Unit 57: Mechatronic System

Unit code: F/601/1416 QCF level: 4 Credit value: 15

OUTCOME 2

TUTORIAL 3 - ACTUATOR TECHNOLOGIES

2 **Understand electro-mechanical models and components in mechatronic systems and products**

Simple mathematical models: mechanical system building blocks; electrical system building blocks; electrical-mechanical analogies; fluid and thermal systems

Sensor technologies: sensor and actuator technologies for mechatronic system e.g. resistive, inductive, capacitive, optical/fibre-optic, wireless, ultrasonic, piezoelectric

Actuator technologies: electric motors; stepper motors; motor control; fluid power; integrated actuators and sensors; embedded systems

CONTENTS

1. INTRODUCTION

- ***Electronic control*** is at the heart of mechatronic systems but most systems must produce some kind of mechanical motion to produce the required result.

- ***Actuators*** are devices for creating mechanical movement of one form or another. They are used in many applications with a wide range of sizes and accuracy. They might be large and powerful e.g. for use in a robot or manufacturing system or small e.g. for zooming in and out with a camera.

- ***The size of the actuator*** may be small or large. Small ones might be suitable to be integrated into an electronic circuit and driven directly by micro chips. Large ones may require so much energy and force that they must be operated through a relay system of some sort to enable the electronics to control them.

- ***There are two main categories***. One uses electric power and the other fluid power.

- ***Electric actuators*** have sub categories such as alternating current (A.C.), direct current (D.C.) and stepper motors.

- ***Fluid power*** has two sub categories, hydraulic and pneumatic.

2. ELECTRIC ACTUATORS

Electrically actuated systems are very widely used in control systems because they are easy to interface with the control systems which are also electric and because electricity is easily available unlike fluid power which requires pumps and compressors.

The advantages of electric systems are

- Electricity is easily routed to the actuators; cables are simpler than pipe work.
- Electricity is easily controlled by electronic units
- Electricity is clean.
- Electrical faults are often easier to diagnose.

The disadvantages of electric actuators are

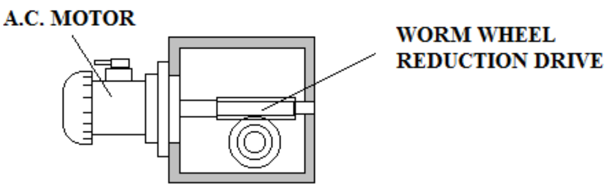
- Electrical equipment is more of a fire hazard than other systems unless made intrinsically safe, in which case it becomes expensive.
- Electric actuators have a poor torque - speed characteristic at low speed.
- Electric actuators are all basically rotary motion and mechanisms are needed to convert rotation into other forms of motion.
- The power to weight ratio is inferior to hydraulic motors a significant factor for powerful applications.

There are three types of motors used in control applications.

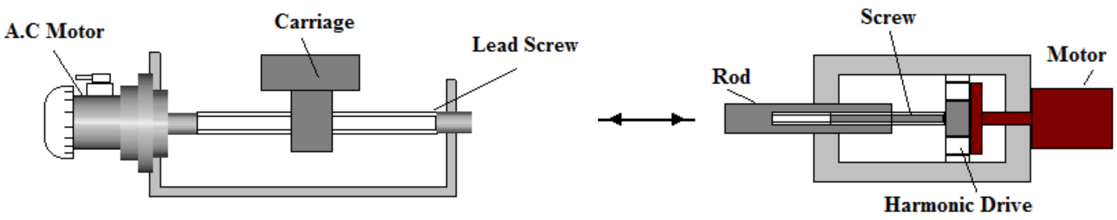
- A.C. motors.
- D.C. motors.
- Stepper motors.

2.1 A.C. MOTORS

A.C. motors are mainly used for producing large power outputs at a fixed speed. Typically these are 1420 or 2900 rev/min. Such motors are controlled by switching them on and off. They are widely used to drive powerful machines such as drills, lathes, fans, pumps and so on. These applications usually involve simply switching them on or off. Mechanical systems are needed to change the speed or change the form of motion. The worm and wheel gear box shown is used for large speed reduction.



The lead screw system shown below (left) produces linear motion of the carriage. A range of linear electric actuators have been developed to perform functions similar to hydraulic and pneumatic cylinders. These are based on a motor driven lead screw. The motors may be AC or DC. The speed of the motor is reduced with a compact gear box before driving the lead screw. Actuators have been developed with thrusts up to 15 kN and strokes up to 3 metres.

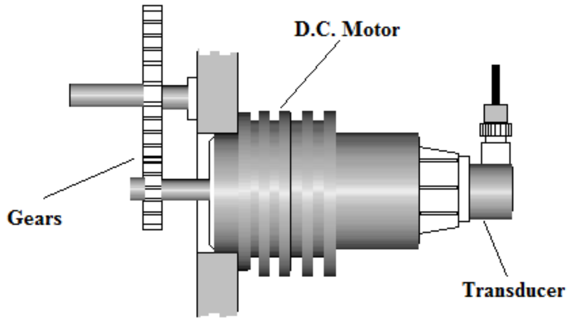


Small A.C. motors have many applications in mechatronic systems. The picture shows three.

A.C. motors may be used in applications where the speed must be varied. This is achieved electronically by varying the frequency or by chopping the power supply. The pictures show one for controlling a powerful motor and the other small electronic controller that could be integrated into a circuit.

2.2. D.C. MOTORS

Direct current motors are more widely used in control applications and they are usually referred to as ***Servo Motors***. The development of more powerful magnets is improving the power to weight ratio. Servo motors usually have a transducer connected to them in order to measure the speed or angle of rotation. The diagram shows a typical arrangement.

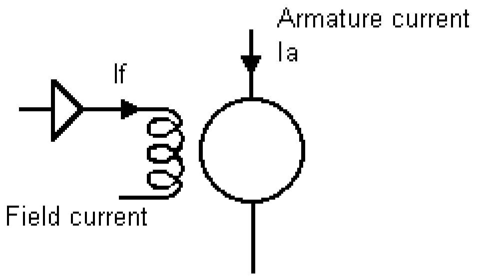


There are many types of Direct Current motors with differing characteristics that make them suitable for various applications. It is not feasible to cover the theory of these here but you will find it in other modules. Here is some of the theory concerning smaller servo motors commercially available.

D.C. SERVO MOTORS MANUFACTURERS APPROACH

Smaller servo motors are used for robotic applications, that is, the control of position and speed of a shaft. They may use field control or armature control or both.

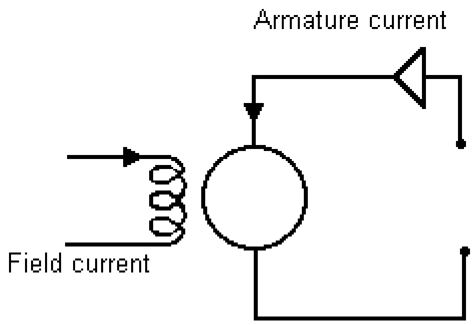
FIELD CONTROL



The armature current I_a is maintained constant and the field current I_f is supplied through a power amplifier and controls the torque. The torque is unaffected by the speed. The relationship between torque and current is

$$T = k\,I_f$$

ARMATURE CONTROL



This is quite common since smaller servo motors use permanent magnets. With the development of more powerful permanent magnets, DC servo motors are improving their power to weight ratio but are still not as good as hydraulic motors in this respect.

Manufacturers of such motors give the steady state characteristics. Here is the way to use the information found in typical manufacturer's data sheets.

- Establish the useful torque T that you need from the motor and the speed N it will run at.
- Establish the friction torque for the selected motor. This is expressed as $\mathbf{T_f}$ in catalogues.
- Establish the damping torque constant $\mathbf{k_d}$ for the selected motor. This is directly proportional to the speed of the motor.
- Calculate the damping torque at the required speed. This torque is T_d and is found by: $\mathbf{T_d = k_d\ N/1000}$.
- Establish the torque constant $\mathbf{k_t}$ for the motor selected.
- Establish the e.m.f. constant $\mathbf{k_e}$ for the motor selected.
- Establish the armature resistance for the motor selected.

Torque is normally quoted in N cm which is not a recommended SI unit. Shaft speeds are often given as N/1000 where N is in rev/min.

The current required to operate such a motor is given by the equation

$$\mathbf{I = (T_L + T_f + T_d)/k_t}$$ where T_L is the load torque

The useful torque from the motor is $\mathbf{T_L = k_t I - T_f - T_d}$

The voltage required at the terminals is $\mathbf{V = (N\ k_e/1000) + (I_a R_a)}$

DATA TABLES FOR MOTORS (from a well known manufacturer)

Motor Constants		**GR12C**	**GR12CH**	**GR16C**	**GR16CH**	**GR19CH**
Torque	K_t N cm/Amp	10.8	17.0	23.7	37.3	24.0
EMF	K_e V/per 1000 rpm	11.3	17.8	24.8	39.0	25.0
Damping	K_d N cm per 1000 rpm	1.16	1.95	3.57	6.44	7.76
Friction Torque	T_f N cm	4.2	4.2	7.7	7.7	9.8
Terminal Resistance @ 5A	R_m Ohm	0.95	0.95	0.95	0.95	0.65
Rotor Moment of Inertia	J Kg cm^2	1.2	1.2	5.93	5.93	12.71

A worked example is best to demonstrate this.

WORKED EXAMPLE No. 1

1. Using the manufacturers data sheet, determine the terminal voltage and current required to produce a torque of 75 Ncm at 2000 rev/min.

SOLUTION

From the data sheet the GR12C has the following constants.
k_t = 10.8 N cm per Amp.
k_e = 11.3 V per 1000 rev/min
k_d = 1.16 N cm per 1000 rev/min
T_f = 4.2 N cm
Armature resistance = 0.95 Ohms.
Voltage at 3000 rpm is 44.5 V
$T_d = (N/1000) \times k_d = (2000/1000) \times 1.16 = 2.32$ N cm

$$I = (T_L + T_f + T_d)/k_t = (75 + 4.2 + 2.32)/10.8 = 7.55 \text{ A}$$
$$V = (N k_e/1000) + (I_a R_a)$$
$$V = (2000 \times 11.3/1000) + (7.55 \times 0.95) = 29.8 \text{ V}$$

SELF ASSESSMENT EXERCISE No. 1

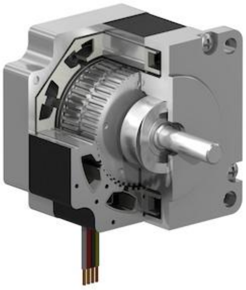
Using the manufacturers data sheet determine the voltage and current needed to run the motor GR16C at 3000 rev/min with a load torque of 40 N cm. (Answer 76.7 V)

2.3. STEPPER MOTORS

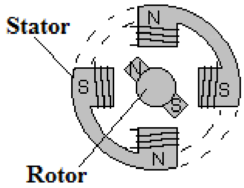
Basically a stepper motor rotates a precise angle according to the number of pulses of electricity sent to it. Because there is confidence that the shaft rotates to the position requested, no transducer is needed to measure and check the position and so they are common on open loop systems. There are 3 types of stepper motor in common use and these are


1. The Permanent Magnet Type.

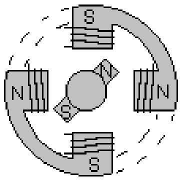

2. The Variable Reluctance Type.


3. The Hybrid Type.

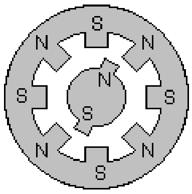
2.3.1 THE PERMANENT MAGNET TYPE.



The rotor is a permanent magnet with a North and South poles as shown.
Two pairs of poles are placed on the stator and energised to produce a pattern of N - S - N - S (starting at the top). The rotor will take up a position in between the poles due to equal and opposite torques being exerted on it.



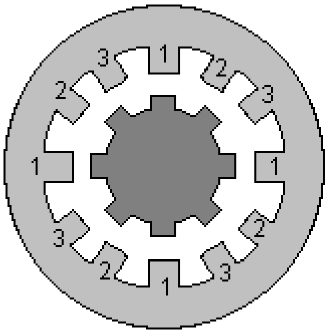
If the polarity of both pairs of poles are reversed the pattern will change to S - N - S - N and the rotor will flip 45^{o} to a new position of balance. In order to obtain more steps, more pairs of poles are used but there are only two windings. Reversing the polarity of both windings moves the rotor on one step. Stepping is produced by simply reversing the polarity.



The rotor is held in position even when the poles are not energised. In order to obtain many steps, the poles are often stacked one behind the other and not in a single ring. The number of steps may also be increased by using a gear box on the output shaft.

2.3.2. VARIABLE RELUCTANCE TYPE

The rotor is constructed of soft iron with a number of teeth which are unequal in number to the number of poles on the stator. The stator has multiple poles which are energised by several separate phases. The diagram shows a system with three phases.



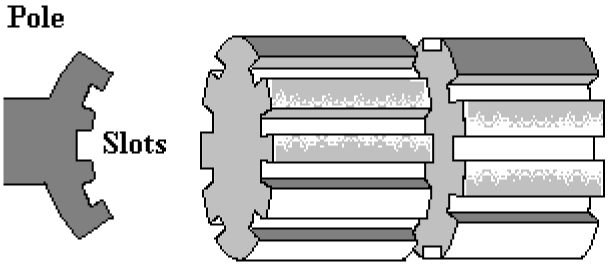
When a current is applied to the stator windings, the rotor aligns itself in the position of least magnetic reluctance. This position depends upon the number of phases energised.

The rotor retains very little magnetism so there is no holding torque when the current is removed.

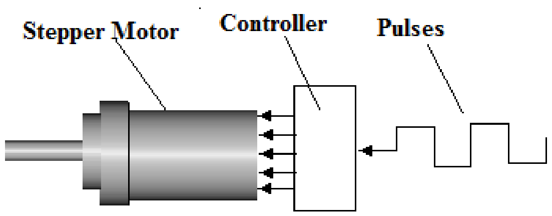
The number of steps is given by N = SR/(S-R) where S is the number of stator slots and R the number of rotor slots.

2.3.3 HYBRID MOTORS

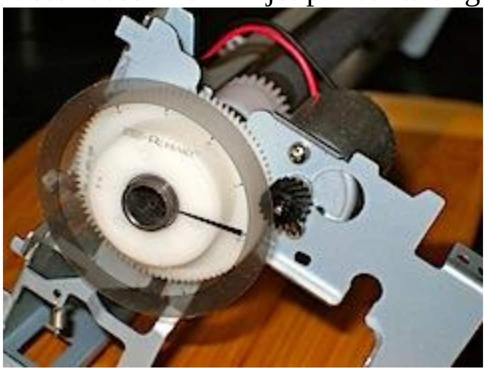
Hybrid motors are a combination of the last two types. Each pole is divided into slots as shown. The rotor has two sets of slots, one behind the other with one set offset to the other by 1/2 slot pitch. The rotor is magnetised longitudinally. This produces a high resolution.



In general all stepper motors are controlled electronically.



The picture shows a typical stepper motor used in an inkjet printer with gears and an optical encoder.



3. HYDRAULIC AND PNEUMATIC ACTUATORS

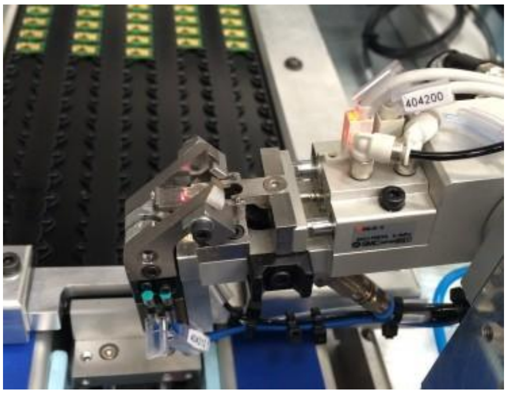
- ***Hydraulic actuators*** use incompressible liquids and are mainly used for power and precision (e.g. power steering, machine tools, heavy duty robots, extrusion presses, aircraft rudder control and so on).

- ***Pneumatic actuators*** use compressed air and are generally used for lower power and less precise applications such as moving objects from a conveyor belt, placing and picking objects and so on.

- ***Fluid Power*** has the disadvantage of needing pipes to carry the fluid to and from the actuators and are generally bulky so they cannot be integrated into compact machines.

- There are ***rotary and linear*** actuators of various sizes,

3.1 LINEAR ACTUATORS



The picture shows a robotic arm attachment for a bottle capping process. It has linear pneumatic actuators for movement and clamping. Linear actuators are commonly called cylinders and they convert fluid power into mechanical power. They are also known as ***Jacks or Rams***.

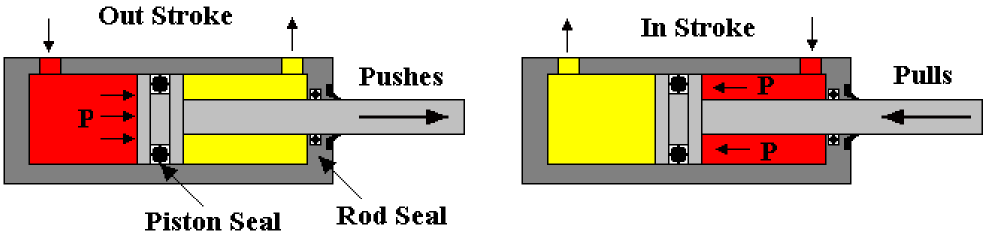
Hydraulic cylinders are used at high pressures and produce large forces and precise movement. For this reason they are constructed of strong materials such as steel and designed to withstand large forces.

Because gas is an expansive substance, it is dangerous to use pneumatic cylinders at high pressures so they are limited to about 10 bar pressure. Consequently they are constructed from lighter materials such as aluminium and brass. Because gas is a compressible substance, the motion of a pneumatic cylinder is hard to control precisely. The basic theory for hydraulic and pneumatic cylinders is otherwise the same.

3.1.1 FORCE

The fluid pushes against the face of the piston and produces a force. The force produced is given by the formula:

$F = pA$ where p is the pressure in N/m^2 and A is the area the pressure acts on in m^2.



Let A be the full area of the piston and a be the cross sectional area of the rod. If the pressure is acting on the rod side, then the area on which the pressure acts is is (A - a).

$F = pA$ on the full area of piston.
$F = p(A-a)$ on the rod side.

This force acting on the load is often less because of friction between the seals and both the piston and piston rod.

3.1.2 SPEED

The speed of the piston and rod depends upon the flow rate of fluid. The volume per second entering the cylinder must be the change in volume per second inside. It follows then that:

$$Q\ m^3/s = \text{Area x distance moved per second}$$

$$Q\ m^3/s = A \text{ x velocity} \quad \text{(full side)}$$

$$Q\ m^3/s = (A-a) \text{ x velocity (rod side)}$$

Note in calculus form velocity is given by v = A dx/dt and this is useful in control applications.

In the case of air cylinders, it must be remembered that Q is the volume of compressed air and this changes with pressure so any variation in pressure will cause a variation in the velocity.

3.1.3 POWER

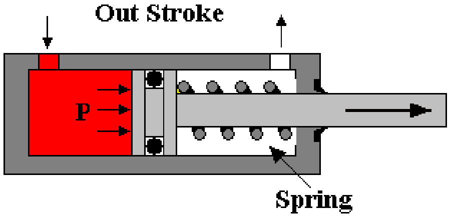
Mechanical power is defined as Force x velocity. This makes it easy to calculate the power of a cylinder. The fluid power supplied is more than the mechanical power output because of friction between the sliding parts.

$$P = F\,v \quad \text{Watts}$$

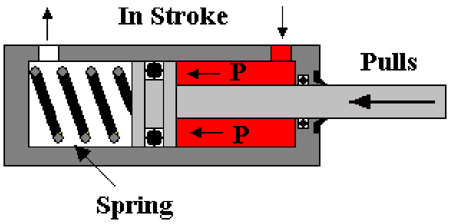
3.1.4 TYPES AND STYLES

Single Acting Cylinders

A simple single acting cylinder is shown below. The cylinder is only powered in one direction and needs another force to return it such as an external load (e.g. in a car hoist or jack) or a spring. No hydraulic fluid is present on the low pressure side.



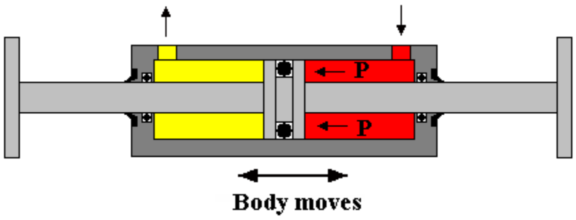
Single Acting Cylinder for Pushing



Single Acting Cylinder for Pulling

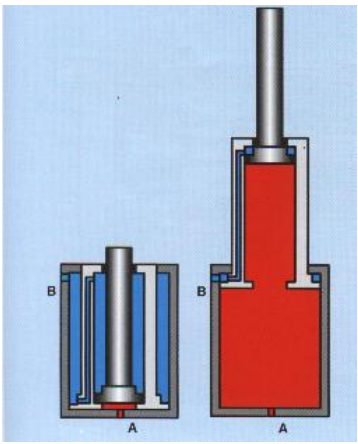
Double Rod Cylinders

The basic design of a double rod cylinder is shown below. The design allows equal force and speed in both directions. It is useful in robotic mechanisms were the rod is clamped at both ends and the body moves instead.



Telescopic Cylinders

These cylinders produce long strokes from an initial short length. Each section slides inside a larger section. These cylinders have from 2 to five stages. They are typically used in refuse lorries for ejecting the compacted refuse. They are also used for lifts, tipping platforms, lifting platforms and other commercial vehicle applications.



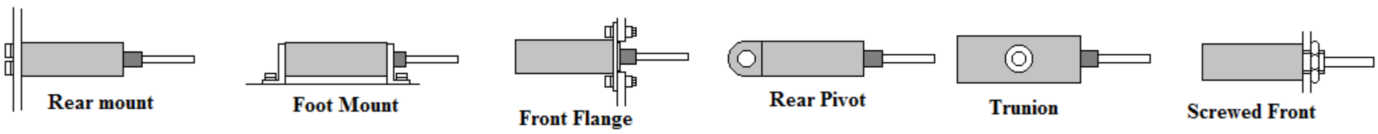
Styles and Sizes

Linear actuators have a range of styles for mounting them and allowing them to pivot.

Hydraulic Cylinders

Small Pneumatic Cylinders   Linear Acting   Short Clamping Cylinders

The diagram shows typical ways of mounting cylinders and attaching them to machines.



WORKED EXAMPLE No. 2

A double acting hydraulic cylinder has a bore of 100 mm. The rod is 40 mm diameter and the stroke is 120 mm. It must produce a pushing force of 12 kN. The flow rate available in both directions is 12 dm^3/min.

Calculate:
i. The system pressure needed.
ii. The force with which it pulls given the same pressure.
iii. The speed on the outward stroke.
iv. The speed of retraction.
v. The power used on the outstroke.

Assume ideal conditions throughout.

SOLUTION

$A = \pi D2/4 = \pi \times 0.1^2/4 = 7.854 \times 10^{-3}\ m^2$

$p = F/A = 12000/\ 7.854 \times 10^{-3} = 1.528 \times 10^6\ N/m^2 =$ or 1.528 MPa

$a = \pi d^2/4 = \pi \times 0.04^2/4 = 1.257 \times 10^{-3}\ m^2$

Pulling force = $p(A-a) = 1.528 \times 10^6 \times (7.854 \times 10^{-3} - 1.257 \times 10^{-3}) = 10008$ N

Flow rate $Q = 0.012/60 = 20 \times 10^{-3}\ m^3/s$

Speed on the outward stroke = $Q/A = 20 \times 10^{-3} / 7.854 \times 10^{-3} = 0.025$ m/s or 25 mm/s

Speed of retraction = $Q/(A-a) = 20 \times 10^{-3}/(7.854 \times 10^{-3} - 5.027 \times 10^{-3}) = 0.03$ m/s or 30 mm/s

Power = $pQ = 1.528 \times 10^6 \times 20 \times 10^{-3} = 305.6$ Watts

SELF ASSESSMENT EXERCISE No. 2

1. A double acting hydraulic cylinder with a single rod must produce a thrust of 80 kN and move out with a velocity of 3 mm/s on the out stroke (positive stroke). The operating pressure is 100 bar gauge. Calculate the bore diameter required and the flow rate of the oil.

   (Answers 101 mm and 24 cm^3/s)

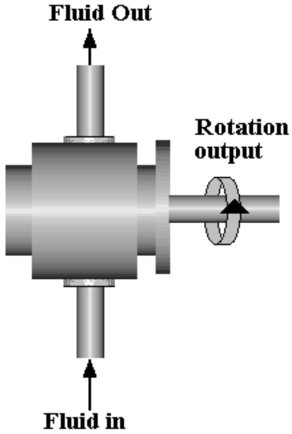
2. The cylinder in question has a rod diameter 25 mm. If the flow rate and pressure are the same on the retraction (negative) stroke, what would be the force and speed available?

   (Answers 75 kN and 3.2 mm/s)

3. A single acting hydraulic cylinder has a piston 75 mm diameter and is supplied with oil at 80 bar gauge and 0.265 dm^3/s. Calculate the thrust, velocity and power.

   (Answers 35.343 kN, 60 mm/s and 2.12 kW)

3.2 MOTORS



There are numerous designs for motors and it is not practical to cover all the designs here. The design best needed for an application depends on the speed and torque and efficiency required. Most designs enable the motor to run in reverse. You will find a full description of designs in the fluid power module on this web site.

The purpose of a motor is to convert fluid power into shaft power by forcing the shaft to rotate. Pressure is converted into torque and flow rate is converted into speed. In other words, the faster you push the fluid through the motor, the faster it goes and the harder it is to turn the shaft, the higher the pressure needed to make it go round. The pictures show a small selection of motors




3.2.1. BASIC THEORY

Air is a very compressible substance and the theory for air motors is more complicated than for hydraulic motors. The volume of hydraulic fluids is considered constant in the following theory. In other words, the volume is unaffected by the pressure. The following applies to hydraulic motors.

Power and Efficiency

Fluid Power is defined as F.P. = $Q\,\Delta p$

Q is the flow rate in m^3/s and Δp is the difference between the inlet and outlet pressure in N/m^2.

Shaft Power is the output power at the shaft given by the formula S.P. = $2\pi NT = \omega T$

N is the speed in rev/s. T is the shaft torque in Nm and ω is the shaft speed in radian/s.

Overall Efficiency is defined as **η_o = Output/Input = Shaft Power/Fluid Power**

The difference in power is due to friction and internal slippage of fluid. It must be remembered that in the case pneumatic motors the volume changes with pressure.

Speed - Flow Relationship

The basic relationship between flow rate and speed is Flow Rate = $Q = K_q$ x Speed

K_q is the nominal displacement of the motor usually expressed in units of cm^3/rev.

Torque - Pressure Relationship

In fluid power, shaft speed is normally given in rev/min or rev/s. The formula for shaft power is given by the well known formula SP = $2\pi NT$. If the motor is 100% efficient, the shaft power is equal to the fluid power so equating we get the following.

$$2\pi NT = Q\,\Delta p$$

Rearrange to make T the subject. $T = (Q/N)\,\Delta p/2\pi$ $\quad T = k_q\,\Delta p/2\pi$

Δp is the difference in pressure between the inlet and outlet of the motor.

K_q is the nominal displacement in m^3/s.

In control theory it is more usual to use radians/s for shaft speed in which case:

$$\omega T = Q\,\Delta p$$

Rearrange to make T the subject. $T = (Q/\omega)\,\Delta p \quad T = k_q\,\Delta p$

K_q is the nominal displacement in m^3/radian.

The operating characteristics of an ideal motor may be summed up by the two equations:

Flow rate = K_q N **T = K_q Δp**

WORKED EXAMPLE No. 3

The pressure difference over a hydraulic motor is 80 bar and it runs at 400 rev/min. The nominal displacement is 5 cm^3/rev. The overall efficiency is 85% and the volumetric efficiency is 90%. Calculate the following.

i. The ideal flow rate.
ii. The actual flow rate.
iii. The fluid power.
iv. The shaft power.
v. The shaft torque.

SOLUTION

N = 400/60 rev/s $k_q = 5 \times 10^{-6}$ m^3/rev

Ideal Flow rate = kq x N = $5 \times 10^{-6} \times 400/60 = 33.33 \times 10^{-6}$ m^3/s

Actual Flow Rate = Ideal Flow rate/η_v = $33.33 \times 10^{-6}/0.9 = 37.04 \times 10^{-6}$ m^3/s

Fluid Power $Q\Delta p = 37.04 \times 10^{-6} \times 80 \times 10^5 = 296.3$ Watt

Shaft Power = Fluid Power x η_o = 296.3 x 0.85 = 251.85 Watt

Torque = SP/2πN = 251.85 /(2π x 400/60) = 6.013 Nm

SELF ASSESSMENT EXERCISE No. 3

1. Calculate the output power of a hydraulic motor which has a flow rate of 5 dm^3/s and a pressure difference of 80 bar. The overall efficiency is 75%.
   (Answer 30 kW)
2. A hydraulic motor must produce an output power of 500 Watts from an oil supply at 50 barg which exhausts at 0 barg. The efficiency is 80%. Calculate the flow rate of oil required.
   (Answer 125 cm^3/s)
3. A hydraulic motor has a flow constant of 1.2 cm^3/rad.
   Calculate the quantity of oil needed to turn the shaft ½ of a revolution. (3.77 cm^3)
   Calculate the speed of the shaft in rev/min when oil is supplied at 20 cm^3/s. (159.1 rev/min)
4. The pressure difference over a hydraulic motor is 120 bar and it runs at 200 rev/min. The nominal displacement is 8 cm^3/rev. The overall efficiency is 80% and the volumetric efficiency is 85%. Calculate the following:

   i. The ideal flow rate. (26.67 cm^3/s)
   ii. The actual flow rate. (31.37 cm^3/s)
   iii. The fluid power. (376.5 W)
   iv. The shaft power. (301.2 W)
   v. The shaft torque. (14.38 Nm)