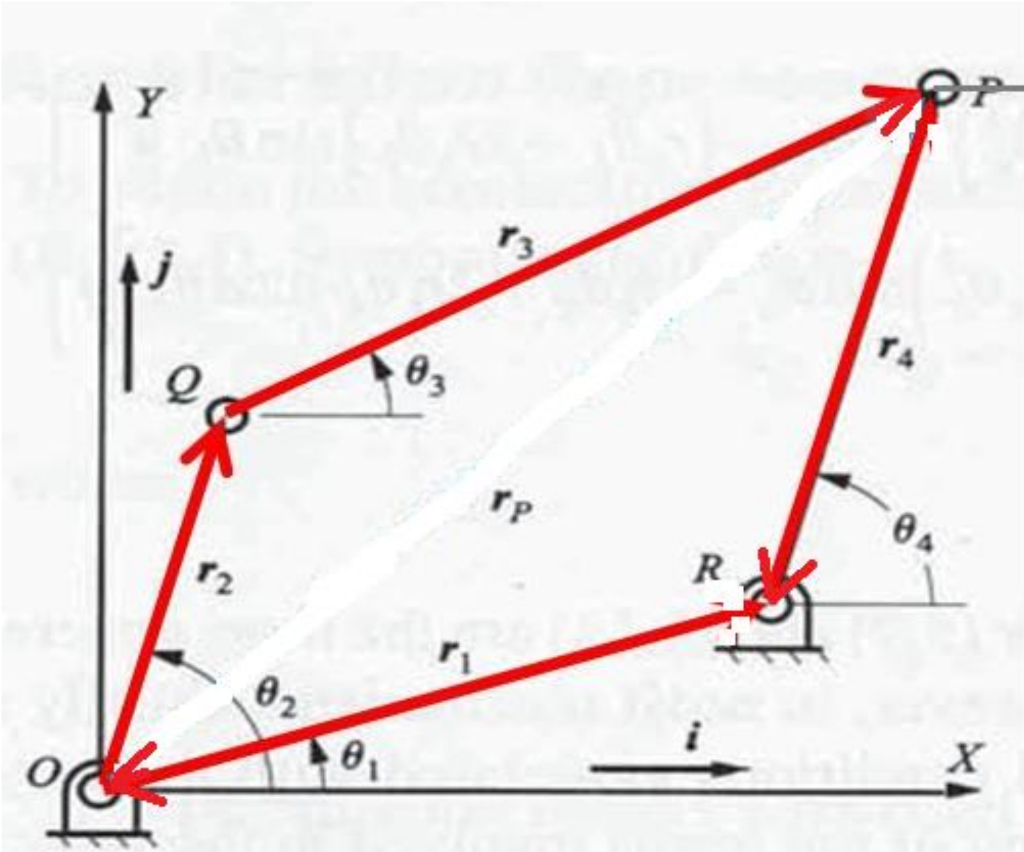
Step 2 - Attach reference coordinate reference frame (RH frame)

Step 3 - Link numbering & Joint numbering

Step 4 - Represent each link as a vector

Step 5 - Formulate Vector Loop closure equation

Position Analysis/Displacement Analysis of 4R linkage

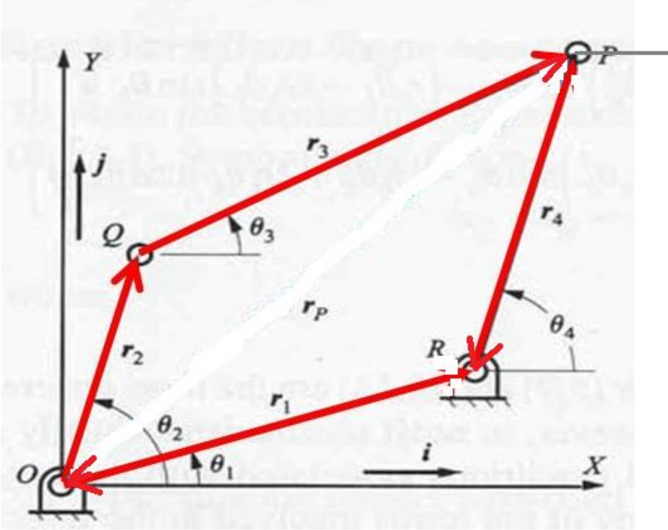


$$\vec{r}_P = r_P\cos\theta_P\,\hat{i} + r_P\sin\theta_P\,\hat{j}$$

Vector Loop Closure Equation or Loop Closure Equation

$$\vec{r}_1 + \vec{r}_2 + \vec{r}_3 + \vec{r}_4 = 0$$

First proposed by **Raven**


Y
j
Q
r_3
θ_3
P
r_4
r_P
θ_4
R
r_2
r_1
θ_2
θ_1
O
i
X

Vector Loop Closure Equation or Loop Closure Equation

$$\vec{r_1} + \vec{r_2} + \vec{r_3} + \vec{r_4} = 0 \qquad \vec{r_p} = r_p \cos\theta_p \hat{i} + r_p \sin\theta_p \hat{j}$$

$$r_2(\cos\theta_2 \hat{i} + \sin\theta_2 \hat{j}) + r_3(\cos\theta_3 \hat{i} + \sin\theta_3 \hat{j}) = r_1(\cos\theta_1 \hat{i} + \sin\theta_1 \hat{j}) + r_4(\cos\theta_4 \hat{i} + \sin\theta_4 \hat{j})$$

Rewriting

where r_2, r_3, r_1, r_4 are scalar lengths of the links. $\theta_2, \theta_3, \theta_1, \theta_4$ are link angles — (3)

$$(r_2\cos\theta_2 + r_3\cos\theta_3)\hat{i} + (r_2\sin\theta_2 + r_3\sin\theta_3)\hat{j} = (r_1\cos\theta_1 + r_4\cos\theta_4)\hat{i} + (r_1\sin\theta_1 + r_4\sin\theta_4)\hat{j}$$

Comparing components in both side

Loop Closure Equation in Scalar Form

$$r_2\cos\theta_2 + r_3\cos\theta_3 = r_1\cos\theta_1 + r_4\cos\theta_4 \quad \text{---} \quad (5)$$

$$r_2\sin\theta_2 + r_3\sin\theta_3 = r_1\sin\theta_1 + r_4\sin\theta_4 \quad \text{---} \quad (6)$$

Here θ_1 is constant. If 'θ_2' is given i.e. if crank 'OQ' is driving crank, it is necessary to solve eqns (5) & (6) for θ_3 & θ_4 in terms of 'θ_2'.

Loop Closure Equation in Scalar Form

$$r_2\cos\theta_2 + r_3\cos\theta_3 = r_1\cos\theta_1 + r_4\cos\theta_4 \quad \text{------} \quad (5)$$

$$r_2\sin\theta_2 + r_3\sin\theta_3 = r_1\sin\theta_1 + r_4\sin\theta_4 \quad \text{------} \quad (6)$$

When the position eqns involve two angles as unknowns, the soln procedure is to isolate the trigonometric fun. involving the angle to be eliminated on the LHS of the eqn.

From eqns (5) + (6)

$$r_3\cos\theta_3 = r_1\cos\theta_1 + r_4\cos\theta_4 - r_2\cos\theta_2 \quad \text{------} \quad (5')$$

$$r_3\sin\theta_3 = r_1\sin\theta_1 + r_4\sin\theta_4 - r_2\sin\theta_2 \quad \text{------} \quad (6')$$

Squaring + adding

$$r_3^2 = r_1^2 + r_2^2 + r_4^2 + 2r_1r_4(\cos\theta_1\cos\theta_4 + \sin\theta_1\sin\theta_4) - 2r_1r_2(\cos\theta_1\cos\theta_2 + \sin\theta_1\sin\theta_2)$$
$$- 2r_2r_4(\cos\theta_2\cos\theta_4 + \sin\theta_2\sin\theta_4) \quad \text{------} \quad (7)$$

Eq^n (7) gives 'θ_4' in terms of the given angle 'θ_2' but not explicitly.

$$\underbrace{(2r_1r_4\cos\theta_1 - 2r_2r_4\cos\theta_2)}_{A}\cos\theta_4 + \underbrace{(2r_1r_4\sin\theta_1 - 2r_2r_4\sin\theta_2)}_{B}\sin\theta_4 = \underbrace{\{r_3^2 - r_1^2 - r_2^2 - r_4^2 + 2r_1r_2\cos(\theta_1-\theta_2)\}}_{C}$$

$$A\cos\theta_4 + B\sin\theta_4 = C \quad \text{- - - - - - - - - - (8)}$$

Using std. trigonometric identities for half angles

$$\sin\theta_4 = \frac{2\tan\theta_4/2}{1+\tan^2\theta_4/2} = \frac{2t}{1+t^2} \quad \text{and} \quad \cos\theta_4 = \frac{1-\tan^2(\theta_4/2)}{1+\tan^2(\theta_4/2)} = \frac{1-t^2}{1+t^2}$$

where $t = \tan\theta_4/2$

$$\underbrace{(2r_1r_4\cos\theta_1 - 2r_2r_4\cos\theta_2)}_{A_1}\cos\theta_4 + \underbrace{(2r_1r_4\sin\theta_1 - 2r_2r_4\sin\theta_2)}_{B_1}\sin\theta_4 + \underbrace{\{r_1^2 + r_2^2 + r_4^2 - r_3^2 - 2r_1r_2\cos(\theta_1-\theta_2)\}}_{C_1} = 0$$

$$\underbrace{(2r_1r_4\cos\theta_1 - 2r_2r_4\cos\theta_2)}_{A_1}\cos\theta_4 + \underbrace{(2r_1r_4\sin\theta_1 - 2r_2r_4\sin\theta_2)}_{B_1}\sin\theta_4 + \underbrace{\{r_1^2 + r_2^2 + r_4^2 - r_3^2 - 2r_1r_2\cos(\theta_1-\theta_2)\}}_{C_1} = 0$$

$$A_1\cos\theta_4 + B_1\sin\theta_4 + C_1 = 0$$

Using std. trigonometric identities for half angles

$$\sin\theta_4 = \frac{2\tan\theta_4/2}{1+\tan^2\theta_4/2}\,;\quad \cos\theta_4 = \frac{1-\tan^2\theta_4/2}{1+\tan^2\theta_4/2}$$

$$A_1\left[\frac{1-\tan^2\theta_4/2}{1+\tan^2\theta_4/2}\right] + B_1\left[\frac{2\tan\theta_4/2}{1+\tan^2\theta_4/2}\right] + C_1 = 0$$

$$A_1\left[1-\tan^2\theta_4/2\right] + B_1\left[2\tan\theta_4/2\right] + C_1\left[1+\tan^2\theta_4/2\right] = 0$$

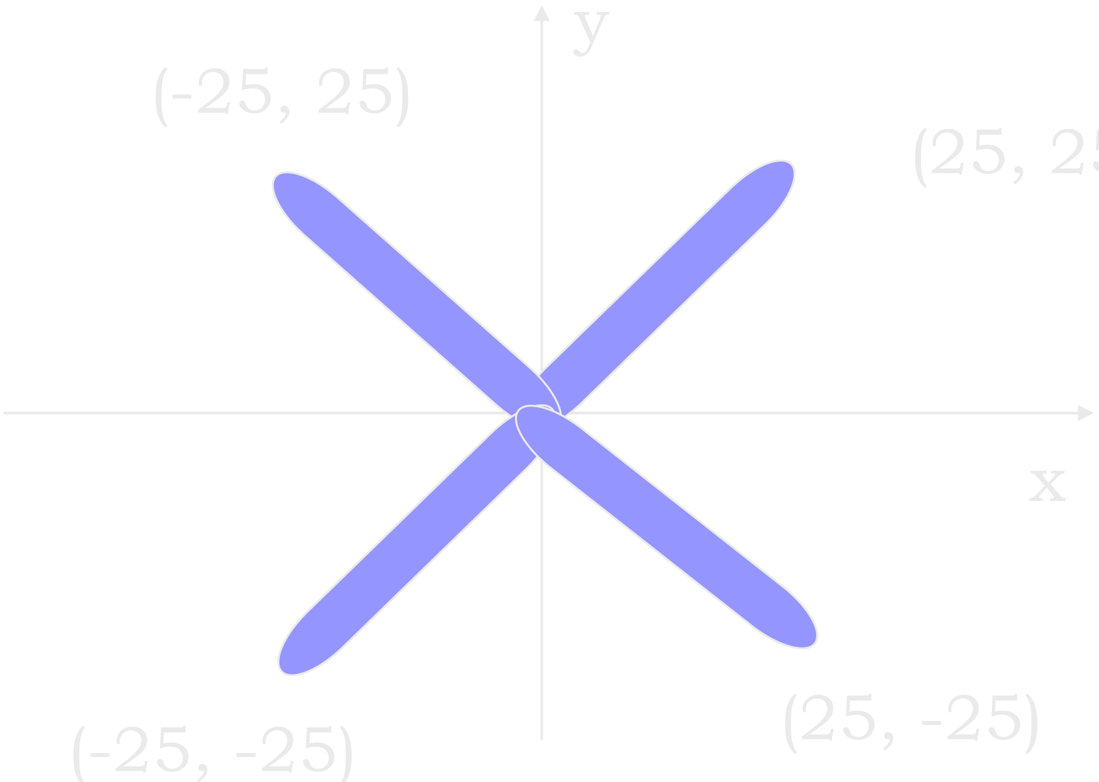
$$(C_1 - A_1)\tan^2\theta_4/2 + 2B_1\tan\theta_4/2 + (C_1 + A_1) = 0$$

$$A\tan^2\theta_4/2 + B\tan\theta_4/2 + C = 0$$

where $A = C_1 - A_1$
$B = 2B_1$
$C = C_1 + A_1$

$$\tan\theta_4/2 = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}$$

$$\theta_4 = 2\tan^{-1}\left[\frac{-B \pm \sqrt{B^2-4AC}}{2A}\right] \qquad \left[-\pi \le \theta_4 \le \pi\right]$$


y
(-25, 25)
(25, 25)
x
(25, -25)
(-25, -25)

Dividing eq^n (6') by eq^n (5')

$$\tan\theta_3 = \frac{r_1 \sin\theta_1 + r_4 \sin\theta_4 - r_2 \sin\theta_2}{r_1 \cos\theta_1 + r_4 \cos\theta_4 - r_2 \cos\theta_2}$$

$$\theta_3 = \tan^{-1}\left[\frac{r_1 \sin\theta_1 + r_4 \sin\theta_4 - r_2 \sin\theta_2}{r_1 \cos\theta_1 + r_4 \cos\theta_4 - r_2 \cos\theta_2}\right]$$

There is two values of θ_4 (i.e. two soln's)

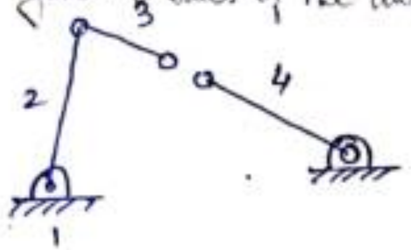
Two Solutions may be of three types —
- → real & equal $[(B^2 - 4AC) = 0]$
- → real & unequal $[(B^2 - 4AC) > 0]$
- → Complex conjugate $[(B^2 - 4AC) < 0]$

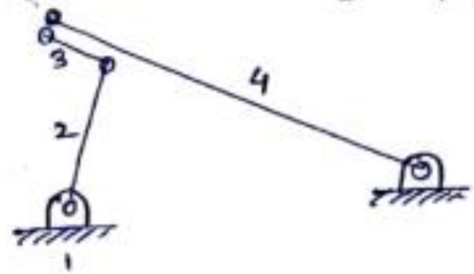
$B^2 - 4AC < 0$

If $B^2-(C^2-A^2)<0$ i.e soln is complex conjugate which means the mechanism cannot be assembled in the specified position (i.e specified values of θ_2). In other words, the link lengths chosen are not capable of connection for the chosen value of the input angle θ_2.

(This can occur when the link length are completely incapable of connection in the specified position)

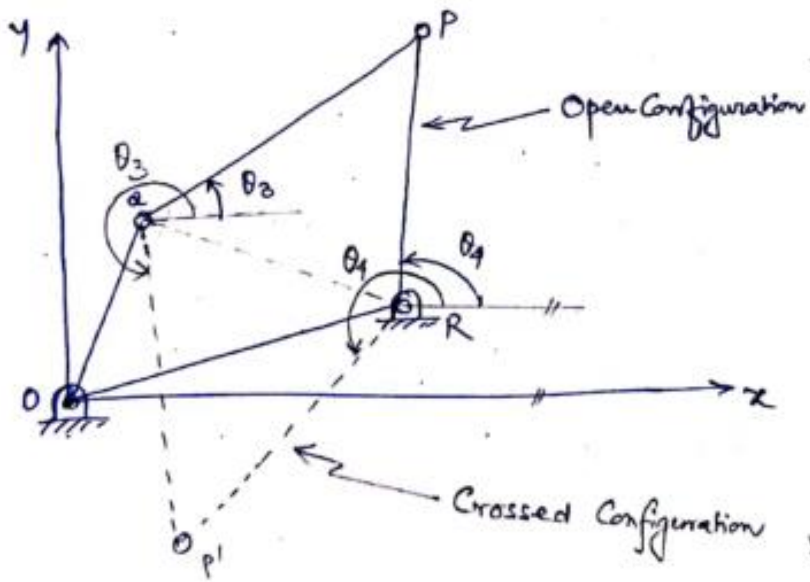
If this happens, the mechanism cannot be assembled for the specified values of θ_2 & for the given values of the link lengths.





$B^2 - 4AC > 0$

If $B^2 - (C^2 - A^2) > 0$ i.e two solutions are real & unequal (two values of θ_4 for any value of θ_2). These two solutions are referred to as the crossed & open configurations of the linkage.



Note: $QP'R$ is the mirror image of QPR about the line QR.

Velocity Analysis of 4R linkage

Vector Loop Closure Equation or Loop Closure Equation

$$\vec{r_1} + \vec{r_2} + \vec{r_3} + \vec{r_4} = 0$$

Loop Closure Equation in Scalar Form

$$r_2 \cos\theta_2 + r_3 \cos\theta_3 = r_1 \cos\theta_1 + r_4 \cos\theta_4 \quad \text{——— (5)}$$

$$r_2 \sin\theta_2 + r_3 \sin\theta_3 = r_1 \sin\theta_1 + r_4 \sin\theta_4 \quad \text{- - - - - - (6)}$$

From eqns (5) & (6)

$$r_3 \cos\theta_3 = r_1 \cos\theta_1 + r_4 \cos\theta_4 - r_2 \cos\theta_2 \quad \text{- - - - - (5')}$$

$$r_3 \sin\theta_3 = r_1 \sin\theta_1 + r_4 \sin\theta_4 - r_2 \sin\theta_2 \quad \text{- - - - (6')}$$

Velocity Equation

Vector Form

$$\vec{\dot{r}_2} + \vec{\dot{r}_3} + \vec{\dot{r}_1} + \vec{\dot{r}_4} = 0$$

Eqn in Component form:

$$r_2 \dot{\theta}_2 \sin\theta_2 + r_3 \dot{\theta}_3 \sin\theta_3 = r_4 \dot{\theta}_4 \sin\theta_4 \quad \text{- - - - - (11)}$$

$$r_2 \dot{\theta}_2 \cos\theta_2 + r_3 \dot{\theta}_3 \cos\theta_3 = r_4 \dot{\theta}_4 \cos\theta_4 \quad \text{- - - - (12)}$$

Velocity Analysis of 4R linkage

Rewrite

$$-r_3\dot{\theta}_3\sin\theta_3 + r_4\dot{\theta}_4\sin\theta_4 = r_2\dot{\theta}_2\sin\theta_2$$

$$-r_3\dot{\theta}_3\cos\theta_3 + r_4\dot{\theta}_4\cos\theta_4 = r_2\dot{\theta}_2\cos\theta_2$$

$$\underbrace{\begin{bmatrix} -r_3\sin\theta_3 & r_4\sin\theta_4 \\ -r_3\cos\theta_3 & r_4\cos\theta_4 \end{bmatrix}}_{\text{Co-efficient Matrix}} \begin{bmatrix} \dot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix} = \begin{bmatrix} r_2\dot{\theta}_2\sin\theta_2 \\ r_2\dot{\theta}_2\cos\theta_2 \end{bmatrix}$$

$$\begin{bmatrix} \dot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix} = \begin{bmatrix} -r_3\sin\theta_3 & r_4\sin\theta_4 \\ -r_3\cos\theta_3 & r_4\cos\theta_4 \end{bmatrix}^{-1} \cdot \begin{bmatrix} r_2\dot{\theta}_2\sin\theta_2 \\ r_2\dot{\theta}_2\cos\theta_2 \end{bmatrix}$$

Where $\dot{\theta}_2$ is known input

$\dot{\theta}_1 = 0$ as $\theta_1 =$ Cons

For Simple prob.

$$-r_3\dot{\theta}_3\cancel{S\theta_3C\theta_3} + r_4\dot{\theta}_4 S\theta_4 C\theta_3 = r_2\dot{\theta}_2 S\theta_2 C\theta_3$$

$$\mp r_3\dot{\theta}_3\cancel{S\theta_3C\theta_3} \pm r_4\dot{\theta}_4 S\theta_3 C\theta_4 = \pm r_2\dot{\theta}_2 S\theta_3 C\theta_2$$

$$r_4\dot{\theta}_4 S(\theta_4-\theta_3) = r_2\dot{\theta}_2 S(\theta_2-\theta_3)$$

$$\dot{\theta}_4 = \frac{r_2\sin(\theta_2-\theta_3)}{r_4\sin(\theta_4-\theta_3)}\dot{\theta}_2$$

$$\dot{\theta}_3 = \frac{r_2\sin(\theta_2-\theta_4)}{r_3\sin(\theta_4-\theta_3)}\cdot\dot{\theta}_2$$

For Simple prob:

$$\cancel{-r_3\dot{\theta}_3 S\theta_3 C\theta_3} + r_4\dot{\theta}_4 S\theta_4 C\theta_3 = r_2\dot{\theta}_2 S\theta_2 C\theta_3$$

$$\cancel{\mp r_3\dot{\theta}_3 S\theta_3 C\theta_3} \pm r_4\dot{\theta}_4 S\theta_3 C\theta_4 = \pm r_2\dot{\theta}_2 S\theta_3 C\theta_2$$

$$r_4\dot{\theta}_4 S(\theta_4-\theta_3) = r_2\dot{\theta}_2 S(\theta_2-\theta_3)$$

$$\dot{\theta}_4 = \frac{r_2 \sin(\theta_2-\theta_3)}{r_4 \sin(\theta_4-\theta_3)}\dot{\theta}_2$$

$$\dot{\theta}_3 = \frac{r_2 \sin(\theta_2-\theta_4)}{r_3 \sin(\theta_4-\theta_3)}\cdot\dot{\theta}_2$$

- - - - (14)

Once the angular velocities are known, it is a simple matter to compute the linear velocities of any of the points on the vector loop.

Linear Velocity of pt. Q : v_Q $\vec{\dot{r}}_Q = \vec{\dot{r}}_2 = r_2\dot{\theta}_2(-\sin\theta_2\,\hat{i} + \cos\theta_2\,\hat{j})$ - - - (15)

Linear Velocity of pt. P : v_P $\vec{\dot{r}}_P = \vec{\dot{r}}_2 + \vec{\dot{r}}_3 = (-r_2\dot{\theta}_2\sin\theta_2 - r_3\dot{\theta}_3\sin\theta_3)\hat{i} + (r_2\dot{\theta}_2\cos\theta_2 + r_3\dot{\theta}_3\cos\theta_3)\hat{j}$

$= \vec{\dot{r}}_1 + \vec{\dot{r}}_4 = (-r_4\dot{\theta}_4\sin\theta_4)\hat{i} + (r_4\dot{\theta}_4\cos\theta_4)\hat{j}$ - - - (16)

Acceleration Analysis of 4R linkage

Acceleration Equation

$$\ddot{\vec{r}}_2 + \ddot{\vec{r}}_3 + \ddot{\vec{r}}_1 + \ddot{\vec{r}}_4 = 0$$

$$\underbrace{r_2\ddot{\theta}_2 \sin\theta_2}_{\text{Tangential comp. of accel}^n \text{ along x-dir}} + \underbrace{r_2\dot{\theta}_2^2 \cos\theta_2}_{\text{Normal comp. of accel}^n \text{ along x-dir}} + r_3\ddot{\theta}_3 \sin\theta_3 + r_3\dot{\theta}_3^2\cos\theta_3 = r_4\ddot{\theta}_4\sin\theta_4 + r_4\dot{\theta}_4^2\cos\theta_4 \quad \text{---- (17)}$$

$$r_2\ddot{\theta}_2\cos\theta_2 - r_2\dot{\theta}_2^2\sin\theta_2 + r_3\ddot{\theta}_3\cos\theta_3 - r_3\dot{\theta}_3^2\sin\theta_3 = r_4\ddot{\theta}_4\cos\theta_4 - r_4\dot{\theta}_4^2\sin\theta_4 \quad \text{---- (18)}$$

When $\ddot{\theta}_2$ is known along with all of the position & velocity terms, the only unknowns are $\ddot{\theta}_3$ & $\ddot{\theta}_4$.

$$-r_3\ddot{\theta}_3\sin\theta_3 + r_4\ddot{\theta}_4\sin\theta_4 = r_2\ddot{\theta}_2\sin\theta_2 + r_2\dot{\theta}_2^2\cos\theta_2 + r_3\dot{\theta}_3^2\cos\theta_3 - r_4\dot{\theta}_4^2\cos\theta_4$$

$$-r_3\ddot{\theta}_3\cos\theta_3 + r_4\ddot{\theta}_4\cos\theta_4 = r_2\ddot{\theta}_2\cos\theta_2 - r_2\dot{\theta}_2^2\sin\theta_2 - r_3\dot{\theta}_3^2\sin\theta_3 + r_4\dot{\theta}_4^2\sin\theta_4$$

$$\underbrace{\begin{bmatrix} -r_3\sin\theta_3 & r_4\sin\theta_4 \\ -r_3\cos\theta_3 & r_4\cos\theta_4 \end{bmatrix}}_{\text{Co-efficient Matrix}} \begin{bmatrix} \ddot{\theta}_3 \\ \ddot{\theta}_4 \end{bmatrix} = \begin{bmatrix} r_2\ddot{\theta}_2\sin\theta_2 + r_2\dot{\theta}_2^2\cos\theta_2 + r_3\dot{\theta}_3^2\cos\theta_3 - r_4\dot{\theta}_4^2\cos\theta_4 \\ r_2\ddot{\theta}_2\cos\theta_2 - r_2\dot{\theta}_2^2\sin\theta_2 - r_3\dot{\theta}_3^2\sin\theta_3 + r_4\dot{\theta}_4^2\sin\theta_4 \end{bmatrix} \quad \text{---- (19)}$$

Once the angular accelerations are known, it is a simple matter to compute the linear accel^n of any of the pts in the linkage.

Linear Acceleration of Point Q:

$$\vec{\ddot{r}}_Q = \vec{\ddot{r}}_2 = \left(-r_2\ddot{\theta}_2\sin\theta_2\,\hat{i} + r_2\ddot{\theta}_2\cos\theta_2\,\hat{j}\right) + \left(-r_2\dot{\theta}_2^2\cos\theta_2\,\hat{i} - r_2\dot{\theta}_2^2\sin\theta_2\,\hat{j}\right)$$

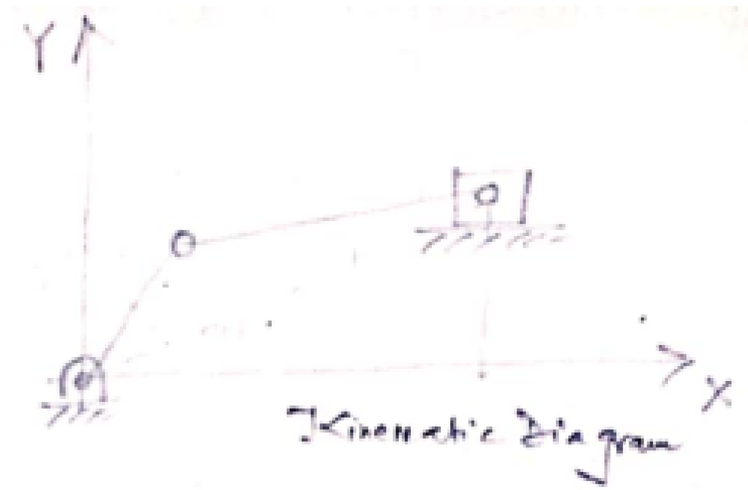
$$= \left(-r_2\ddot{\theta}_2\sin\theta_2 - r_2\dot{\theta}_2^2\cos\theta_2\right)\hat{i} + \left(r_2\ddot{\theta}_2\cos\theta_2 - r_2\dot{\theta}_2^2\sin\theta_2\right)\hat{j} \quad \ldots (20)$$

Linear Acceleration of point 'P':

$$\vec{\ddot{r}}_P = \vec{\ddot{r}}_2 + \vec{\ddot{r}}_3 = -\left(r_2\ddot{\theta}_2\sin\theta_2 + r_2\dot{\theta}_2^2\cos\theta_2 + r_3\ddot{\theta}_3\sin\theta_3 + r_3\dot{\theta}_3^2\cos\theta_3\right)\hat{i}$$
$$+ \left(r_2\ddot{\theta}_2\cos\theta_2 - r_2\dot{\theta}_2^2\sin\theta_2 + r_3\ddot{\theta}_3\cos\theta_3 - r_3\dot{\theta}_3^2\sin\theta_3\right)\hat{j}$$
$$= \vec{\ddot{r}}_1 + \vec{\ddot{r}}_4 = -\left(r_4\ddot{\theta}_4\sin\theta_4 + r_4\dot{\theta}_4^2\cos\theta_4\right)\hat{i} + \left(r_4\ddot{\theta}_4\cos\theta_4 - r_4\dot{\theta}_4^2\sin\theta_4\right)\hat{j} \quad \ldots (21)$$

Position Analysis/Displacement Analysis of Slider-Crank Mechanism

Slider-crank mechanism (RRRP) — → offset → Centred



Main Steps in Position Analysis

Step 1 - Draw kinematic diagram of the mechanism

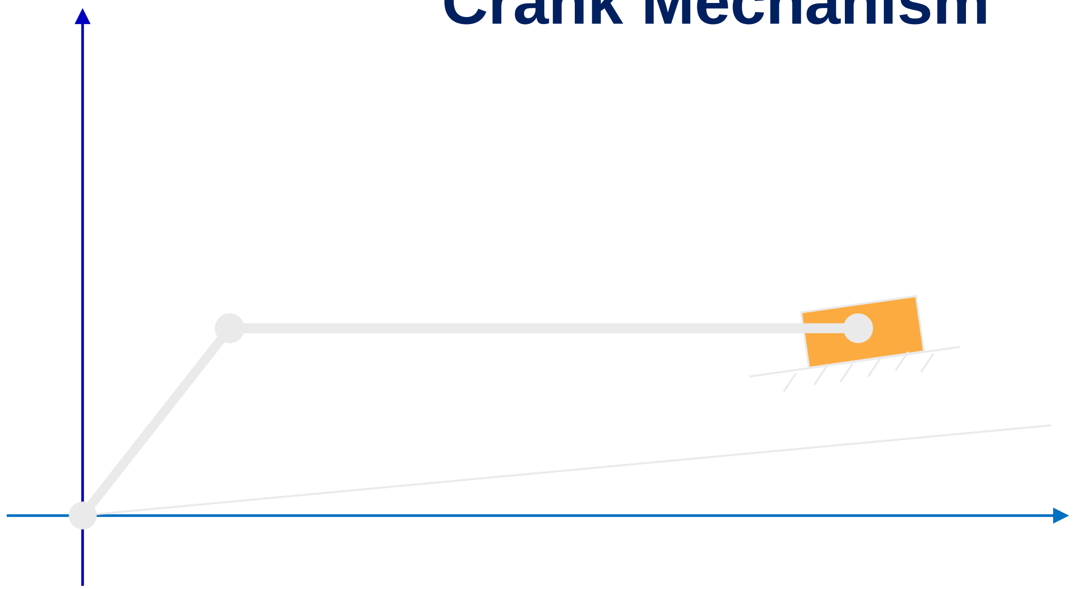
Step 2 - Attach reference coordinate reference frame (RH frame)

Step 3 - Link numbering & Joint numbering

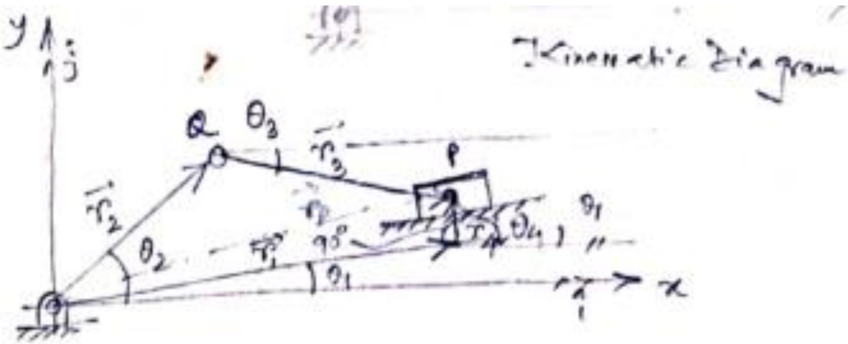
Step 4 - Represent each link as a vector

Step 5 - Formulate Vector Loop closure equation

Position Analysis/Displacement Analysis of Slider-Crank Mechanism



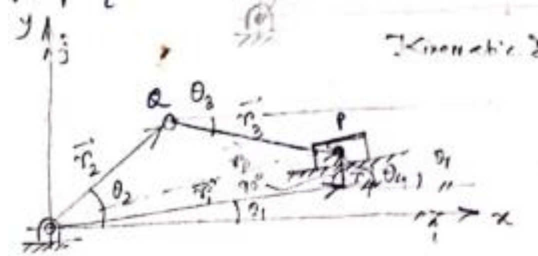
Position Analysis/Displacement Analysis of Slider-Crank Mechanism



[$\vec{r}_2$, $\vec{r}_3$, $\vec{r}_p$, The linkage could be represented by only three vectors $\vec{r}_2$, $\vec{r}_3$, $\vec{r}_p$ but one of them ($\vec{r}_p$) will be a vector of varying magnitude & angle. $\vec{r}_1$ & $\vec{r}_4$ are arranged parallel to axis of sliding & perp. resp. ($\vec{r}_1$ & $\vec{r}_4$ are orthogonal comp. of the P.V $\vec{r}_p$ from origin)

A general slider-crank mechanism is represented in above fig.

- To develop the loop-closure eqn, locate vectors $\vec{r}_2$ & $\vec{r}_3$ as was done in the regular four-bar linkage.
- To form the other part of the loop closure eqn, draw two vectors, one in the direction of the slider velocity and one perpn. to the velocity direction
- The variables associated with the problem are then located as shown in fig.
- The loop closure eqn is then the same as that for regular 4-bar linkage



The loop closure eqn is then the same as that for regular 4-bar linkage

$$\vec{r_2} + \vec{r_3} = \vec{r_1} + \vec{r_4}$$

$$r_2(\cos\theta_2\,\hat{i} + \sin\theta_2\,\hat{j}) + r_3(\cos\theta_3\,\hat{i} + \sin\theta_3\,\hat{j}) = r_1(\cos\theta_1\,\hat{i} + \sin\theta_1\,\hat{j}) + r_4(\cos\theta_4\,\hat{i} + \sin\theta_4\,\hat{j})$$

where $\theta_4 = \pi/2 + \theta_1$

$\therefore$ As θ_1 = Constant so θ_4 = Constᵗ

$$(r_2\cos\theta_2 + r_3\cos\theta_3)\hat{i} + (r_2\sin\theta_2 + r_3\sin\theta_3)\hat{j} = (r_1\cos\theta_1 + r_4\cos\theta_4)\hat{i} + (r_1\sin\theta_1 + r_4\sin\theta_4)\hat{j}$$

Scalar component of the eqn

$$r_2\cos\theta_2 + r_3\cos\theta_3 = r_1\cos\theta_1 + r_4\cos\theta_4 \quad \text{--------- (A)}$$

$$r_2\sin\theta_2 + r_3\sin\theta_3 = r_1\sin\theta_1 + r_4\sin\theta_4 \quad \text{--------- (B)}$$

Here, the base vector $\vec{r_1}$ will vary in magnitude but be constant in direction. The vector $\vec{r_4}$ will be constant.

$\therefore$ r_2, r_3, r_4, θ_1 & θ_4 are constants.

(in case of Air Compressor)

Case(i) If θ_2 is given, it is necessary to solve eqn ( ) & ( ) for θ_3 & $\vec{r_1}$ in terms of θ_2

Case(ii) If $\vec{r_1}$ is given, " " " " " " " for θ_2 & θ_3

(in case of IC engine)

Case (i) <u>When θ_2 is given</u>

From eqn (A) & (B)

$$\left.\begin{aligned} r_3 \cos\theta_3 &= r_1 \cos\theta_1 + r_4 \cos\theta_4 - r_2 \cos\theta_2 \\ r_3 \sin\theta_3 &= r_1 \sin\theta_1 + r_4 \sin\theta_4 - r_2 \sin\theta_2 \end{aligned}\right\}$$

Here, θ_1 & θ_4 are known consts. but r_1 varies & is unknown.

Squaring & adding

$$r_3^2 = r_1^2 + r_2^2 + r_4^2 + 2 r_1 r_4 (\cos\theta_1 \cos\theta_4 + \sin\theta_1 \sin\theta_4) - 2 r_1 r_2 (\cos\theta_1 \cos\theta_2 + \sin\theta_1 \sin\theta_2)$$
$$- 2 r_2 r_4 (\cos\theta_2 \cos\theta_4 + \sin\theta_2 \sin\theta_4) \quad \text{———} \quad (C)$$

$$r_1^2 + \underbrace{\{2 r_4 \cos(\theta_1 - \theta_4) - 2 r_2 \cos(\theta_1 - \theta_2)\}}_{B} r_1 \underbrace{- 2 r_2 r_4 \cos(\theta_2 - \theta_4) + r_2^2 + r_4^2 - r_3^2}_{C} = 0$$

$$r_1^2 + B r_1 + C = 0$$

$$r_1 = \frac{-B \pm \sqrt{B^2 - 4C}}{2}$$

$\pm$ indicates two assembly modes corresponding to the two configurations.

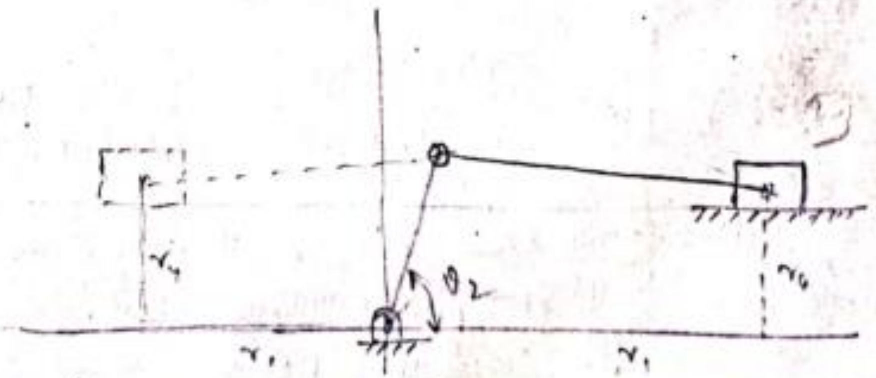
$$r_1 = \frac{-B \pm \sqrt{B^2 - 4C}}{2}$$

$\pm$ Indicates two assembly modes corresponding to the two configurations.

Once a value of 'r_1' is determined, eqs ( ) & ( ) can be solved for θ_3'

$$\theta_3 = \tan^{-1}\left[\frac{r_1 \sin\theta_1 + r_4 \sin\theta_4 - r_2 \sin\theta_2}{r_1 \cos\theta_1 + r_4 \cos\theta_4 - r_2 \cos\theta_2}\right]$$

- It is essential that the signs of the numerator & denominator in above eqn be maintained to determine the quadrant in which the angle 'θ_3' lies.



If $B^2 - 4C < 0$, r_1 will be complex. If this happens, the mechanism cannot be assembled in the position specified.

Case (ii) When r_1 is given:

From eq^n (c)

$$\underbrace{\left(-2r_1r_2\cos\theta_1 - 2r_2r_4\cos\theta_4\right)}_{A_1}\cos\theta_2 + \underbrace{\left(-2r_1r_2\sin\theta_1 - 2r_2r_4\sin\theta_4\right)}_{B_1}\sin\theta_2 + \underbrace{r_1^2+r_2^2+r_4^2-r_3^2+2r_1r_4\cos(\theta_1-\theta_4)}_{C_1} = 0$$

$$A_1\cos\theta_2 + B_1\sin\theta_2 + C_1 = 0$$

where $\cos\theta_2 = \dfrac{1-\tan^2\theta_2/2}{1+\tan^2\theta_2/2}$

$\sin\theta_2 = \dfrac{2\tan\theta_2/2}{1+\tan^2\theta_2/2}$

$$A_1\left[1-\tan^2\theta_2/2\right] + B_1\left[2\tan\theta_2/2\right] + C_1\left[1+\tan^2\theta_2/2\right] = 0$$

$$(C_1-A_1)\tan^2\theta_2/2 + 2B_1\tan\theta_2/2 + (C_1+A_1) = 0$$

$$A\tan^2\theta_2/2 + B\tan\theta_2/2 + C = 0$$

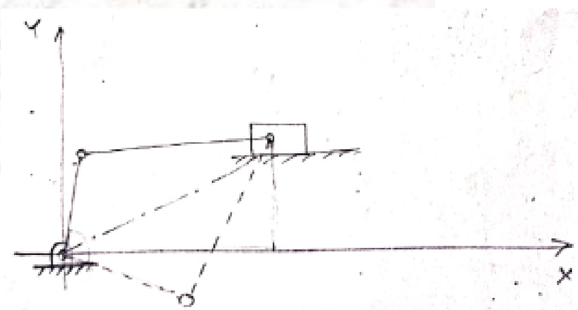
where $A = C_1 - A_1$

$B = 2B_1$

$C = C_1 + A_1$

$$\tan\theta_2/2 = \frac{-B \pm \sqrt{B^2-4AC}}{2A}$$

$$\theta_2 = 2\tan^{-1}\left[\frac{-B \pm \sqrt{B^2-4AC}}{2A}\right]$$



Velocity Analysis of Slider-Crank Mechanism

By Differentiating the loop-closure eqn or vector-loop eqn.

$$\vec{\dot{r}}_2 + \vec{\dot{r}}_3 = \vec{\dot{r}}_1 + \vec{\dot{r}}_4$$

$$\vec{r}_K = r_K(\cos\theta_K\,\hat{i} + \sin\theta_K\,\hat{j})$$

$$\vec{\dot{r}}_K = \dot{r}_K(\cos\theta_K\,\hat{i} + \sin\theta_K\,\hat{j}) + r_K\dot{\theta}_K(-\sin\theta_K\,\hat{i} + \cos\theta_K\,\hat{j})$$

Resulting component eqns.: Analytical form of the velocity eqn for the linkage

$$-r_2\dot{\theta}_2\sin\theta_2 - r_3\dot{\theta}_3\sin\theta_3 = \dot{r}_1\cos\theta_1$$

$$r_2\dot{\theta}_2\cos\theta_2 + r_3\dot{\theta}_3\cos\theta_3 = \dot{r}_1\sin\theta_1$$

As $\theta_4 = \pi/2 + \theta_1 = \text{Const}^n$

$\dot{\theta}_4 = 0$

$\vec{\dot{r}}_4 = 0$

If $\dot{\theta}_2$ is ~~port~~ input, then $\dot{r}_1$ and $\dot{\theta}_3$ will be unknown

$$-\dot{r}_1\cos\theta_1 - r_3\dot{\theta}_3\sin\theta_3 = r_2\dot{\theta}_2\sin\theta_2$$

$$-\dot{r}_1\sin\theta_1 + r_3\dot{\theta}_3\cos\theta_3 = -r_2\dot{\theta}_2\cos\theta_2$$

$$\underbrace{\begin{bmatrix} -\cos\theta_1 & -r_3\sin\theta_3 \\ -\sin\theta_1 & r_3\cos\theta_3 \end{bmatrix}}_{\text{Co-efficient Matrix}} \begin{bmatrix} \dot{r}_1 \\ \dot{\theta}_3 \end{bmatrix} = \begin{bmatrix} r_2\dot{\theta}_2\sin\theta_2 \\ -r_2\dot{\theta}_2\cos\theta_2 \end{bmatrix}$$

Velocity Analysis of Slider-Crank Mechanism

If $\dot{r}_1$ is input, then $\dot{\theta}_2$ and $\dot{\theta}_3$ will be unknown

$$\underbrace{\begin{bmatrix} -r_2 \sin\theta_2 & -r_3 \sin\theta_3 \\ r_2 \cos\theta_2 & r_3 \cos\theta_3 \end{bmatrix}}_{\text{Co-efficient Matrix}} \begin{bmatrix} \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} = \begin{bmatrix} \dot{r}_1 \cos\theta_1 \\ \dot{r}_1 \sin\theta_1 \end{bmatrix}$$

Once the angular velocities (ie $\dot{\theta}_2$ & $\dot{\theta}_3$) are known, it is a simple matter to compute the linear velocities of any of the points on the vector loop.

Linear vel. at pt. Q $\quad \vec{\dot{r}}_Q = \vec{\dot{r}}_2 = r_2 \dot{\theta}_2 (-\sin\theta_2 \hat{i} + \cos\theta_2 \hat{j})$

Linear vel. at pt 'P' $\quad \vec{\dot{r}}_P = \vec{\dot{r}}_2 + \vec{\dot{r}}_3 = \{-r_2 \dot{\theta}_2 \sin\theta_2 - r_3 \dot{\theta}_3 \sin\theta_3\} \hat{i} + \{r_2 \cos\theta_2 \cdot \dot{\theta}_2 + r_3 \dot{\theta}_3 \cos\theta_3\} \hat{j}$

Acceleration Analysis of Slider Crank Mechanism

The analytical form of the acceleration eqns for the linkage

$$\ddot{\vec{r}}_p = \ddot{\vec{r}}_2 + \ddot{\vec{r}}_3 = \ddot{\vec{r}}_1 + \ddot{\vec{r}}_4$$

The resulting component eqns are :

$$-r_2\ddot{\theta}_2\sin\theta_2 - r_2\dot{\theta}_2^2\cos\theta_2 - r_3\ddot{\theta}_3\sin\theta_3 - r_3\dot{\theta}_3^2\cos\theta_3 = \ddot{r}_1\cos\theta_1$$

$$r_2\ddot{\theta}_2\cos\theta_2 - r_2\dot{\theta}_2^2\sin\theta_2 + r_3\ddot{\theta}_3\cos\theta_3 - r_3\dot{\theta}_3^2\sin\theta_3 = \ddot{r}_1\sin\theta_1$$

If $\ddot{\theta}_2$ is input, then $\ddot{r}_1$ and $\ddot{\theta}_3$ will be unknown

$$-\ddot{r}_1\cos\theta_1 - r_3\ddot{\theta}_3\sin\theta_3 = +r_2\ddot{\theta}_2\sin\theta_2 + r_2\dot{\theta}_2^2\cos\theta_2 + r_3\dot{\theta}_3^2\cos\theta_3$$

$$-\ddot{r}_1\sin\theta_1 + r_3\ddot{\theta}_3\cos\theta_3 = -r_2\ddot{\theta}_2\cos\theta_2 + r_2\dot{\theta}_2^2\sin\theta_2 + r_3\dot{\theta}_3^2\sin\theta_3$$

$$\underbrace{\begin{bmatrix} -\cos\theta_1 & -r_3\sin\theta_3 \\ -\sin\theta_1 & r_3\cos\theta_3 \end{bmatrix}}_{\text{Co-efficient Matrix}} \begin{bmatrix} \ddot{r}_1 \\ \ddot{\theta}_3 \end{bmatrix} = \begin{bmatrix} +r_2\ddot{\theta}_2\sin\theta_2 + r_2\dot{\theta}_2^2\cos\theta_2 + r_3\dot{\theta}_3^2\cos\theta_3 \\ -r_2\ddot{\theta}_2\cos\theta_2 + r_2\dot{\theta}_2^2\sin\theta_2 + r_3\dot{\theta}_3^2\sin\theta_3 \end{bmatrix}$$

If $\ddot{r}_1$ is input, then $\ddot{\theta}_2$ and $\ddot{\theta}_3$ will be unknown

$$\underbrace{\begin{bmatrix} -r_2 \sin\theta_2 & -r_3 \sin\theta_3 \\ r_2 \cos\theta_2 & r_3 \cos\theta_3 \end{bmatrix}}_{\text{Co-efficient Matrix}} \begin{bmatrix} \ddot{\theta}_2 \\ \ddot{\theta}_3 \end{bmatrix} = \begin{bmatrix} r_2 \dot{\theta}_2^2 \cos\theta_2 + r_3 \dot{\theta}_3^2 \cos\theta_3 + \ddot{r}_1 \cos\theta_1 \\ r_2 \dot{\theta}_2^2 \sin\theta_2 + r_3 \dot{\theta}_3^2 \sin\theta_3 + \ddot{r}_1 \sin\theta_1 \end{bmatrix}$$

– The eq^n can be solved manually / Programmable Calculator / matrix solver like MATLAB.

Note: the Co-efficient matrix is the same for both the velocities & for the accelerations.

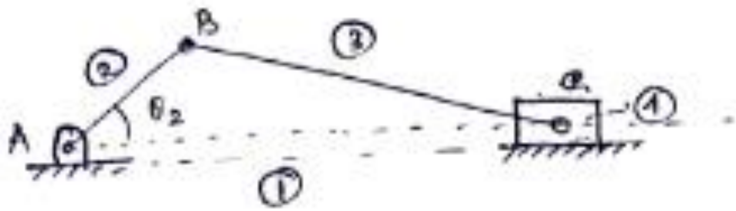
Once the angular accelerations are known, it is a simple matter to compute the linear accel^n. of any pt. on the vector loop.

Linear accel^n of pt. Q: $\ddot{r}_Q = \ddot{r}_2 = (r_2 \ddot{\theta}_2 \sin\theta_2 - r_2 \dot{\theta}_2^2 \cos\theta_2)\hat{i} + (r_2 \ddot{\theta}_2 \cos\theta_2 - r_2 \dot{\theta}_2^2 \sin\theta_2)\hat{j}$

Linear accel^n of pt. P: $\ddot{r}_P = \ddot{r}_2 + \ddot{r}_3 = -(r_2 \ddot{\theta}_2 \sin\theta_2 + r_2 \dot{\theta}_2^2 \cos\theta_2 + r_3 \ddot{\theta}_3 \sin\theta_3 + r_3 \dot{\theta}_3^2 \cos\theta_3)\hat{i} +$

$(r_2 \ddot{\theta}_2 \cos\theta_2 - r_2 \dot{\theta}_2^2 \sin\theta_2 + r_3 \ddot{\theta}_3 \cos\theta_3 - r_3 \dot{\theta}_3^2 \sin\theta_3)\hat{j}$.

Example # In the Slider-Crank mechanism shown in Fig. , $\theta_2 = 45^\circ$, $\dot{\theta}_2 = 10$ rad/s and $\ddot{\theta}_2 = 0$. The link lengths r_2 and r_3 are 5" and 8" respectively and the line of motion of point C is along the line AC. Find the position, velocity and accel^n of C and the angular velocity and acceleration of link 3.



Given Data : $\theta_2 = 45^\circ$, $\dot{\theta}_2 = 10$ rad/s , $\ddot{\theta}_2 = 0$

$r_2 = 5''$, $r_3 = 8''$

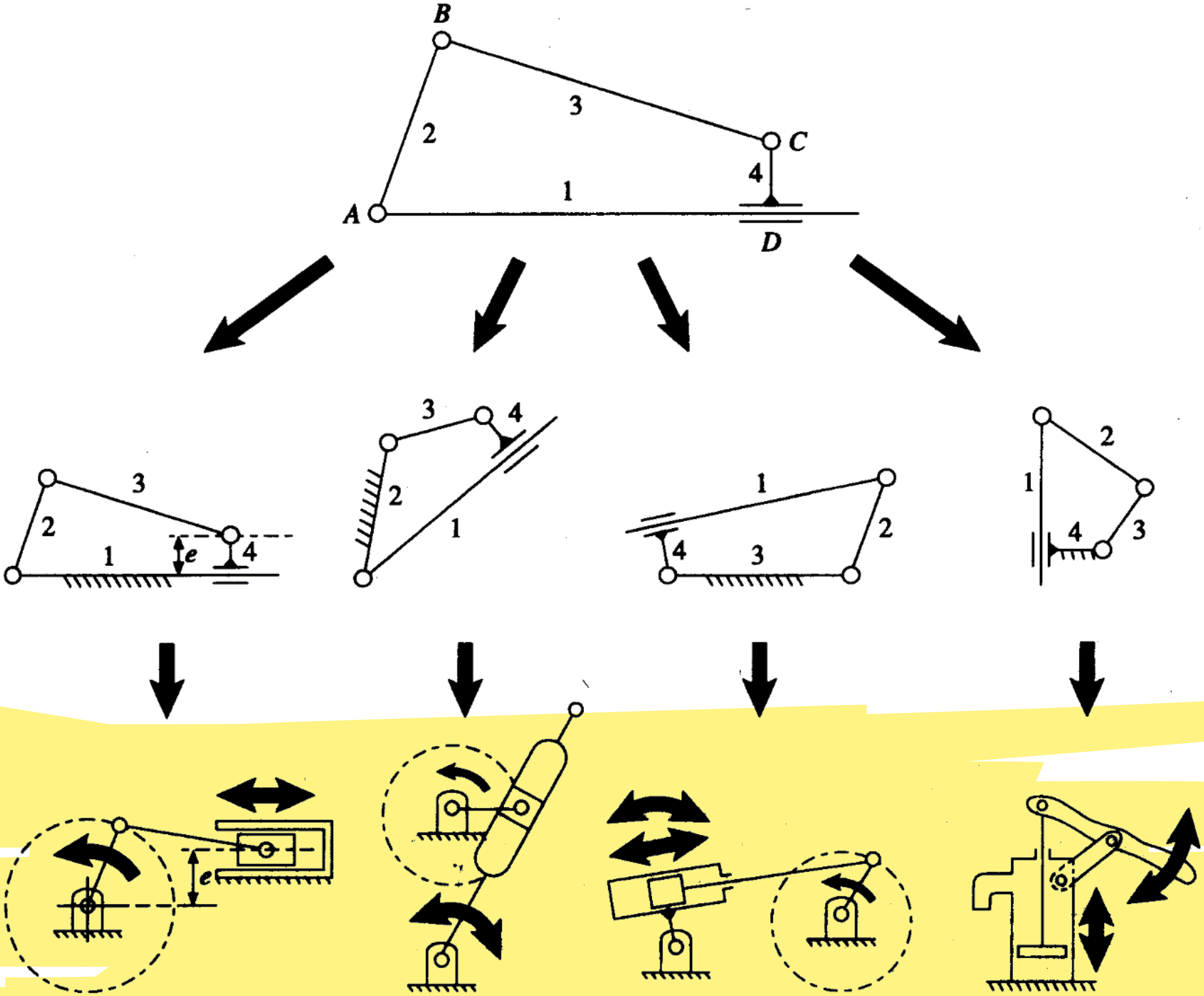
From Fig. $\theta_1 = 0^\circ$, $r_4 = 0$

Loop - Closure eq^n:

$$r_2 \cos\theta_2 + r_3 \cos\theta_3 = r_1 \cos\theta_1 + r_4 \cos\theta_4 \quad \text{------- (1)}$$
$$r_2 \sin\theta_2 + r_3 \sin\theta_3 = r_1 \sin\theta_1 + r_4 \sin\theta_4 \quad \text{------- (2)}$$

From (1) $5\cos 45^\circ + 8\cos\theta_3 = r_1 + 0 \Rightarrow 8\cos\theta_3 = r_1 - 5/\sqrt{2}$ ---- (3)

From (2) $5\sin 45^\circ + 8\sin\theta_3 = 0 \Rightarrow 8\sin\theta_3 = -5/\sqrt{2}$ ---- (4)

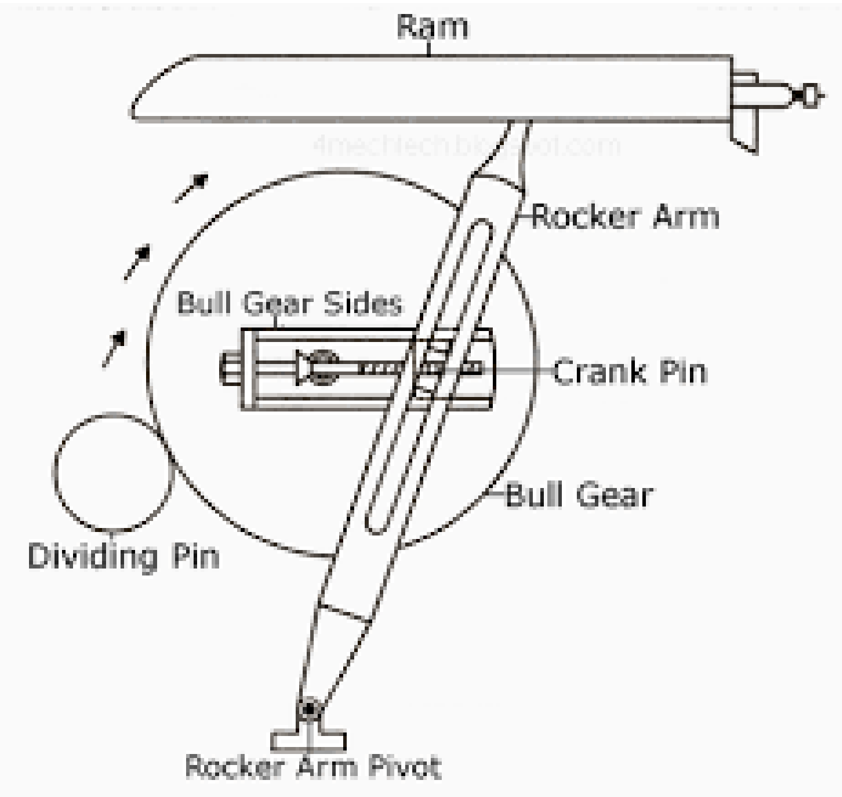


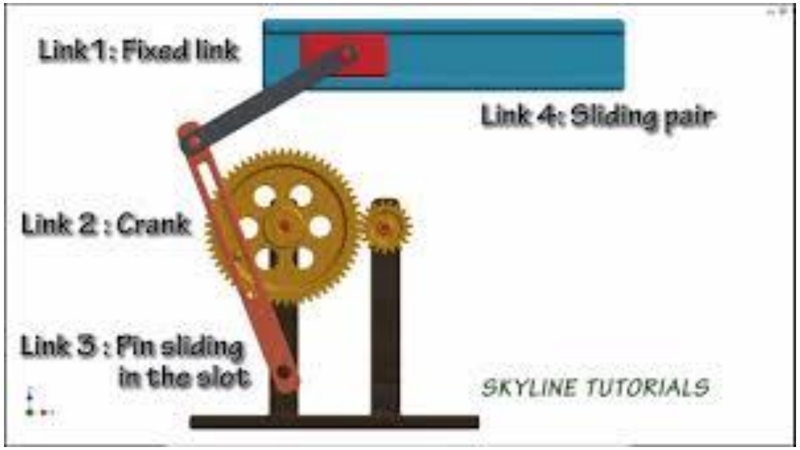
Direct-acting engine mechanism

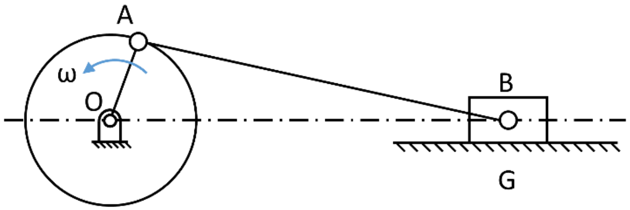
Slotted-lever quick-return mechanism

Oscillating-cylinder engine mechanism

Hand-pump mechanism

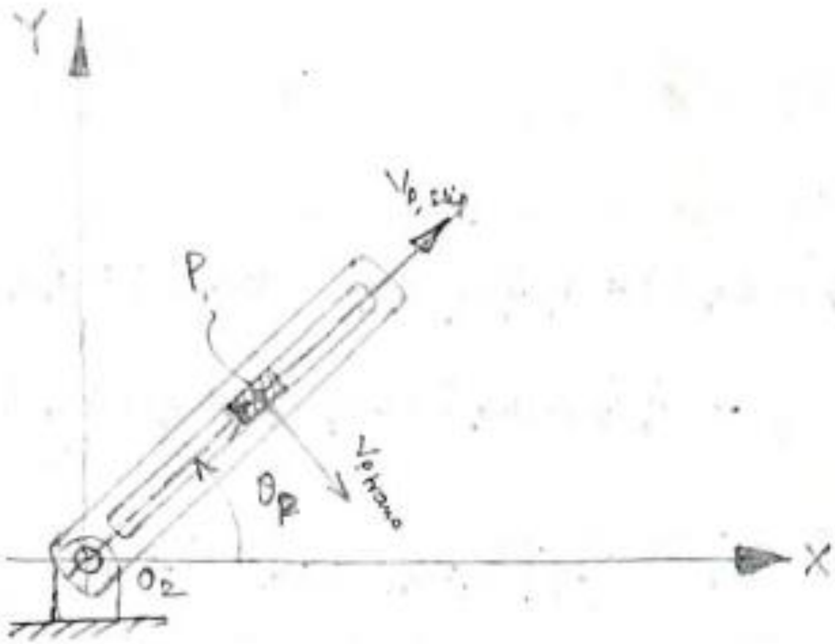

Ram
Rocker Arm
Bull Gear Sides
Crank Pin
Bull Gear
Dividing Pin
Rocker Arm Pivot


Link 1: Fixed link
Link 4: Sliding pair
Link 2 : Crank
Link 3 : Pin sliding in the slot
SKYLINE TUTORIALS


A
ω
O
B
G

Coriolis Acceleration

When a sliding joint is present on a rotating link, an additional component of acceleration will be present, called the CORIOLIS COMPONENT.



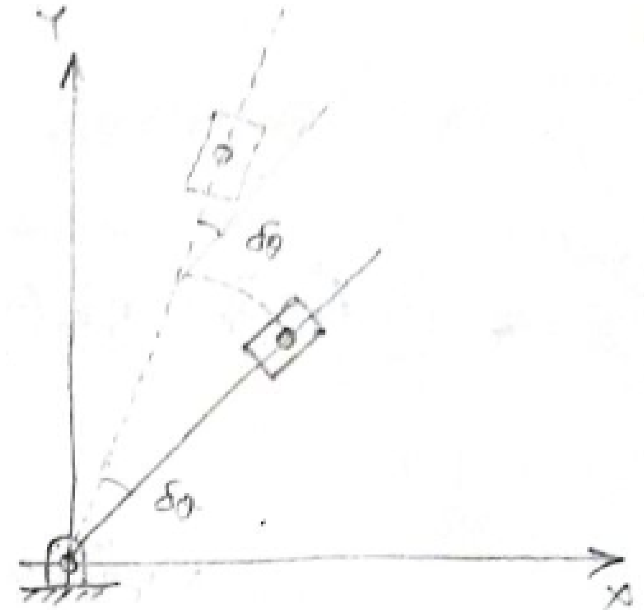


Fig. shows a simple, two link system consisting of a link with a radial slot and a slider block free to slip within that slot.

- The instantaneous location of the slider block is defined by a position vector (r_p) referenced to the ~~gto~~ origin of global frame at link centre.
- This vector (r_p) is both rotating and changing length as the system moves.

The two inputs to the system are the angular accel^n (α) of the link & relative linear slip velocity (V_{slip}) of the block.

- The transmission component of velocity ($V_{p,trans}$) is a result of the 'ω' of the link acting at 'p'.

Aim:
~~We want~~ is to determine the accel^n at center of the block (i.e. 'p') under this combined motion of rotation and sliding.

Position vector at point 'p' : $\vec{r_p} = r_p(\cos\theta_p\,\hat{i} + \sin\theta_p\,\hat{j})$ .... (1)

here $\vec{r_p}$ is fun of r_p & θ_p

Velocity at pt. $p \rightarrow$ $\vec{v_p} = \dot{\vec{r_p}} = \underbrace{r_p\,\dot{\theta}_p(-\sin\theta_p\,\hat{i} + \cos\theta_p\,\hat{j})}_{V_{p,trans}} + \underbrace{\dot{r}_p(\cos\theta_p\,\hat{i} + \sin\theta_p\,\hat{j})}_{V_{p,slip}}$ ..... (2)

$$\overrightarrow{V_p} = \dot{\vec{r}}_p = \underbrace{r_p \dot{\theta}_p \left(-\sin\theta_p\, \hat{i} + \cos\theta_p\, \hat{j}\right)}_{\substack{\text{transmission comp. of vel.} \\ \text{due to } \omega \\ (V_{tran})}} + \underbrace{\dot{r}_p \left(\cos\theta_p\, \hat{i} + \sin\theta_p\, \hat{j}\right)}_{\substack{\text{relative linear slip vel.} \\ (V_{P,slip})}}$$

Here $V_{P,tran}$ is fun. of $r_p, \theta_p, \dot{\theta}_p$

$V_{P,slip}$ is fun of $\dot{r}_p, \theta_p$

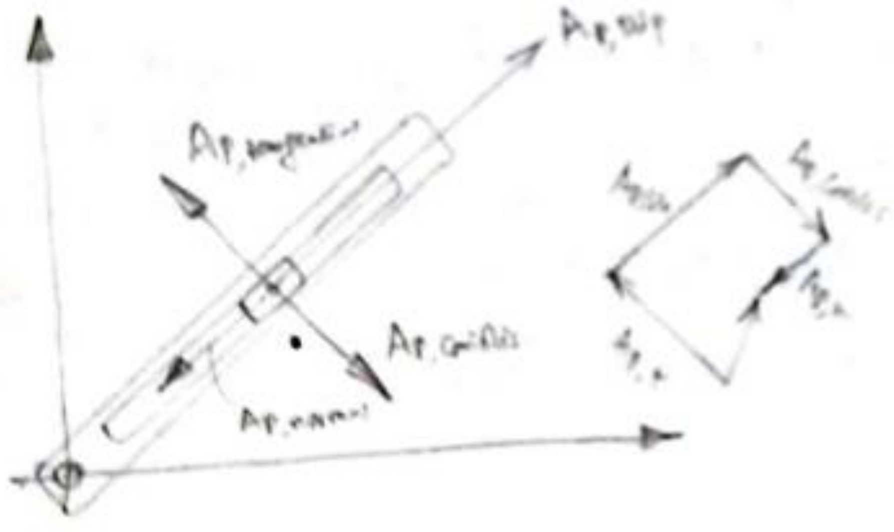
$$\vec{A}_p = \ddot{\vec{r}}_p = r_p\ddot{\theta}_p\left(-\sin\theta_p\,\hat{i} + \cos\theta_p\,\hat{j}\right) + r_p\dot{\theta}_p^2\left(-\cos\theta_p\,\hat{i} - \sin\theta_p\,\hat{j}\right) + \dot{r}_p\dot{\theta}_p\left(-\sin\theta_p\,\hat{i} + \cos\theta_p\,\hat{j}\right)$$

$$+ \dot{r}_p\dot{\theta}_p\left(-\sin\theta_p\,\hat{i} + \cos\theta_p\,\hat{j}\right) + \ddot{r}_p\left(\cos\theta_p\,\hat{i} + \sin\theta_p\,\hat{j}\right)$$

$$= \underbrace{r_p\ddot{\theta}_p\left(-\sin\theta_p\,\hat{i} + \cos\theta_p\,\hat{j}\right)}_{A_{p,\,tangential}} + \underbrace{\left\{-r_p\dot{\theta}_p^2\left(\cos\theta_p\,\hat{i} + \sin\theta_p\,\hat{j}\right)\right\}}_{A_{p,\,normal}} + \underbrace{2\dot{r}_p\dot{\theta}_p\left(-\sin\theta_p\,\hat{i} + \cos\theta_p\,\hat{j}\right)}_{A_{p,\,Coriolis}}$$

$$+ \underbrace{\ddot{r}_p\left(\cos\theta_p\,\hat{i} + \sin\theta_p\,\hat{j}\right)}_{A_{p,\,slip}}$$

$$= A_{p,\,tangential} + A_{p,\,normal} + A_{p,\,Coriolis} + A_{p,\,slip}$$



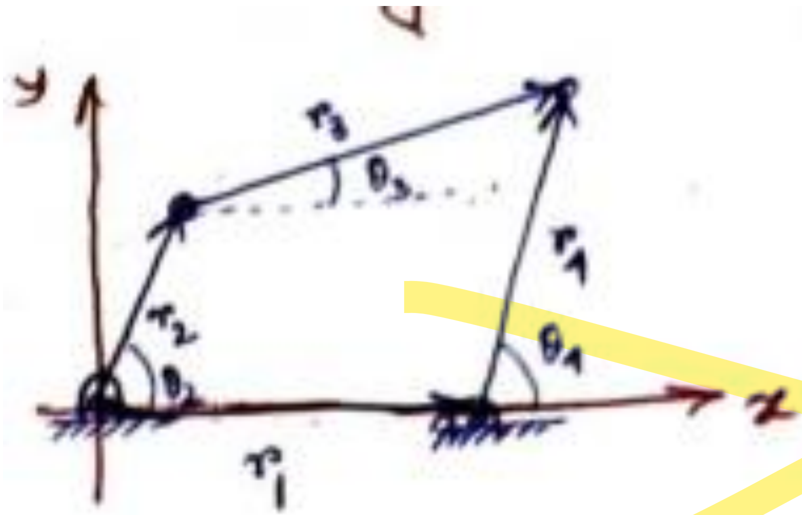
$$|A_{p,\text{tangen}}| = r_p \dot{\theta}_p$$

$$|A_{p,\text{normal}}| = r_p \dot{\theta}_p^{\,2}$$

$$|A_{p,\text{slip}}| = \dot{r}_p$$

$$|A_{p,\text{coriolis}}| = 2 \dot{r}_p \dot{\theta}_p$$

Displacement Analysis of 4R linkage



Two scaler eqns.

$$r_2\cos\theta_2 + r_3\cos\theta_3 = r_1\cos\theta_1 + r_4\cos\theta_4 \Rightarrow r_2\cos\theta_2 + r_3\cos\theta_3 = r_1 + r_4\cos\theta_4$$

$$r_2\sin\theta_2 + r_3\sin\theta_3 = r_1\sin\theta_1 + r_4\sin\theta_4 \Rightarrow r_2\sin\theta_2 + r_3\sin\theta_3 = r_4\sin\theta_4$$

as $\theta_1 = 0^\circ$

$$r_3\cos\theta_3 = r_1 + r_4\cos\theta_4 - r_2\cos\theta_2$$

$$r_3\sin\theta_3 = r_4\sin\theta_4 - r_2\sin\theta_2$$

$$r_3 \cos\theta_3 = r_1 + r_4 \cos\theta_4 - r_2 \cos\theta_2$$

$$r_3 \sin\theta_3 = r_4 \sin\theta_4 - r_2 \sin\theta_2$$

$$r_3^2 = (r_1 + r_4 \cos\theta_4 - r_2 \cos\theta_2)^2 + (r_4 \sin\theta_4 - r_2 \sin\theta_2)^2$$

$$r_3^2 = r_1^2 + r_2^2 + r_4^2 - 2r_1r_2\cos\theta_2 + 2r_1r_4\cos\theta_4 - 2r_2r_4\cos\theta_2\cos\theta_4 - 2r_2r_4\sin\theta_2\sin\theta_4$$

$$r_3^2 = r_1^2 + r_2^2 + r_4^2 - 2r_1r_2\cos\theta_2 + 2r_1r_4\cos\theta_4 - 2r_2r_4\cos(\theta_2 - \theta_4)$$

$$2r_1r_4\cos\theta_4 - 2r_1r_2\cos\theta_2 + (r_1^2 + r_2^2 + r_4^2 - r_3^2) = 2r_2r_4\cos(\theta_2 - \theta_4)$$

$$\frac{r_1}{r_2}\cos\theta_4 - \frac{r_1}{r_4}\cos\theta_2 + \frac{r_1^2 + r_2^2 + r_4^2 - r_3^2}{2r_2r_4} = \cos(\theta_2 - \theta_4)$$

$$K_1\cos\theta_4 - K_2\cos\theta_2 + K_3 = \cos(\theta_2 - \theta_4) \quad \text{------ (A)} \quad F$$

FREUDENSTEIN'S

Computer Aided Kinematic Analysis of Mechanisms

- Writing Code using MATLAB, C, C++ or python
- SolidWorks/CATIA DMU Kinematics
- ADAMS
- MechAnalyser

Analysis vs. Synthesis

Analysis

- These are the technique that allow the designer to critically examine an already existing design in order to judge its suitability for the task.
- Analysis is simply a scientific tool

Kinematic Analysis

In Kinematic Analysis one is given a mechanism & the task is to determine the various relative motion that can take place in that mechanism.

Steps

Position Analysis/ Displacement Analysis

⇓

Velocity Analysis

⇓

Acceleration Analysis

⇓

Jerk Analysis

Kinetic Analysis

Force Analysis

Torque Analysis

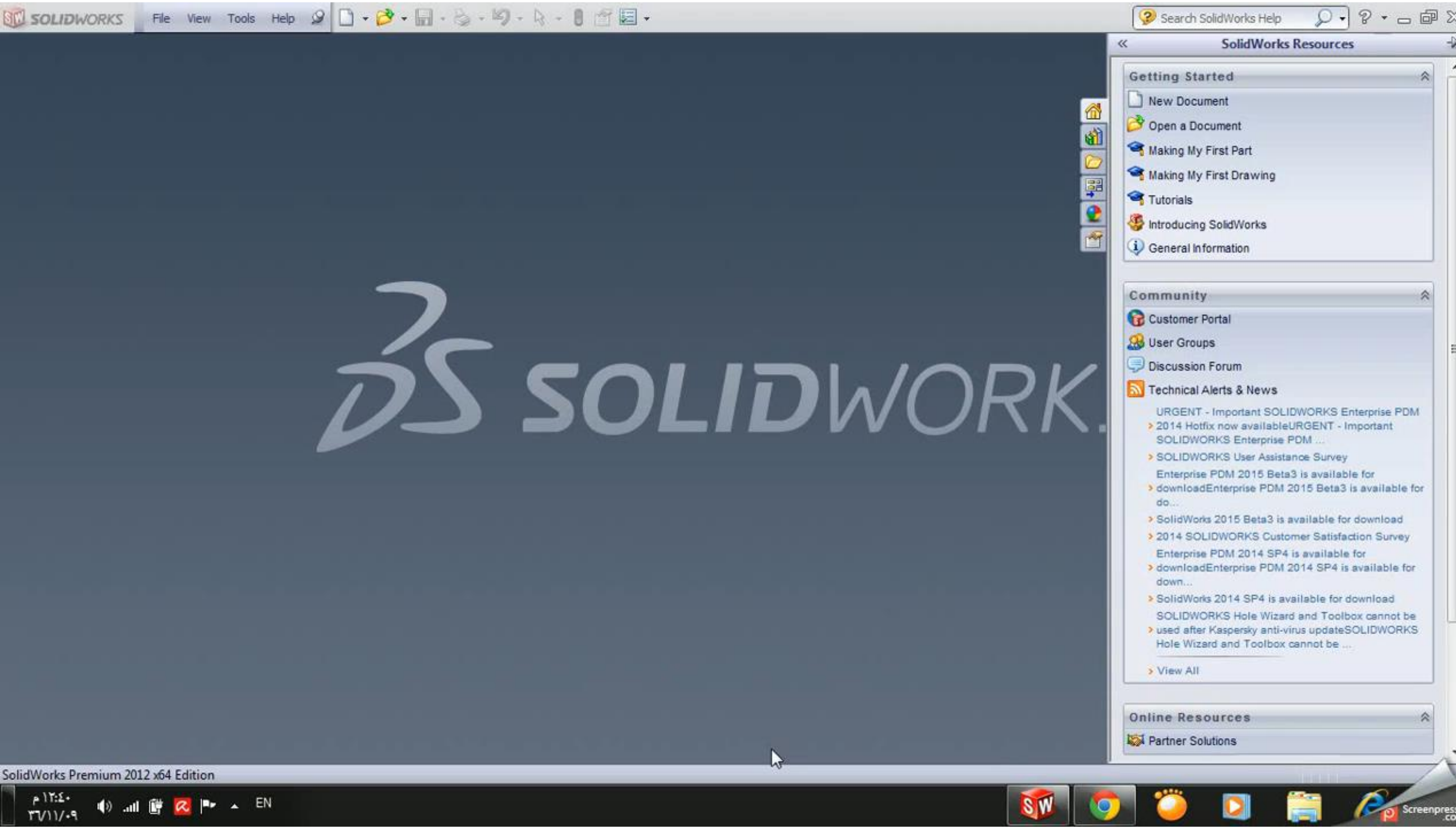
Prob # 1

In a four-link mechanism, the dimensions of the links are as under:
AB = 20 mm, BC = 66 mm, CD = 56 mm and AD = 80 mm
AD is the fixed link. The crank AB rotates at uniform angular velocity of 10.5 rad/s in the counter-clockwise direction. Determine using the program **(MATLAB)** *the angular displacements, angular velocities and angular accelerations of the output link DC and the coupler BC for a complete revolution of the crank at an interval of 4* ***degree***

Prob # 2

In a slider-crank mechanism, the lengths of the crank and the connecting rod are 480 mm and 1.6 m respectively. It has an eccentricity of 100 mm. Assuming a velocity of 20 rad/s of the crank OA, calculate the following at an interval of 3 degree

(i) Velocity and the acceleration of the slider
(ii) Angular velocity and angular acceleration of the connecting rod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