EDEXCEL NATIONAL CERTIFICATE/DIPLOMA

FURTHER MECHANICAL PRINCIPLES AND APPLICATIONS
UNIT 11 - NQF LEVEL 3

OUTCOME 4 - LIFTING MACHINES

CONTENT
Be able to determine the operating characteristics of lifting machines

Parameters of lifting machines: kinetic parameters e.g. input motion, output motion, velocity or movement ratio, overhauling; dynamic parameters e.g. input effort, load raised, mechanical advantage or force ratio, law of a machine, efficiency, limiting efficiency

Lifting machines**:** lifting machines e.g. simple (such as inclined plane, screw jack, pulley blocks, wheel and axle, simple gear train winch), differential (such as differential wheel and axle, Weston differential pulley block, compound gear train winch)

It is assumed that the student has studied Mechanical Principles and Applications Unit 6.

1. **GENERAL INFORMATION FOR LIFTING MACHINES**

A lifting machine is any machine designed to enable a load (F_L) to be raised by a much smaller effort (F_E). The ratio is called the:

MECHANICAL ADVANTAGE OR FORCE RATIO. **M.A. = F_L/F_E**

The distance moved by the load is X_L and the distance moved by the effort is X_E. The ratio of the two is called the:

VELOCITY RATIO OR MOVEMENT RATIO. **V.R. = X_E / X_L**

If we plot a graph of Effort against Load for an ideal frictionless machine we get a straight line through the origin as shown. The gradient of the straight line is F_E/F_L = 1/M.A.

The law of energy conservation tells us that if there is no energy lost, the work done by the effort must equal the work done by the load so it follows that : $F_E X_E = F_L X_L$

In a real machine, there is friction and energy is lost. The effort has to overcome the dead load of the lifting machine so some effort F_S is required before any external load is applied. If F_L is the external load and this is plotted against effort, we get a graph as shown labelled actual.

EFFICIENCY Symbol η (eta)

η = Work done by the load/Work done by the Effort
$\eta = F_L X_L/F_E X_E$
η = M.A./V.R

This is the same formula for ideal and actual machines so long as we use the actual load and effort.

When the external load is zero the Effort is F_s and the Mechanical Advantage is zero so it follows that the efficiency is zero.

At large loads the Mechanical Advantage tends to become constant and the efficiency reaches a limiting value. In between these extremes the efficiency varies and the plot is a curve as shown.

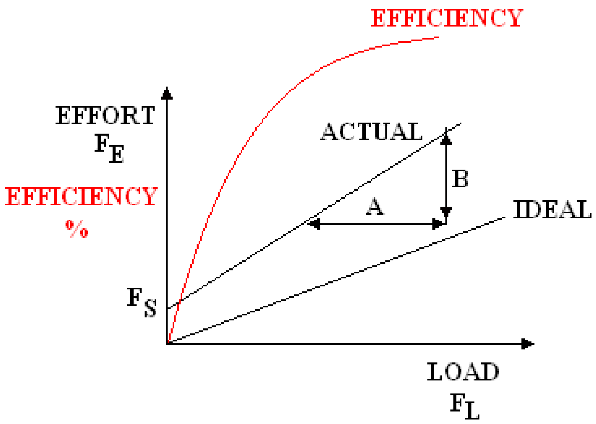

Figure 1

The law of the straight line is $F_E = F_S + F_L$ x gradient
$F_E = F_S + F_L \times B/A$
$F_E = F_S + (F_L/M.A.)$

$$F_E = F_S + \frac{F_L}{\eta(V.R.)}$$

WORKED EXAMPLE No.1

The table shows the values of load and corresponding effort for a lifting machine with a velocity ratio of 140. Plot the graph and also plot the efficiency.

Load F_L(N)	0	100	200	300	400	500	600	700	800	900	1000
Effort F_E(N)	5	8	11	14	17	20	23	25.5	28.5	31.5	34

SOLUTION

Calculate the efficiency at each point using η % = (M.A./V.R) x 100% = (M.A./40) x 100%

For example when F_L = 400 N   M.A. = 400/17 = 23.53   η % = (23.54/40) x 100 = 59%

Load F_L(N)	0	100	200	300	400	500	600	700	800	900	1000
Effort F_E(N)	5	8	11	14	17	20	23	25.5	28.5	31.5	34
η %	0	31.3	45.5	53.6	59	62.5	65.2	68.6	70.2	71.4	73.5

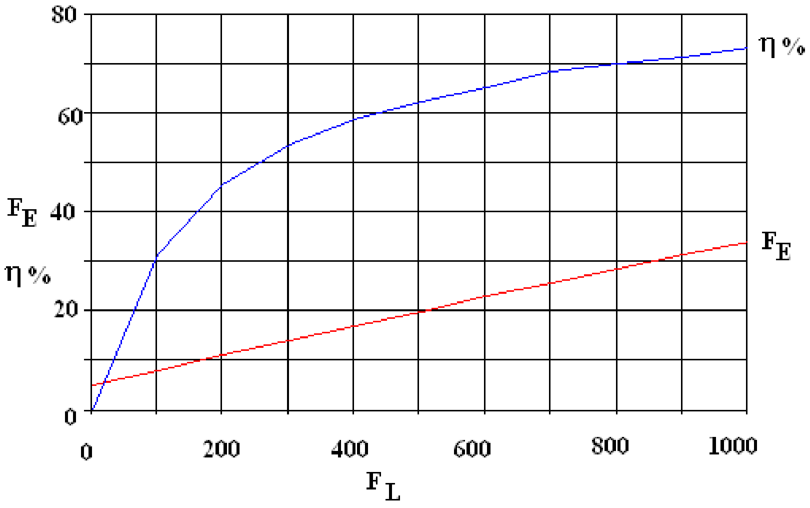

Figure 2

SELF ASSESSMENT EXERCISE No.1

1. A lifting machine has a velocity ratio of 5. The Effort required to raise a load of 5 KN is 2 kN. Calculate the mechanical advantage and the efficiency. (Answer 2.5 and 50%)

2. A Lifting machine has a velocity ratio of 8. Given the efficiency is 30% when the load is 580 N, calculate the effort required. (Answer 242 N)

Next we will look at particular lifting devices.

2. LEVERS

A lever is one of the simplest lifting devices but it is limited to small movements. It is very efficient however and it is found in many mechanisms. A crow bar is an example of a lever used to lift heavy objects a small distance. The lever principle is used in cutting tools such as pliers, wire cutters, bolt cutters and branch loppers.

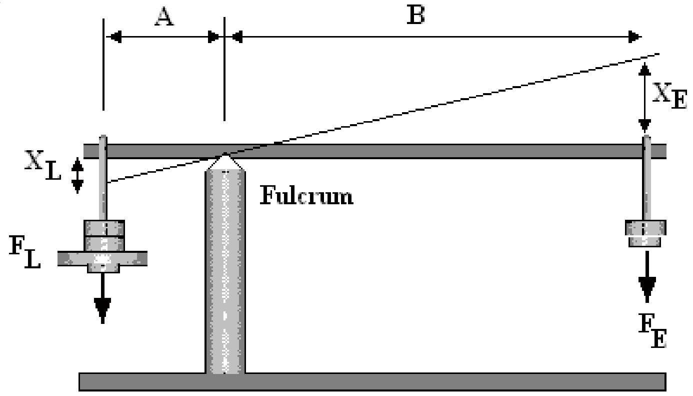

Figure 3

The ratio of the movements is strictly related to the lengths A and B so the velocity ratio is

$$\mathbf{V.R. = X_E / X_L = A/B}$$

WORKED EXAMPLE No.2

The load on a lever is 2 kN and acts 20 mm from the fulcrum. The effort is 200 mm from the fulcrum. Assuming 100% efficiency, calculate the effort.

SOLUTION

η = M.A./V.R = 1.0 (100%) hence M.A. = V.R

V.R = A/B = 200/20 = 10

M.A. = 10 = F_L/F_E = 2000/ F_E

F_E = 2000/10 = 200 N

SELF ASSESSMENT EXERCISE No. 2

1. A lever has a total length of 1.2 m with the pivot 0.2 m from one end. Assuming 100% efficiency, calculate:

(i) The velocity Ratio. (6)
(ii) The Mechanical Advantage. (6)
(iii) The effort required to move a load of 2000 N. (333.3 N)

3. **SCREW JACKS**

Screw jacks work on the principle that the nut forms the lifting platform or point and the screw is rotated with a lever. Every complete revolution of the screw raises the load by the pitch of the thread.

The Effort is applied at radius R to produce a torque F_E R. They are commonly used as car jacks in various forms such as the scissors screw jack. There is a lot of friction in screw threads so they are not very efficient. In order to understand this you need to study friction on inclined planes.

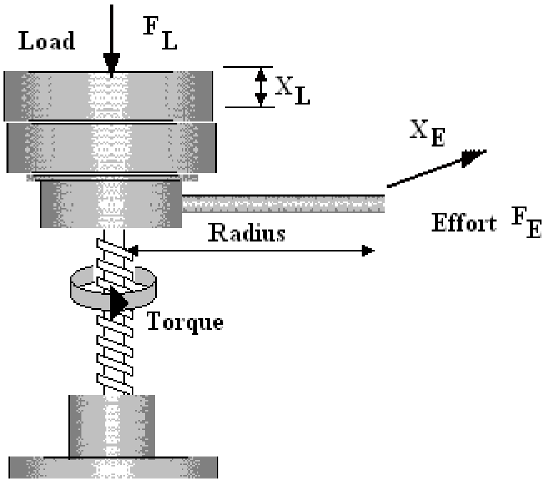

Figure 4

The distance moved by the effort when the screw is turned once = $2\pi R$
The distance moved by the load = pitch = p The velocity ratio = $2\pi R / p$

WORKED EXAMPLE No. 3

A screw jack has a thread with a pitch of 5 mm. It must raise a load of 6000 N by turning the thread with a handle 500 mm long. The efficiency is 20% and the effort required to overcome the dead weight and friction with no external load is 20 N. Calculate the effort required.

SOLUTION

The velocity ratio $= 2\pi R / p = 2\pi \times 500/5 = 628.3$
We need to use the law of the machine in this case.

$$F_E = F_S + F_L \div (\text{V.R. } \eta)$$

$$F_E = 20 + 6000 \div (628.3 \times 0.2) = 67.7 \text{ N}$$

SELF ASSESSMENT EXERCISE No. 3

1. A screw jack has a thread with a pitch of 6 mm. It must raise a load of 2 kN by turning the thread with a handle 250 mm long. The effort is 25 N Calculate the efficiency. (30.6 %)

4. **PULLEYS**

A pulley is two sets of wheels as shown. The rope starts from the axle of one set and goes around the pulleys wheels before coming off to the point where the effort is applied.

Each rope between the two sets of wheels gets shorter by the same amount so if there are N ropes, the distance moved by the effort is N times more than the distance moved by the load so the velocity ratio is N.

V.R. = Number of ropes connecting the blocks.

If the end of the rope is attached as shown the V.R. will always be an even number. The number of pulley wheels in each block will be half this. For example two wheels in each block will give 4 ropes. If the rope is attached to the bottom block instead, the V.R. will always be on odd number with one extra wheel in the top block.

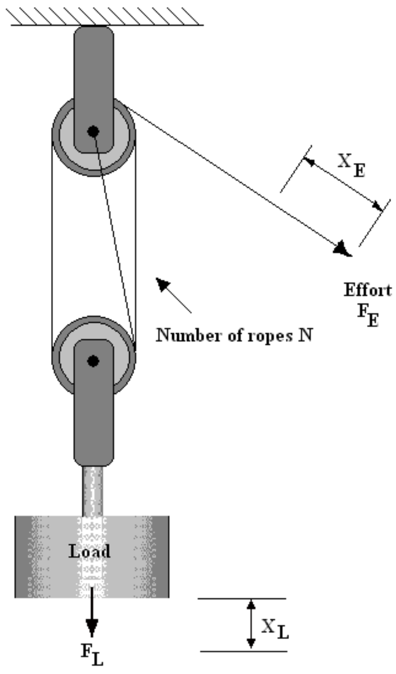

Figure 5

WORKED EXAMPLE No. 4

A pulley as shown is 50% efficient. Calculate the effort required to lift 12 KN if there are 6 lengths of rope between the blocks. If the dead weight of the pulleys and hook is 500 N what would the effort be then?

SOLUTION

V.R. = 6
M.A. = η x V.R. = 50% x 6 = 3
Effort = 12/3 = 4 kN

With the dead weight taken into consideration the total load is 12.5 kN
Effort = 12.5/3 = 4.18 kN

SELF ASSESSMENT EXERCISE No. 4

1. A pulley system similar to that shown above has 5 ropes. The load is 850 N and the effort is 300 N.

Calculate
(i) The velocity Ratio. (5)
(ii) The Mechanical Advantage. (2.83)
(iii) The efficiency. (57%)

5. DIFFERENTIAL AXLE

The diagram shows a typical arrangement of the differential axle. The load is suspended on a rope and one end if the rope unwinds from the small diameter D_3 and the other end winds in about the larger diameter D_2. The effort is applied by another rope wrapped around a wheel diameter D_1 on the same axle.

When the effort is pulled so that the axle turns one revolution the effort moves one circumference πD_1

$X_E = \pi D_1$

The rope on the differential gets shorter by πD_2 on the one side and longer by πD_3 on the other. The change in length is the difference and the load is raised by half this amount.

$$X_L = \frac{\pi D_2 - \pi D_3}{2}$$

The velocity ratio is V.R. $= \frac{X_E}{X_L} = \frac{2\pi D_1}{\pi D_2 - \pi D_3} = \frac{2D_1}{D_2 - D_3}$

The efficiency of this system is normally high.

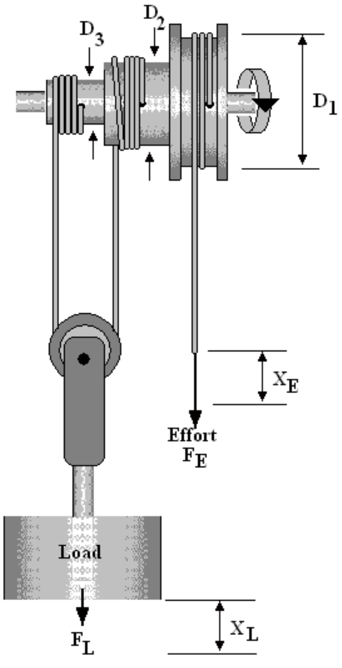

Figure 6

WORKED EXAMPLE No. 5

A differential axle as shown above has two diameters 100 mm and 150 mm. The wheel is 200 mm diameter. The load is 80 N and the effort is 13 N.

Calculate

(i) The velocity ratio

(ii) The Mechanical Advantage.

(ii) The efficiency.

SOLUTION

$$\text{V.R.} = \frac{X_E}{X_L} = \frac{2D_1}{D_2 - D_3} = \frac{2 \text{ x } 200}{150 - 100} = 8$$

$$\text{M.A.} = \frac{F_L}{F_E} = \frac{80}{13} = 6.15$$

$$\eta = \frac{\text{M.A.}}{\text{V.R.}} = \frac{6.15}{8} \text{ x } 100 = 77\%$$

SELF ASSESSMENT EXERCISE No. 5

1. A differential axle as shown above has two diameters 75 mm and 100 mm. It is expected that the efficiency will be 80% when raising a load of 500 N and the effort must be 25 N.

Calculate

(i) The Mechanical Advantage (20)

(ii) The Velocity Ratio (25)

(iii) The diameter of the wheel. (312.5 mm)

6. WESTON DIFFERENTIAL PULLEY

This is the basis of modern chain hoists and uses the same principle as the differential axle. When the effort is pulled so that the wheel rotates one revolution, the distance moved is one circumference πD_1 $X_E = \pi D_1$

The rope on the differential gets shorter by πD_2 on the one side and longer by πD_1 on the other. The change in length is the difference and the load is raised by half this amount.

$X_L = \frac{\pi D_1 - \pi D_2}{2}$ The velocity ratio is

$$V.R. = \frac{X_E}{X_L} = \frac{2\pi D_1}{\pi D_1 - \pi D_2} = \frac{2D_1}{D_1 - D2}$$

Although the diagram shows a rope, in reality a chain is used and the wheel and axle has flats that interlock with the links so that the chain does not slip. The two free ends shown are in fact joined so that a continuous loop is formed. It is not practical to diameters and a better measure is the number of flats on each (similar to using the number of gear teeth instead of diameter).

$$V.R. = = \frac{\text{2 x Flats on (1)}}{\text{Flats on (1) - Flats on (2)}}$$

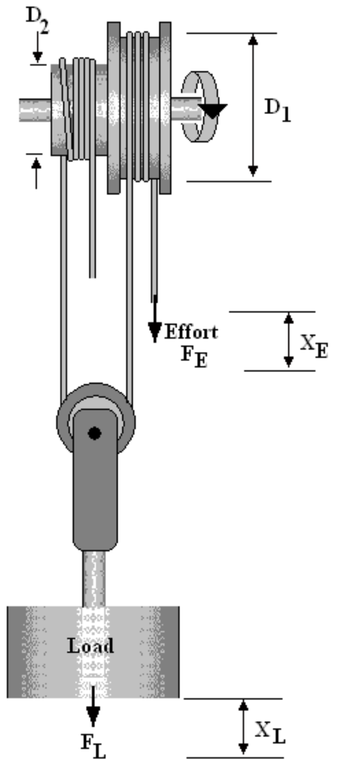

Figure 7

WORKED EXAMPLE No. 6

A Weston differential pulley has a wheel with 12 Flats on it and an axle with 10 Flats. The load is 1200 N and the effort is 150 N.

Calculate (i) The velocity ratio
(ii) The Mechanical Advantage.
(ii) The efficiency.

SOLUTION

$V.R. = \frac{2 \times 12}{10 - 8} = 12$ M.A. $= \frac{F_L}{F_E} = \frac{1200}{150} = 8$

$\eta = \frac{M.A.}{V.R.} = \frac{8}{12} \times 100 = 66.7\%$

SELF ASSESSMENT EXERCISE No. 6

1. A Weston differential pulley as shown above has a wheel with 15 flats. It is expected that the efficiency will be 53.33 % when raising a load of 1000 N and the effort must be 125 N.
Calculate
(i) The Mechanical Advantage (8)
(ii) The Velocity Ratio (15)
(iii) The flats on the axle. (13)

7. GEARS

The simplest gear is the simple gear train shown. The speed ratio of the wheels is exactly the same as the ratio as the diameters and also the ratio of the number of teeth in each. The small wheel always goes around faster than the large wheel.

In order to get larger ratios compound gears are used which are really two or more sets of wheels each driving the next.

Figure 8

There are many other types of gears such as the worm gear and bevel gear which allows the axis of the wheels to be changed. To use a gear box in a lifting machine requires that a pulley be placed on the shaft that will raise the load. A good example is that of winch in which a motor with a high speed and low torque is geared down to turn the drum at a low speed with a large torque. The diagram shows a typical winch that has a reduction gear box built inside the drum.

Figure 9

WORKED EXAMPLE No.7

A simple winch is shown in the diagram.
The small gear is turned by a handle 300 mm long.
This rotates the larger gear.
A drum on the same shaft as the large gear rotates and winds in a rope and raises the load.
The gears have 50 teeth and 300 teeth respectively.
The drum is 100 mm diameter. The efficiency is 30%

Calculate the
(i) Velocity Ratio
(ii) Mechanical Advantage
(iii) Effort required to raise 800 kg

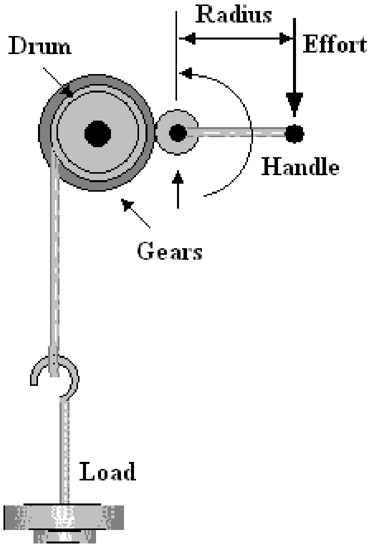

Figure 10

SOLUTION

Let the handle rotate one revolution. The distance moved by the effort is the circumference of a circle 300 mm radius.

$X_E = 2\pi \times 300 = 600\pi$ mm

The gear ratio is the ratio of the teeth so the gear ratio is 300/50 = 6. This means that the large wheel and drum rotates 1/6 of a revolution. The distance moved by the load is hence 1/6 of the circumference of the drum.

$X_L = 2\pi \times 50/6 = 16.67\pi$ mm
The velocity ratio is hence $X_E/X_L = 600\pi / 16.67\pi = 36$

The Mechanical Advantage is M.A. = η x V.R. = 0.3 x 36 = 10.8

Load = 800 x 9.81 = 7848 N
Effort = 7848/10.8 = 726.7 N

SELF ASSESSMENT EXERCISE No. 7

1. A simple winch as shown previously has a drum 100 mm diameter and a gear ring with 125 teeth is attached to it. The gear meshes with a small gear with 25 teeth. This gear is attached to a handle 300 mm long. The efficiency is expected to be 30% when a load of 1200 N is raised.
Calculate
(i) The Velocity Ratio (30)
(ii) The Mechanical Advantage (9)
(iii) The Effort. (133.3 N)
(iv) The torque produced by the effort. (40 Nm)

8. TORQUE and POWER TRANSMISSION

When a force moves work is done and the rate of doing work is the mechanical power. This power is transmitted through the machine from the effort to the load with some being lost on the way through friction.

Mechanical power is defined as work done per second. Work done is defined as force times distance moved. Hence

$$\text{Power} = P = Fx/t$$

F is the force
x is distance moved.
t is the time taken.

Since distance moved/time taken is the velocity of the force ($x/t = v$) we may write

$$\mathbf{P = F\,v} \qquad \text{where } v \text{ is the velocity.}$$

When a force rotates at radius R it travels one circumference in the time of one revolution. Hence the distance moved in one revolution is $x = 2\pi R$

If the speed is N rev/second then the time of one revolution is 1/N seconds. The mechanical power is hence

$$P = F\,2\pi R/(1/N) = 2\pi NFR$$

Since FR is the torque produced by the force this reduces to $\mathbf{P = 2\pi NT}$

In the context of handles, gears and winches we may define Torque = Force x Radius

If the speed is in rev/min then $\mathbf{S.P. = 2\pi NT/60}$

WORKED EXAMPLE No. 8

The drive shaft which connects a motor to the drum of a winch transmits 45 kW of power at 2000 rev/min. This is geared down to the winch drum 100 mm diameter and the drum revolves at 120 rev/min. The system is 30% efficient.
Calculate the:
(i) Torque in the motor shaft.
(ii) Torque on the drum.
(iii) The speed at which the load is moving.
(iv) The load

SOLUTION

$T = 60P/2\pi N = 60 \times 45000/(2\pi \times 2000) = 215$ Nm on the motor shaft.
The power available at the drum is 30% x 45 kW = 13.5 kW
$T = 60P/2\pi N = 60 \times 13500/(2\pi \times 120) = 1074$ Nm on the drum.
Mechanical Power = Force x velocity
Velocity = $\pi ND/60 = \pi \times 120 \times 0.1/60 = 0.628$ m/s
Power = load x velocity Load = 13500/0.628 = 21486 N
Check T = Load x Radius = 21486 x 0.05 = 1074 Nm

SELF ASSESSMENT EXERCISE No.8

The diagram shows a simple winch. The motor drives the small gear and the large gear rotates the drum and raises the load.

The load is 3 kN and it is raised at 0.5 m/s. The system is 25% efficient.
Calculate the following.

(i) The torque acting on the drum. (120 Nm)
(ii) The power produced by the load. (1500 W)
(iii) The speed of the drum. (119.4 rev/min)
(iv) The power produced by the motor. (6000 W)
(v) The speed of the motor. (596.8 rev/min)

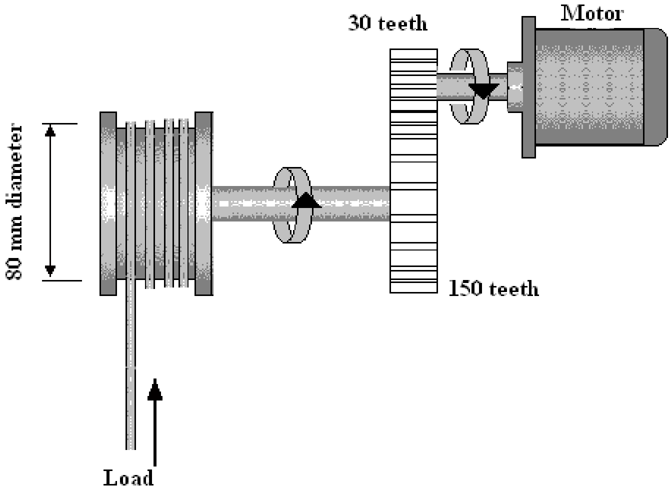

Figure 11