

SIMPLE MACHINE

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Abstract

A machine is a device that converts energy from one form to another, to make work easier. This usually involves overcoming a resistance force or load by applying another more convenient force. This chapter discusses the mechanical advantage, velocity ratio, efficiency of a machine, work done against friction, pulley systems, steering mechanism as a machine

Introduction

A machine is a device that receives energy in some available form and converts it to a useable form. For example, a person may wish to lift a weight of 2 tonnes; this is not possible unaided but the use of a jack or a hoist permits the person to achieve their objective. A lever such as a pry bar is an example of a simple machine. A relatively small manual force can be converted into a large force to lift or move an object.

- Mechanical Advantage (MA)

The mechanical advantage of a machine is the ratio of the load to the effort:

$$\text{Mechanical Advantage (MA)} = \frac{\text{Load}}{\text{effort}}$$

Lifting machines such as jacks and cranes have a large mechanical advantage so that relatively small manual forces can be used to raise heavyweights.

Velocity Ratio (VR)

The velocity ratio, VR, of a machine, or movement ratio, MR, is the ratio of the distance moved by the effort to the distance moved by the load:

$$\text{Velocity Ratio (VR)} = \frac{\text{Distance moved by effort}}{\text{Distance moved by load}}$$

The efficiency of a Machine

The efficiency of a machine =

$$\text{Efficiency of a machine} = \frac{\text{Energy output}}{\text{Energy input}}$$

The energy out is the performance of a machine. The energy is what is required for the machine to operate, the part we usually have to pay for, e.g. fuel. The higher the efficiency of a machine, the less energy input is required for the same energy output. The difference between the two represents energy 'losses' such as overcoming friction and other resistance forces and should be kept as low as possible. Internal friction of a machine causes an opposing force and so work is done in overcoming this.

The efficiency then is the energy out of a system measured as a fraction of the energy in. Usually, this is expressed as a percentage:

$$\text{Efficiency} = \frac{\text{Energy out}}{\text{Energy in}} * 100$$

At the same time and this also

$$\text{Efficiency of a machine} = \frac{\text{MA}}{\text{VR}} * 100\%$$

$$\text{Efficiency} = \frac{\text{Useful workdone}}{\text{Work supplied}} * 100\%$$

Usually, though efficiency is calculated in terms of power, i.e.

$$\text{Efficiency} = \frac{\text{Power in}}{\text{Power out}} * 100\%$$

Example: In the trolley jack, an effort of 250 newtons is lifting a load of 2 tonnes. In lifting the load through a distance of 15 cm the operator performs 40 pumping strokes of the handle each of which is 50 cm long. Calculate the mechanical advantage, velocity ratio and efficiency of the jack.

Solution

Effort= 250N

MA= ?

Load= 2 tonnes

Distance moved by the load= 15cm

Distance moved by the effort= 40 * 50= 200cm

$$MA = \frac{\text{Load}}{\text{Effort}}$$

$$MA = \frac{2 * 1000 * 9.81}{250} = 78.5$$

$$VR = \frac{\text{Distance moved by the effort}}{\text{Distance moved by the load}}$$

$$VR = \frac{40 * 50}{15} = 133.3$$

$$\text{Efficiency} = \frac{\text{Energy output}}{\text{Energy input}}$$

$$\text{Efficiency of a machine} = \frac{MA}{VR} * 100\%$$

$$\text{Efficiency} = \frac{78.5}{133.3} * 100 = 59\%$$

Work done against friction

In the previous example above,

the energy input = effort x distance moved = 250 x 40 x 0.5 = 5000 J.

In the same time, the energy output = load x distance raised = 2000 x 9.81 x 0.1
= 2943 J.

The difference between the input energy of 5000 J and the output energy of 2943 J is a loss of 2057 J. This loss of energy is accounted for by work done against friction in the machine.

Example: When using a simple floor crane, the operator inputs 25 000 joules to lift a load of 1 tonne through a height of 1.2 metres. Taking $g = 9.81 \text{ m/s}^2$ calculate the efficiency of the crane and determine the energy loss due to friction.

Solution

$$\text{Efficiency} = \frac{\text{Energy output}}{\text{Energy input}}$$

Energy output = work done in lifting the load

$$= 1000 * 9.81 * 1.2 = 11772 \text{ J}$$

Therefore,

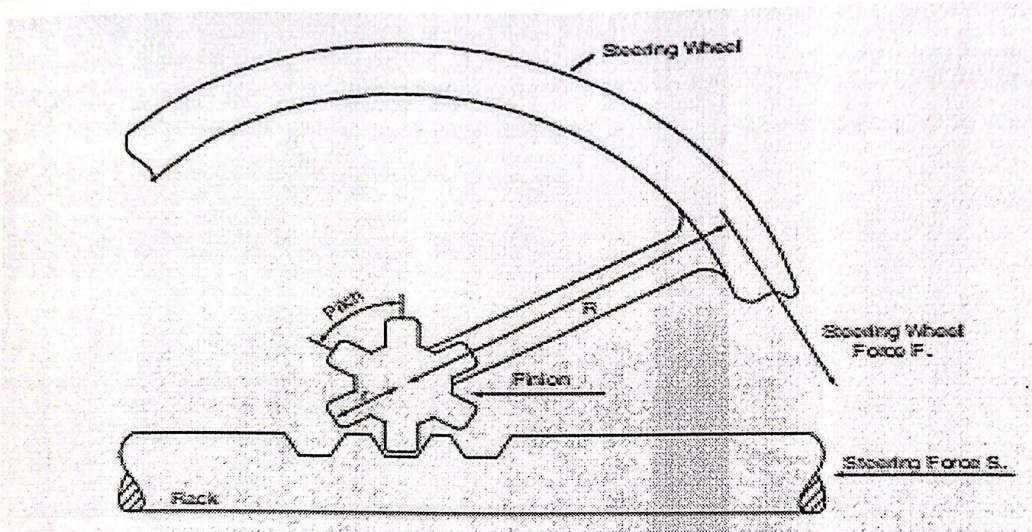
$$\text{Efficiency} = \frac{\text{Energy output}}{\text{Energy input}}$$

$$\text{Efficiency} = \frac{11,772}{25,000} * 100 = 0.471 * 100 = 47.1\%$$

Therefore, energy loss due to friction = 25,000 - 11,772 = 13,228J

A steering mechanism as a machine

The force required to steer a vehicle is often considerably larger than a driver can comfortably exert. A steering mechanism is a machine that allows the driver of a vehicle to operate the steering without having to exert a large force at the steering wheel. The rack and pinion steering.



The steering wheel radius = R

The tangential force at the rim of the steering wheel = F (this is the effort)

The number of teeth on the pinion = Nt

The circular pitch of the pinion gear = p

The force produced at the rack = S (this is the load)

$$\text{Mechanical advantage (MA)} = \frac{\text{load}}{\text{Effort}} = \frac{S}{F}$$

Consider one revolution of the steering wheel

The circular pitch of the gear is the distance between the teeth as measured on the circumference of the pitch circle one revolution of the pinion is a circular distance of $Nt \times p$

Where Nt = number of teeth on the pinion. This is the distance that the rack moves when the steering wheel makes one revolution

$$\text{Movement Ratio (MR)} = \frac{\text{distance moved by effort}}{\text{distance moved by load}} = \frac{2\pi R}{Nt \cdot p}$$

Example: A rack and pinion steering system have 5 teeth of 10 mm pitch and a steering wheel of 320 mm diameter. Calculate:

(a) the movement ratio

(b) the mechanical efficiency of the steering gear if a tangential force of 30 N at the rim of the steering wheel produces a force of 560 N on the rack.

Solution

(a).

$$\text{Movement Ratio (MR)} = \frac{\text{distance moved by effort}}{\text{distance moved by load}} = \frac{2\pi R}{Nt \cdot p}$$

$$= \frac{2 \cdot \pi \cdot 160}{5 \cdot 10} = 20.1$$

(b)

$$\text{Mechanical efficiency} = \frac{MA}{MR}$$

$$\text{Mechanical advantage (MA)} = \frac{\text{load}}{\text{Effort}}$$

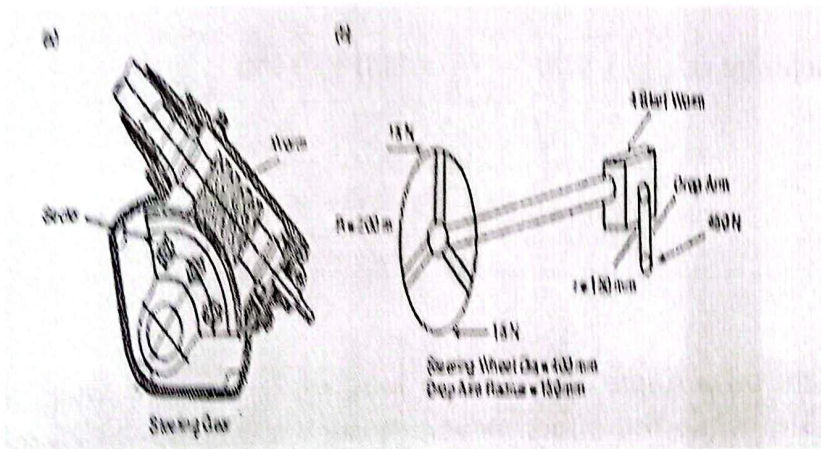
$$= \frac{450}{40} = 11.25$$

Therefore,

$$\text{Mechanical efficiency} = \frac{MA}{MR} = \frac{11.25}{12.1} = 0.93 + 100 = 93\%$$

Example: A worm and sector steering gear of the type shown in Figure below has a 4-start worm and a sector that is a sector of a 48-tooth worm wheel. The steering wheel has a diameter of 400 mm and the drop arm has a length of 150 mm. Two tangential forces each of 15 N applied at the rim of the steering wheel produce a force in the drag link of 450 N, which acts at right angles to the drop arm. Calculate:

- (a) the movement ratio, MR, of the steering system;
- (b) the mechanical advantage, MA, of the system;
- (c) the mechanical efficiency of the system.



Solution

(a)

$$\text{Movement Ratio (MR)} = \frac{\text{distance moved by effort}}{\text{distance moved by load}}$$

The worm is 4-start so the worm wheel (sector) rotates by four teeth when the steering wheel makes one revolution.

The distance moved by an effort at the steering wheel during one revolution
 $= 2\pi * 200 = 400\pi$

The distance moved by the load $= \frac{4}{48} * 2\pi * 150 = 25\pi$

$$\text{MR} = \frac{400\pi}{25\pi} = 16$$

(b)

$$\text{Mechanical advantage (MA)} = \frac{\text{load}}{\text{Effort}} = \frac{\text{drag link force}}{\text{Steering wheel force}} = \frac{450}{30} = 15$$

(c)

$$\text{efficiency} = \frac{\text{MA}}{\text{MR}} * 100 = \frac{15}{16} * 100 = 94\%$$

Exercise

1. A hydraulic system on a tipper truck lifts a load of 2 tonnes through a distance of 0.125 m while the effort moves through a distance of 20 m. Calculate:

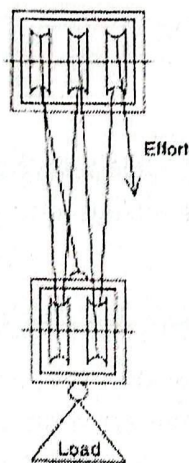
(a) the movement ratio;

(b) the actual effort required if the efficiency of the lifting system is 75%. Take $g = 10 \text{ m/s}^2$

2. An effort of 180 N will lift a load of 3860 N in a certain lifting machine. If the efficiency of the machine is 80% what is its movement ratio?
3. A trolley jack requires an effort of 200 newtons to lift a load of 2 tonnes. In lifting the load through a distance of 15 cm the operator performs 40 pumping strokes of the handle each of which is 50 cm long. Calculate the mechanical advantage, movement ratio and efficiency of the jack. Take $g = 10 \text{ m/s}^2$

Pulley Systems

A pulley is a simple machine. A rope pulley consists of two pulley blocks, one at the top and one at the bottom." Each pulley block has several pulley wheels that can turn freely. There will be either the same number of pulley wheels in each block or there will be one more in one than the other. A rope is threaded over each pulley in turn. One end of the rope is fastened to the block opposite the last pulley. The other end is used to apply the effort. The effort is directed downwards and the load moves up see Figure below:



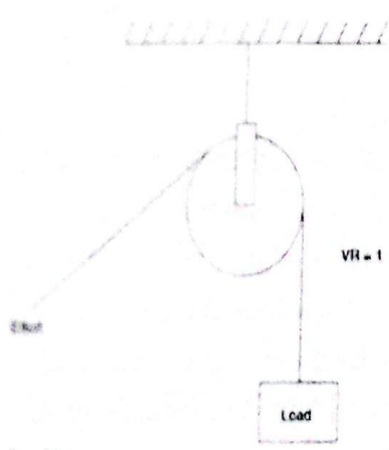
When a pulley system is connected like this there are five ropes between the load block. If we want to lift the load by saying one metre, then all of the five

lengths of the rope must be shortened by one metre. To do this, then the effort must pull down by five metres.

$$\text{Velocity Ratio (VR)} = \frac{\text{distance moved by effort}}{\text{distance moved by load}} = \frac{5}{1} = 5$$

The same calculation can be applied to any number of pulley wheels:

i.e. VR of rope pulley blocks = number of ropes lifting the load block



Also, the number of ropes supporting the load is equal to the number of pulley in the system. Hence, the number of pulleys is equal to the VR.

For example, a system with two pulleys at the top and one at the bottom has a VR of three; a system with three pulleys at the top end and three at the bottom has a VR of six.

This is only true when the direction of the effort opposes the direction of the movement of the load, which is the usual case. If the rope is wound in some way so that the direction of the effort is the same as that of the load then the velocity ratio equals the total number of pulleys plus one.

This can also be calculated from the work done by a machine and the work supplied to the machine.

Example: A rope pulley system has two pulleys in each block. An effort of 116 N is required to lift a load of 390 N. Calculate the efficiency of the machine.

Solution

There are four pulleys in total and therefore the VR = 4.

$$\text{Mechanical advantage (MA)} = \frac{\text{Load}}{\text{effort}} = \frac{390}{116} \\ = 3.362$$

$$\text{efficiency} = \frac{\text{MA}}{\text{VR}} * 100 = \frac{3,362}{4} * 100 = 84.05\%$$

Exercise

1. A set of rope pulley blocks has three pulleys at the top and two at the bottom. An effort of 300 N is required to lift a load of 1.341 kN. Calculate the VR, the MA and the efficiency.

References no

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