INTRODUCTION TO THEORY OF MACHINE

Simply speaking, "A machine is a device which received energy in some available form and utilizes it to do some particular type of work" or "A machine may be regarded as an agent for transmitting or modifying energy".

THE MACHINE

A machine is a combination of components which can transmit power in a controlled manner and which is capable of performing useful work. A machine consists of a number of kinematically related links.

A machine is a combination of resistant bodies (links or elements) with successfully constrained relative motions, which is used for transmitting other forms of energy into mechanical energy or transmitting and modifying available energy to do some particular kind of work.

INPUT	**MACHINE**	**OUTPUT**
Mechanical Electrical Hydraulic Chemical or Nuclear	**Kinematic Arrangement of Links** - Rigid - Rigid-Hydraulic - Rigid-Pneumatic	Mechanical Electrical Hydraulic or Thermal
Force Velocity Energy/Time Power	A machine has moving parts, which must be constrained and controlled.	Force Velocity Energy/Time Power

Machine Arrangement

Every machine will be found to consist of a system of parts (links or elements) connected together in such a manner that, if one be made to move, they all receive a motion, the relation of which to that of the first depends upon the nature of connections (i.e. joints).

The links may be rigid, rigid-hydraulic, or rigid-pneumatic. The power input may be mechanical, electrical, hydraulic, chemical, or nuclear. The power output may be mechanical, electrical hydraulic or thermal.

Examples of machines:

Heat engine- Receives heat energy and transformers it into mechanical energy.

Electric motor- Changes electric energy into mechanical energy.

A pump- Input electric power and output hydraulic power.

The majority of machines receives mechanical energy, and modifies it so that the energy can be used for doing some specific task, for which it is designed, common examples of such machines being hoist, lathe, screw jack, etc.

Note:-It should be noted that machine must be capable of doing useful work. A series of kinematically related links put into motion with no output link, and which simply converts input energy to friction heat, is not a machine, unless the original purpose was only to generate heat.

CLASSIFICATION OF MACHINES

1. Machines for generating mechanical energy

   - Converts other forms of energy into mechanical work

   Examples: Steam engines, Steam turbines, I. C. engines, gas turbines, water turbines etc

2. Machines for transmitting mechanical energy into other form of energy

   - Known as converting machines

   Examples: Electric generators, air or hydraulic pumps, etc.

3. Machines for utilizing mechanical energy in the performance of useful work.

Examples: Lathe, and other machine tools, etc.

The transmission and modification of energy within the machine require the inclusion of a number of parts (links or elements), which are so selected that they will produce the desired motion and carry with safety the forces to which they are subjected so that the machine can perform its task successfully.

The study of relative motion between the various parts of a machine, and the forces which act on them, is covered under they field of "**Theory of machines**", or "**The Theory of Machines** may be defined as that branch of engineering science which deals with the study of relative motion between various elements of a machine and the forces which act on them.

DIFFERENCE BETWEEN MACHINE AND MECHANISM

In kinematics, a mechanism is a mean of transmitting, controlling, or constraining relative movement. The central theme for mechanisms is rigid bodies connected together by joints. It can also be defined as a combination of resistant bodies that are shaped and connected in such a way that they move with definite relative motion with respect to each other.

A machine is a combination of rigid or resistant bodies, formed and connected in such a way that they move with definite relative motions with each other and transmit force also. A machine has two functions: transmitting definite relative motion and transmitting force. The term mechanism is applied to the combination of geometrical bodies which constitute a machine or part of a machine.

MACHINE	MECHANISM
• It is a combination of links having relative motion and has the capability of modifying available energy in a suitable form. • A machine can consist of one or more than one mechanism. e.g. lathe machine has several mechanisms • Its objective is to transmit mechanical energy. • It is a combination of links which transmit and transform its motion only.	• A mechanism is a single system to transmit motion. • Its objective is to transmit motion only.

Example: A simple example of machine and mechanism is IC engine and slider crank mechanism. A slider crank mechanism converts rotary motion of crank into sliding motion of slider. Whereas, in the IC engine the same mechanism is used to convert available mechanical energy at the piston into the required torque at the crank shaft.

KINEMATIC ANALYSIS OF MECHANSIM

Various mechanisms have its own set of outputs when they are put in motion. The analysis of the mechanism is done by calculating the position, velocity and acceleration at various points on the mechanisms. For the analysis of velocity & acceleration at any point on the mechanism we don't need to calculate forces & stresses acting in the parts of the mechanism. In other means, in analysis of motion of a particular mechanism we don't need to consider the cross section area or strength of the parts in that mechanism. Also, it does not matter whether the parts are made of cast iron or wood or anything else to study it motion analysis.

GRAPHICAL AND ANALYTICAL METHOD:

Analysis of the Mechanism can be done by two types of methods, generally known as graphical and analytical methods. Each method has its own advantages and disadvantages. The graphical method is easy to follow and gives the visual image of the working of mechanism which can be applied in some simple problems. But for more complex problems analytical methods are more suitable. It is up to us by which method we want to solve the problem in hand. With the advent of high speed computing, analytical methods has very useful tool for solving complex problems. In this course will concentrate our study to graphical methods due its ease and simplicity.

SYNTHESIS OF DESIGN

In the design of a mechanism, we will consider stress analysis & others design parameters like bending, fatigue etc. to find the dimensions of the parts. The synthesis of a mechanism can be done by following two approaches. In the first approach the dimensions of the parts in a mechanism is found by considering load, stress & bending etc. in the different parts of the mechanism. In the second approach, the dimensions of the parts are assumed first and then the analysis is done to check its strength. The second method of synthesis is preferred by most of the engineers.

KINEMATICS OF MECHANISM

It involves the study of the relative motions of various parts of a mechanism without considering the forces producing the motion in the parts. It is the study from the geometric point of view by which we can know the displacement, velocity and acceleration at the various points on the parts of a mechanism.

DYNAMICS OF MECHANISM

It involves the calculations of the forces impressed upon various parts of a mechanism. The forces impressed on a mechanism can be divided into static & kinetics. In static, the study of forces is done when all the parts of the mechanisms are in equilibrium. Where in kinetics the study of inertia forces are done which may occur due to the combination of mass and motion of the parts.

PLANER MECHANISM

LINK

A link is defined as a single part which can be a resistant body or a combination of resistant bodies having inflexible connections and having a relative motion with respect to other parts of the machine. A link is also known as kinematic link or element. Links should not be confused with the parts of the mechanism. Different parts of the mechanism can be considered as single link if there is no relative motion between them.

Example: The frame of any machine is considered as single link as there is no relative motion between the various parts of the frame. As shown in slider crank mechanism shown below, the frame is considered as one link (link 1) as there is no relative motion in frame itself. The crank here is link 2 & connecting rod is again single link (link 3). The slider or piston is link 4 as there is no relative motion it. In this way, many complex mechanisms can be describe by simple configuration diagram by considering the definition of a link.

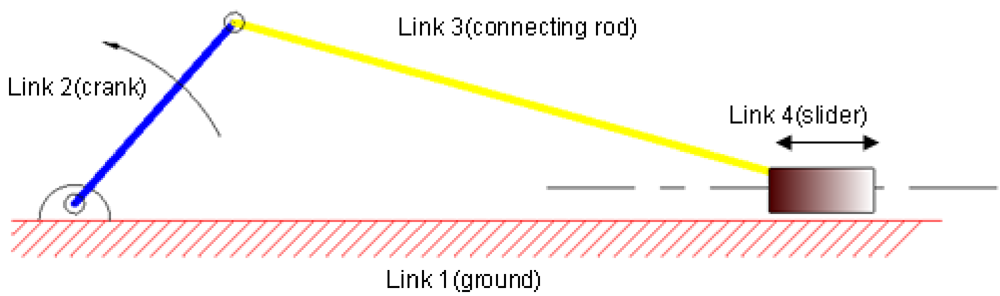


Fig: 2.1 Slider crank mechanism

TYPES OF LINKS: Links can be classified into **Binary, Ternary, and Quaternary etc.** depending upon its ends on which revolute or turning pairs can be placed.

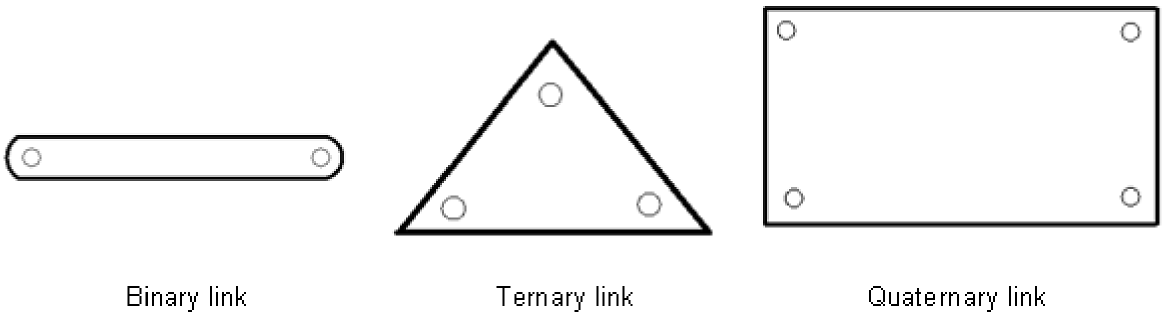


Fig.2.2 Types of links

The links can also be classified into **Rigid, Flexible, Fluid** according to its nature such as

Rigid link is the link which do not deform while transmitting the motion

Flexible link is the link which deform while transmitting the motion but does not affect its function of transmitting motion such as belts, chains etc.

Fluid link is the link which uses the fluid pressure to transmit the motion such as hydraulics jack, brakes and lifts.

RIGID BODY

A rigid body is a body in which the distance between the two points on the body remains constant or it does not deform under the action of applied force. In actual practice no body is perfectly rigid but we assume it to be rigid to simplify our analysis.

RESISITANT BODY

A Resistant body is a body which is not a rigid body but acts like a rigid body whiles its functioning in the machine. In actual practice, no body is the rigid body as there is always some kind of deformation while transmitting motion or force. So, the body should be resistant one to transmit motion or force.

Examples: The cycle chain is the resistant body as it acts like rigid body while transmitting motion to the rear wheel of the cycle, Belt in belt and pulley arrangement.

KINEMATIC PAIR OR PAIR

A kinematic pair is a connection between rigid bodies, which permits relative motion between them. When the links are supposed to be rigid in kinematics, then, there cannot be any change in the relative positions of any two chosen points on the selected link. In other words, the relative position of any two points does not change and it is treated as one link. Due to this rigidness, many complex shaped links can be replaced with simple schematic diagrams for the kinematic and synthesis analysis of mechanism.

CLASSIFICATION OF PAIRS

Kinematic pairs can be classified according to

a) Type of contact between elements

b) Type of relative motion

c) Nature of constraint or Type of closure

a) Type of contact between elements

Lower Pairs: A pair of links having surface or area contact between the members is known as a lower pair. The surfaces in contact of the two links are similar.

Examples: Nut turning on a screw, shaft rotating in a bearing, universal joint, etc.

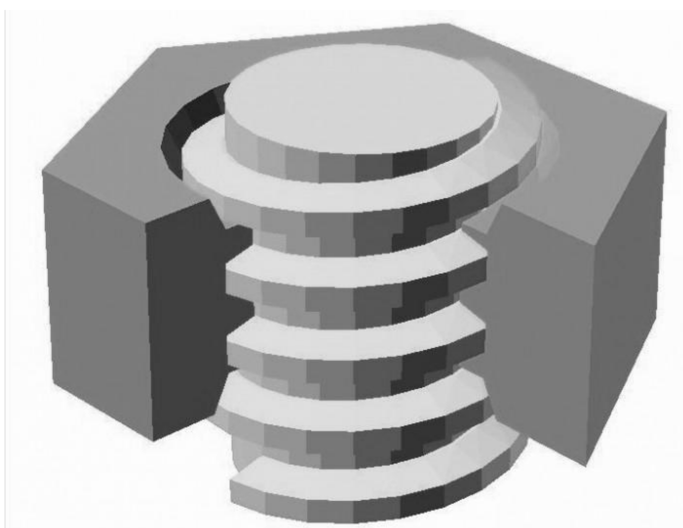


Fig. 2.3 Nut and screw (lower pair)

Higher Pair: When a pair has a point or line joint contact between the links, it is known as a higher pair. The contact surfaces of the two links are dissimilar.

Examples: Wheel rolling on a surface, cam and follower pair, tooth gears, ball and roller bearings, etc.

Fig. 2.4 ball and roller bearing (higher pair)

b) Type of relative motion

Sliding Pair: When two pairs have sliding motion relative to each other.

Examples: piston and cylinder, rectangular rod in rectangular hole.

Turning Pair: When one element revolves around another element it forms a turning pair.

Examples: shaft in bearing, rotating crank at crank pin.

Screw Pair: This is also known as helical pair. In this type of pair two mating elements have threads on it or its relative motion takes place along a helical curve.

Examples: Nut and screw pair as shown in figure 2.4, Screw jack

Rolling Pair: When one element is free to roll over the other one.

Examples: Ball and rolling as shown in figure 2.5, motion of wheel on flat surface

Spherical pair: When one element move relative to the other along a spherical surface.

Examples: Ball and socket joint

Explanation

In slider crank mechanism (Fig.2.6), crank (link 2) rotates relative to ground (link 1) and form a turning pair. Similarly, crank (link 2), connecting rod (link 3) and connecting rod (link 3), slider (link 4) also form turning pairs. Slider (link 4) reciprocates relative to ground (link 1) and form a sliding pair.

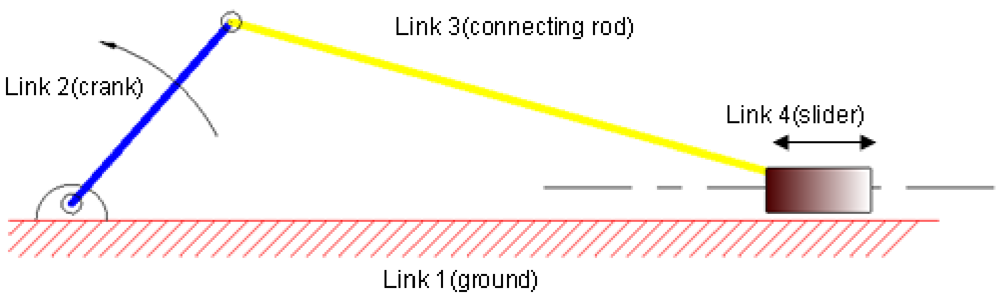


Fig.2.5 Slider crank mechanism

It should be noted here that the slider crank mechanism showed here is useful only in kinematic analysis and synthesis of the mechanism as actual physical appearance will be different and more complex than showed here. For designing the machine component the different approach will be followed.

c) Nature of Constraint or Type of closure

Closed pair: One element is completely surrounded by the other.

Examples: Nut and screw pair

Open Pair: When there is some external mean has been applied to prevent them from separation.

Examples: cam and follower pair

DEGREE OF FREEDOM

DEGREE OF FREEDOM

An object in space has six degrees of freedom.

Translatory motion along X, Y, and Z axis (3 D.O.F.)

Rotary motion about X, Y, and Z axis (3 D.O.F)

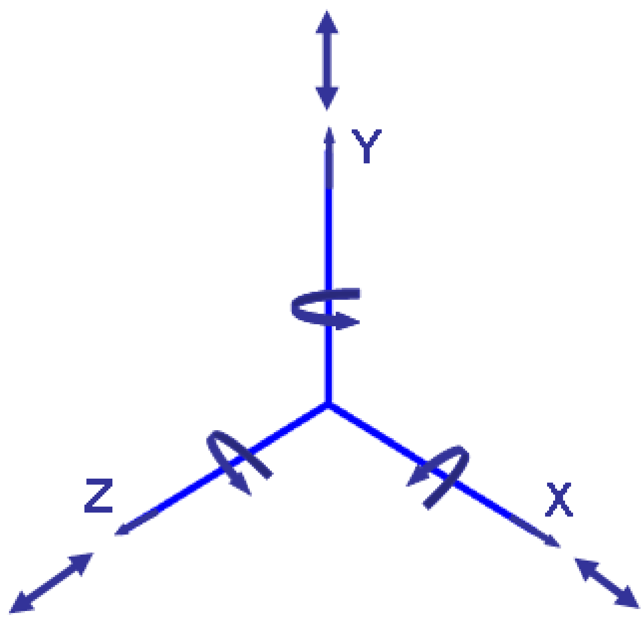


Fig.2.6 Degree of freedom

The rigid body has 6 DOF in space but due to formation of linkage one or more DOF is lost due to the presence of constraint on the body. The total number constraints cannot be zero as the body has to be fixed at some place to make the linkage possible. Thus the degree of freedom is given by

DOF= 6- (Numbers of Restraints)

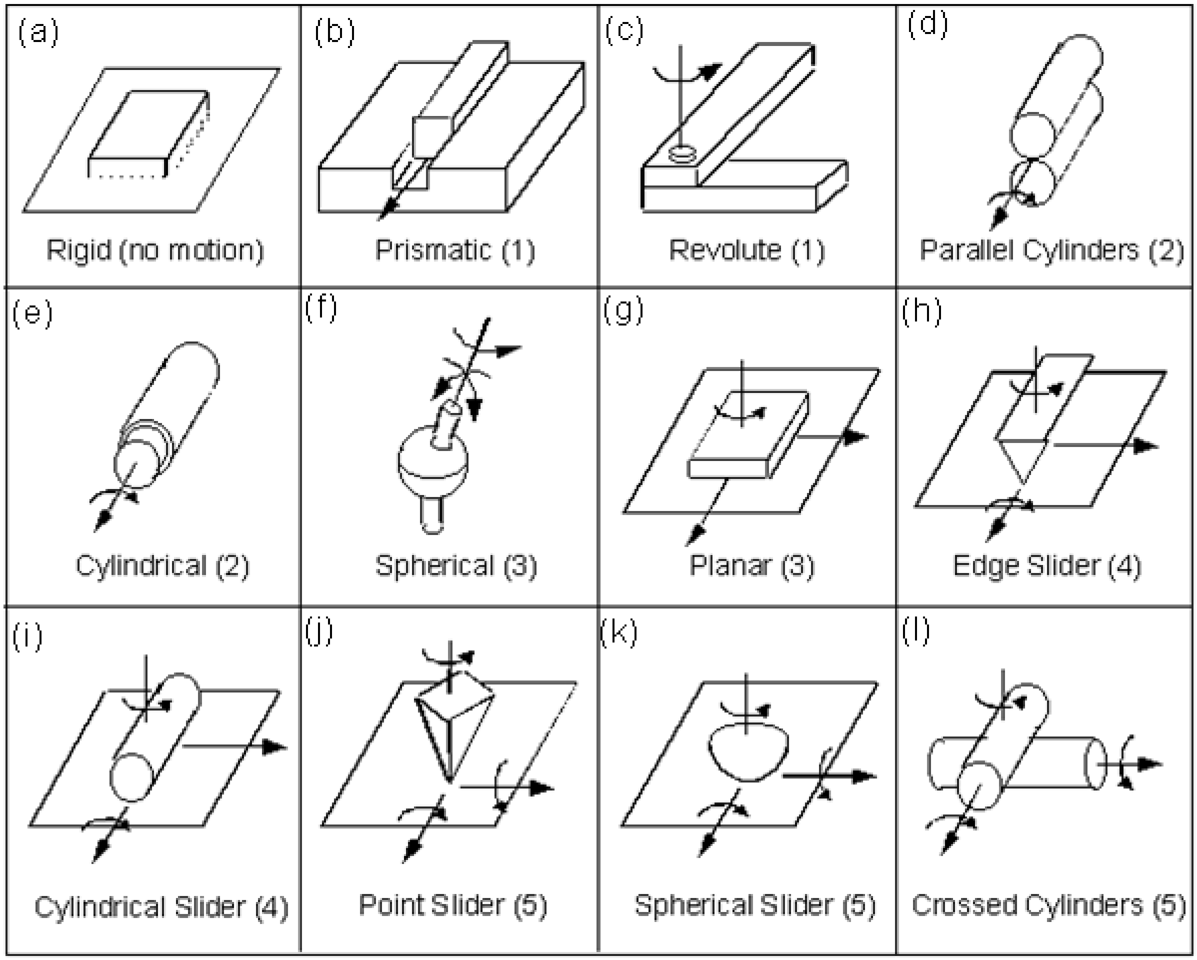


Fig.2.7 Pairs having varying degree of freedom

S. No.	Geometrical Shapes involved	Restraints on		Degree of freedom	Total restraints
		Translatory motion	Rotary motion		
(a)	Rigid	0	0	0	6
(b)	Prismatic	2	3	1	5
(c)	Revolute	3	2	1	5
(d)	Parallel cylinders	2	2	2	4
(e)	Cylindrical	2	2	2	4
(f)	Spherical	3	0	3	3
(g)	Planer	1	2	3	3
(h)	Edge slider	1	1	4	2
(i)	Cylindrical slider	1	1	4	2
(j)	Point slider	1	0	5	1
(k)	Spherical slider	1	0	5	1
(l)	Crossed cylinder	1	0	5	1

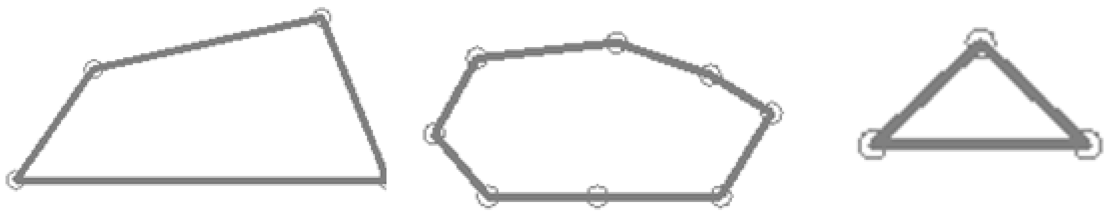
Table 2.1

Figure	Explanation for DOF
2.9 a	(0) As there is no motion hence DOF is zero
2.9 b	(1) As movement is possible only in Z direction.
2.9 c	(1) As it can revolve around Y axis
2.9 d	(2) As one element can move in Z axis & also revolve around Z axis
2.9 e	(2) As element inside can revolve around Z axis and also move in Z axis
2.9 f	(3) As element can revolve around X,Y&Z axis
2.9 g	(3) As element can revolve around Y axis & can move in Z & X axis
2.9 h	(4) As element can revolve around Z & Y axis & can move in Y axis
2.9 i	(4) As element can revolve around Z & Y axis & can move in Z & X axis
2.9 j	(5) As an element can revolve around X,Y&Z axis & can move in X & Z axis
2.9 k	(5) As element can revolve around X,Y & Z axis & can move in X & Z axis
2.9 l	(5) As element can revolve around X,Y & Z axis & can move in X & Z axis

Table 2.2

KINEMATIC CHAIN

a) Kinematic chain: A kinematic chain is an assembly of links which are interconnected through joints or pairs, in which the relative motions between the links is possible and the motion of each link relative to the other is definite.



a. kinematic chain **b. non kinematic chain** **c. redundant chain**

Fig.2.8 kinematic chains

b) Non-kinematic chain: In case the motion of a link results in indefinite motions of others links, it is a non-kinematic chain. The reason for this indefinite motion lies in the fact that if we give motion to any of the link in the chain then the other links can take indefinite position.

c) Redundant chain: There is no motion possible in the redundant chain. It can be observed from the figure 2.9 c that this chain is locked due to its geometry.

DEGREE OF FREEDOM IN A MECHANISM

Degrees of freedom of a mechanism in space can be explained as follows:

Let

N = total number of links in a mechanism

F = degrees of freedom

J_1 = number of pairs having one degree of freedom

J_2 = number of pairs having two degree of freedom and so on.

When one of the links is fixed in a mechanism

Then, the number of the movable links are = N - 1

Degrees of freedom of (N- 1) movable links = 6(N-1)

(Because each movable link has six degree of freedom) Each pair having one degree of freedom imposes 5 restraints on the mechanism reducing its degrees of freedom by $5J_1$ this is because of the fact that the restraint on any of the link is common to the mechanism as well. Other pairs having 2, 3, 4 and 5 degrees of freedom reduce the degree of freedom of the mechanism by putting constraints on the mechanism as well.

Then, the DOF can be given by

$$F = 6(N-1) - 5J_1 - 4J_2 - 3J_3 - 2J_4 - 1J_5$$

Most of the mechanism we generally study are two dimensional in nature, such as slider-crank mechanism in which translatory motion is possible along two axes(one restraint) and rotary motion about only one axis(two restraints).Thus there are three general restraints in a two dimensional mechanism. This can be shown with the help of figure 2.10 that a link has three degree of freedom in two dimensions.

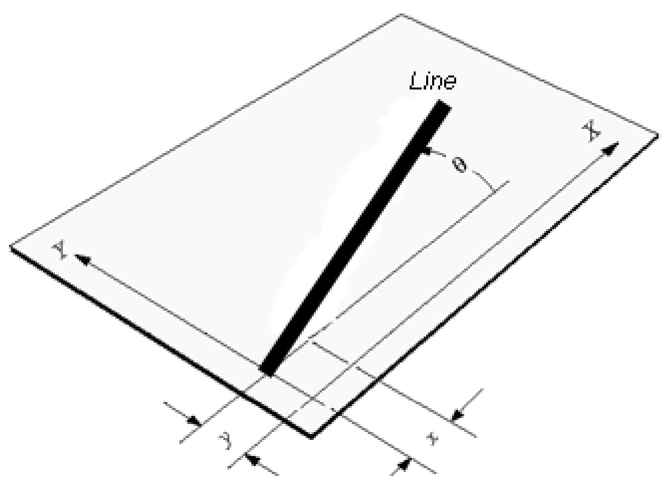


Fig.2.9 a line in a plane has three DOF: x, y, θ

Therefore, for plane mechanism, the following relation can be used for degrees of freedom,

$$F = 3(N-1) - 2J_1 - 1J_2$$

This equation is known as Gruebler's criterion for degrees of freedom of plane mechanism. It should be noted here that gruebler's criterion does not take care of geometry of the mechanism so it can give wrong prediction. So, inspection should be done in certain cases to find the degrees of freedom.

Example: 2.1 Find the degree of freedom of the mechanism given below.

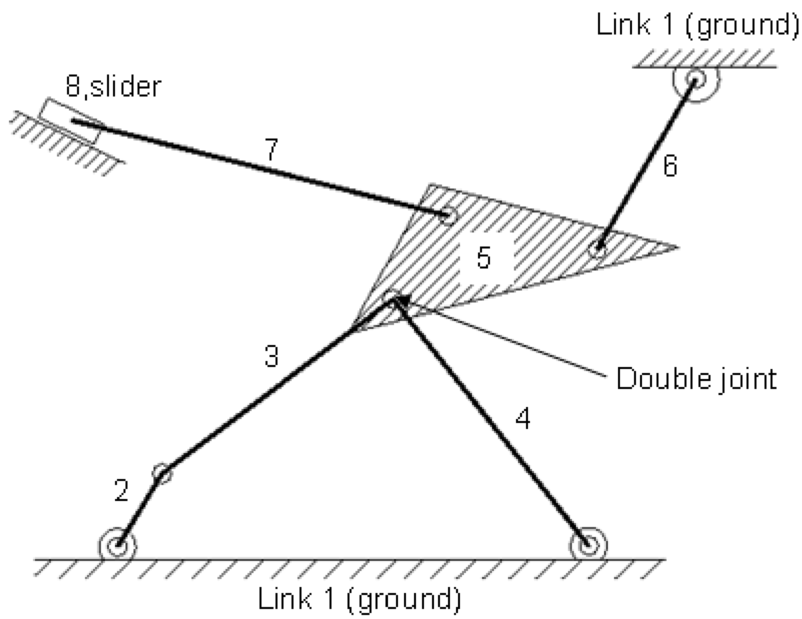


Fig.2.10

Solution:

Number of links=8

Numbers pairs having one degrees of freedom=10 by counting

How to calculate pairs

Pair 1	Link 1 (ground) and link 2 constitute a single turning pair
Pair 2	Link 2 and link 3 constitute a single turning pair
Pair 3	Link 3 and link 5 constitute a single turning pair
Pair 4	Link 4 and link 5 constitute a single turning pair
Pair 5	Link 5 and link 6 constitute a single turning pair
Pair 6	Link 6 and ground (link 1) constitute a turning pair
Pair 7	Link 5 and link 7 constitute a turning pair
Pair 8	Link 7 and link 8 constitute a turning pair
Pair 9	Link 8 and ground (link 1) constitute a sliding pair
Pair 10	Link 4 and ground (link 1) constitute a turning pair

As all the pair calculated have one degree of freedom so there is only term J_1 is used as it denotes the pair having single degree of freedom.

$J_1 = 10$ (as all pairs have one degree of freedom)

$F = 3(N-1) - 2J_1 - 1J_2$

DOF=3(8-1)-2×10=1

The degree of freedom is one for this mechanism.

Example 2.2 Find the degree of freedom of the mechanism given below.

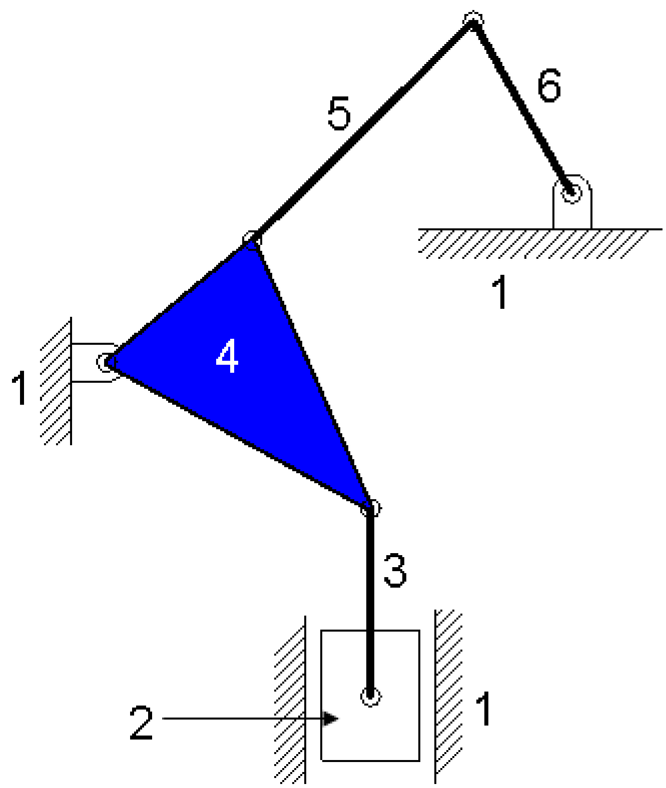


Fig. 2.11

Solution:

Number of links = 6

Number of Pairs = 7

$J_1 =$ 7 (six turning pairs and one sliding pair)

DOF=3(6-1)-2×7=1

The degree of freedom is one.

Example 2.3: Find the mobility or degree of freedom of the following mechanism.

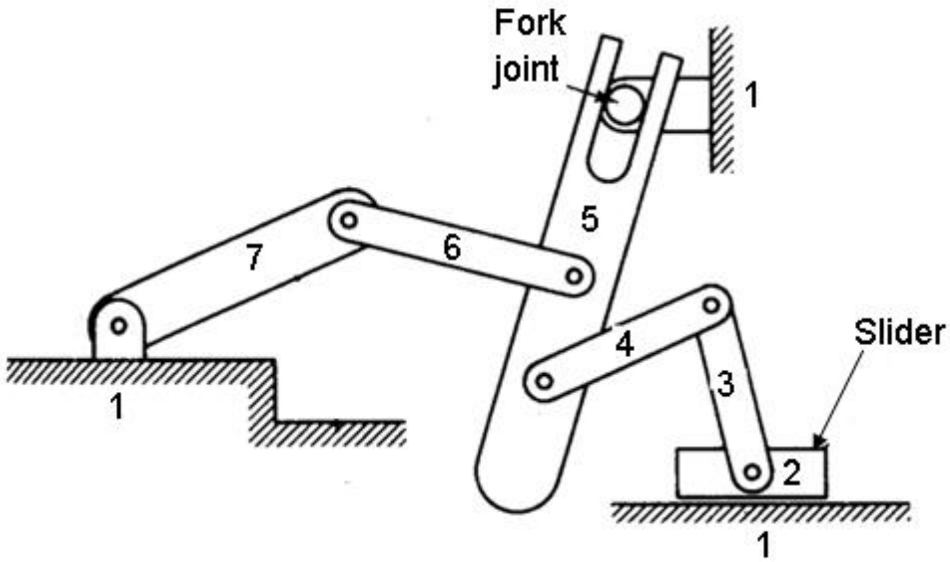


Fig. 2.12

Solution:

Number of links = 7

Number of Pairs = 8

J_1 = 7 (six turning pairs and one sliding pair)

J_2 = 1 (Fork joint is two DOF joint)

DOF=3(7-1)-2×7-1×1=3

The degree of freedom is one.

FOUR BAR MECHANISM

The four bar linkage, as shown in figure 2.13 below, is a basic mechanism which is quite common. Further, the vast majority of planar one degree-of-freedom (DOF) mechanisms have "equivalent" four bar mechanisms. The four bar has two rotating links (2 and 4)) which have fixed pivots. One of the levers would be an input rotation, while the other would be the output rotation. The two levers have their fixed pivots with the ground link (1) and are connected by the coupler link (3).

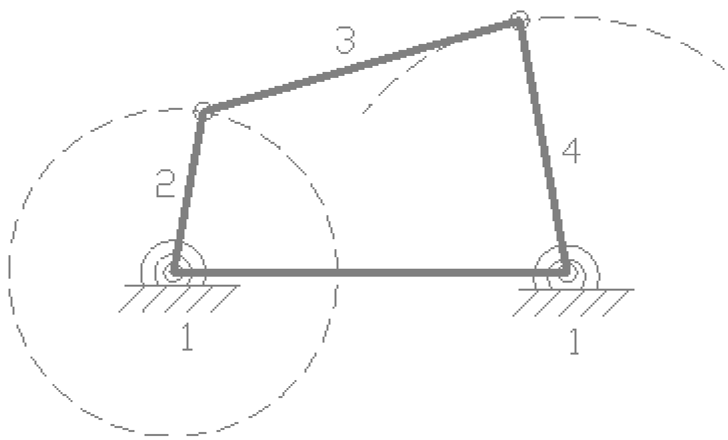


Fig.2.13 four bar mechanism

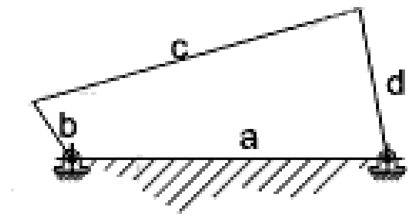
Crank (2) **-** a ground pivoted link which is continuously rotatable.

Rocker (4) **-** a ground pivoted link that is only capable of oscillating between two limit positions and cannot rotate continuously.

Coupler (3) - a link opposite to the fixed link.

1. If the length of any link is greater than the sum of lengths of other three links then it cannot act as four bar linkage.

2. If the sum of the lengths of the largest and the shortest links is less than the sum of the lengths of the other two links, then the linkage is known as a class-1 four bar linkage

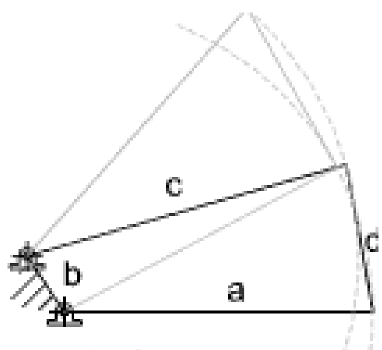


a = frame: b=crank :
c = coupler:d = lever:

Fig.2.14 crank rocker

In fig 2.14 the links adjacent to the shortest link b is fixed. The mechanism such obtained is known as crank-lever or crank rocker mechanism.

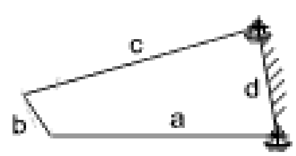
If the shortest link b is fixed, the mechanism obtained is crank-crank or double crank mechanism.



b = frame: c=crank :
d = coupler:a = lever:

Fig.2.15 double crank

If the link opposite to the shortest link is fixed then the mechanism is know as double-rocker or double lever mechanism.



d = frame: a=crank :
b = coupler:c = lever:

Fig. 2.16 double rocker

INVERSIONS OF SLIDER CRANK MECHANISM

Different mechanisms are obtained when we fixed different links of a Kinematic chain and the phenomenon is known as inversion of mechanism. A slider crank mechanism has the following inversions.

First Inversion

This inversion is obtained when link 1 is fixed (as shown in fig 2.17) and links 2 and 4 are made the crank and the slider respectively.

Application: This mechanism is commonly used in I.C. engines, steam engines and reciprocating compressor mechanism.

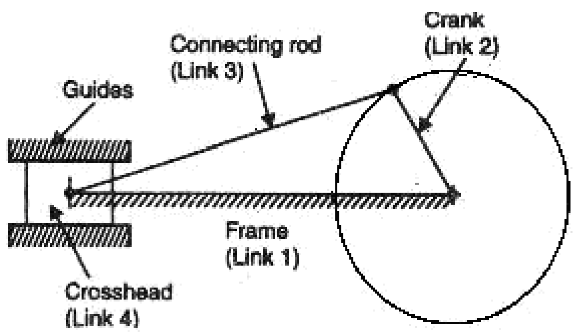


Fig.2.17 reciprocating engine

Second Inversion

By fixing link 2 of a slider mechanism gives second inversion. Rotary engine mechanism or gnome engine is the application of second inversion. It is a rotary cylinder V – type internal combustion engine used as an aero engine. The rotary engine has generally seven cylinders in one plane. The crank (link 2) is fixed and all the connecting rods from the pistons are connected to this link. In this mechanism when the pistons reciprocate in the cylinders, the whole assembly of cylinders, pistons and connecting rods rotate about the axis O, where the entire mechanical power developed, is obtained in the form of rotation of the crank shaft.

Application: Rotary engine mechanism or gnome engine

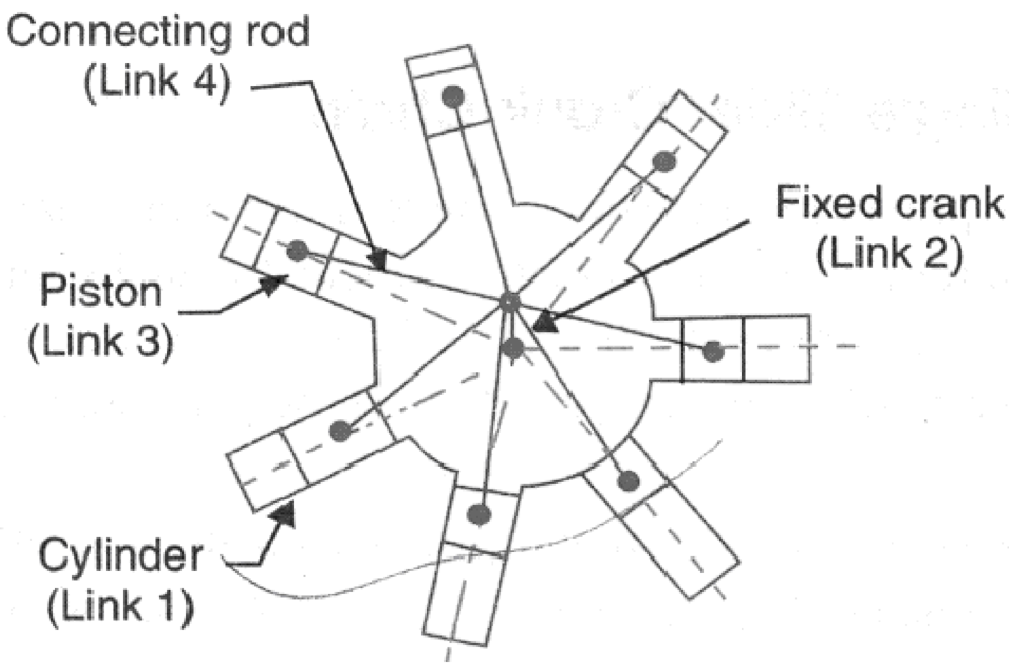


Fig.2.18 rotary engine

Third Inversion

By fixing the link 3(connecting rod) of the slider crank mechanism we can obtain third inversion (as shown in fig.2.19). It is used in hoisting engine mechanism and also in toys. In hoisting purposes, its main advantages lie in its compactness of construction as it allows simple method of supplying steam to the cylinder.

Application: It is used in hoisting engine mechanism and also in toys

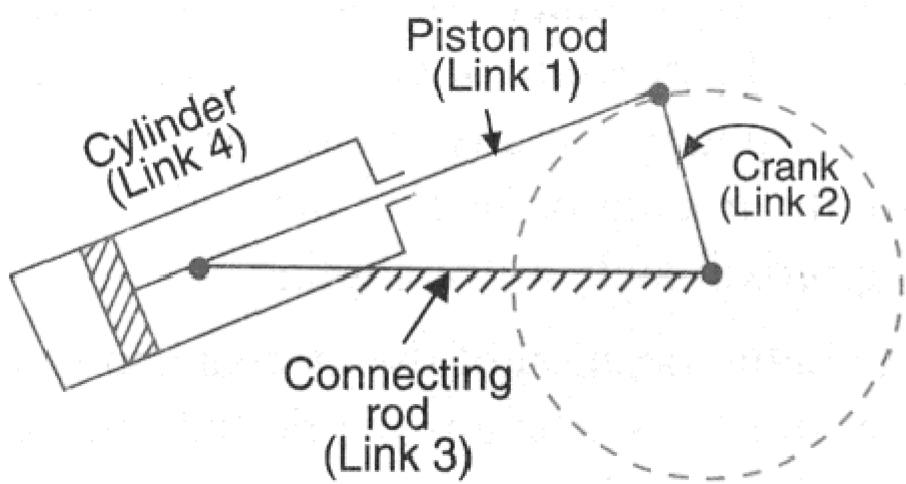


Fig.2.19 oscillating cylinder engine

Fourth Inversion

By fixing the link 4 of the slider crank mechanism we can obtain the fourth inversion of slider crank. Fixing the slider means that the slider should be fixed in position and also should be fixed in respect to rotation. In this case, the cylinder will have to be slotted to give passage to piston pin of connecting rod as the cylinder slides over the piston. Due to this difficulty, the shapes of the cylinder and piston are exchanged as shown in figure below.

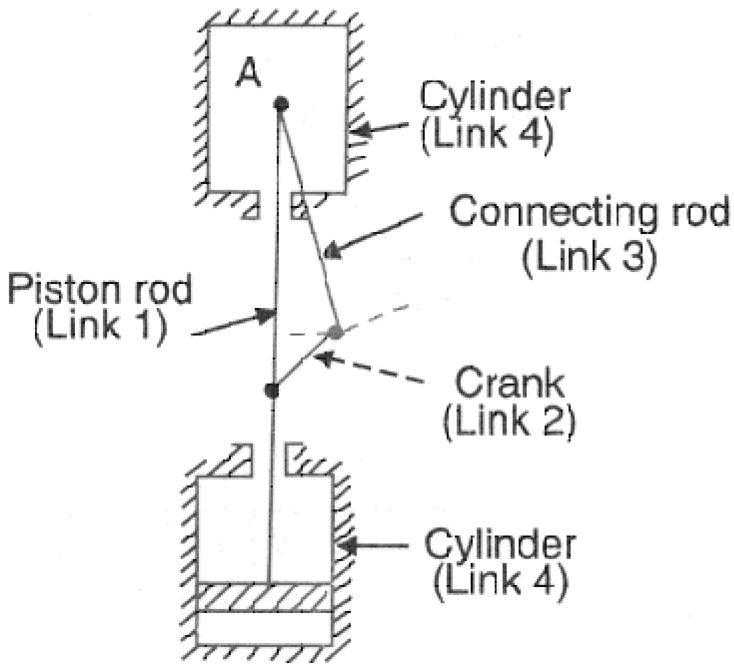


Fig.2.20 pendulum pump

Application: hand pump