```
' Subroutine to calculate the PWM on and off pulse widths based on the desired
'   motor speed (motor_speed)
pwm_periods:
  ' Be careful to avoid integer arithmetic and
  '   WORD overflow [max=65535] problems
  If (pwm_period >= 655) Then
    on_time = pwm_period/100 * motor_speed
    off_time = pwm_period/100 * (100-motor_speed)
  Else
    on_time = pwm_period*motor_speed / 100
    off_time = pwm_period*(100-motor_speed) / 100
  Endif
Return

' Subroutine to output a full PWM pulse based on the data from pwm_periods
pwm_pulse:
  ' Send the ON pulse
  High motor_pwm
  Pauseus on_time

  ' Send the OFF pulse
  Low motor_pwm
  Pauseus off_time
Return
```

10.6 STEPPER MOTORS

A special type of DC motor, known as a **stepper motor,** is a permanent magnet or variable reluctance DC motor that has the following performance characteristics: it can rotate in both directions, move in precise angular increments, sustain a holding torque at zero speed, and be controlled with digital circuits. It moves in accurate angular increments, known as **steps,** in response to the application of digital pulses to an electric drive circuit. The number and rate of the pulses control the position and speed of the motor shaft. Generally, stepper motors are manufactured with steps per revolution of 12, 24, 72, 144, 180, and 200, resulting in shaft increments of 30°, 15°, 5°, 2.5°, 2°, and 1.8° per step. Special **micro-stepping** circuitry can be designed to allow many more steps per revolution, often 10,000 steps/rev or more.

Stepper motors are either **bipolar,** requiring two power sources or a switchable polarity power source, or **unipolar,** requiring only one power source. They are powered by DC sources and require digital circuitry to produce coil energizing sequences for rotation of the motor. Feedback is not always required for control, but the use of an encoder or other position sensor can ensure accuracy when exact position control is critical. The advantage of operating without feedback (i.e., in open-loop mode) is that a closed-loop control system is not required. Generally, stepper motors produce less than 1 hp (746 W) and are therefore used only in low-power position control

Video Demo

9.2 Automated laboratory rat exercise machine with IR sensor and stepper motor

applications. Video Demo 9.2 shows an interesting example of a stepper motor application.

A commercial stepper motor has a large number of poles that define a large number of equilibrium positions of the rotor. In the case of a permanent magnet stepper motor, the stator consists of wound poles, and the rotor poles are permanent magnets. Exciting different stator winding combinations moves and holds the rotor in different positions. The **variable reluctance** stepper motor has a ferromagnetic rotor rather than a permanent magnet rotor. Motion and holding result from the attraction of stator and rotor poles to positions with minimum magnetic reluctance that allow for maximum magnetic flux. A variable reluctance motor has the advantage of a lower rotor inertia and therefore a faster dynamic response. The permanent magnet stepper motor has the advantage of a small residual holding torque, called the **detent torque,** even when the stator is not energized.

To understand how the rotor moves in an incremental fashion, consider a simple design consisting of four stator poles and a permanent magnet rotor as illustrated in Figure 10.21. In step 0, the rotor is in equilibrium, because opposite poles on the stator and rotor are adjacent to and attract each other. Unless the magnet polarities of the stator poles are changed, the rotor remains in this position and can withstand an opposing torque up to a value called the **holding torque.** When the stator polarities are changed as shown (step 0 to step 1), a torque is applied to the rotor, causing it to move 90° in the clockwise direction to a new equilibrium position shown as step 1. When the stator polarities are again changed as shown (step 1 to step 2), the rotor experiences a torque driving it to step 2. By successively changing the stator polarities in this manner, the rotor can move to successive equilibrium positions in the clockwise direction. The sequencing of the pole excitations is the means by which the direction of rotation occurs. Counterclockwise motion can be achieved by applying the polarity sequence in the opposite direction. The motor torque is directly related to the magnetic field strength of the poles and the rotor.

The dynamic response of the rotor and attached load must be carefully considered in applications that involve starting or stopping quickly, changing or ramping speeds quickly, or driving large or changing loads. Due to the inertia of the rotor and attached load, rotation can exceed the desired number of steps. Also, as illustrated in Figure 10.22, a stepper motor driving a typical mechanical system through one step

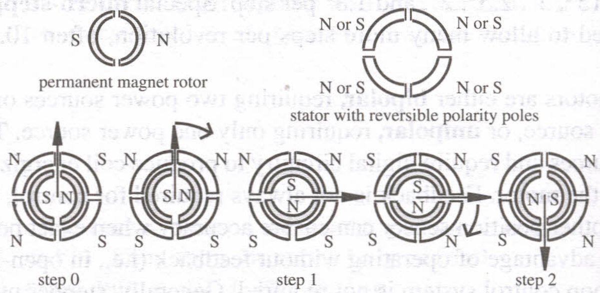


Figure 10.21 Stepper motor step sequence.

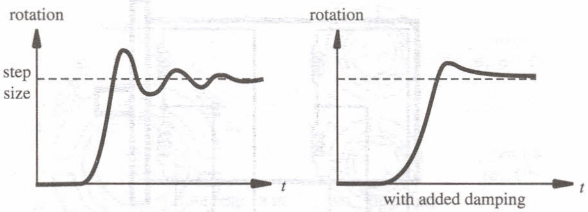


Figure 10.22 Dynamic response of a single step.

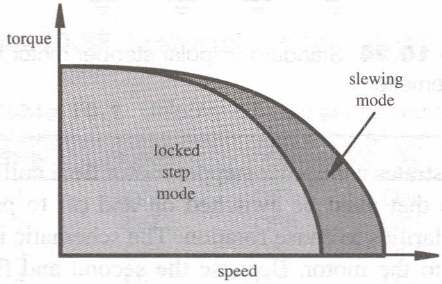


Figure 10.23 Stepper motor torque-speed curves.

will exhibit an underdamped response. If damping is increased in the system, for example, with mechanical, frictional, or viscous damping, the response can be modified to reduce oscillation, as shown in the figure. Note, however, that even with an ideal choice for damping, the motor requires time to totally settle into a given position, and this settling time varies with the step size and the amount of damping. It is also important to note that the torque required from the motor increases with added damping. Video Demo 10.13 shows an example of a typical underdamped second-order system response of a stepper motor with a fairly large step size. It also shows how the response changes as the step rate increases. Video Demo 10.14 shows slow-motion footage of the motor turning at a medium speed to show how the step response effects are less pronounced at higher step rates.

Video Demo

10.13 Stepper motor step response and acceleration through resonance

10.14 High-speed video of medium speed response

The torque-speed characteristics for a stepper motor are usually divided into two regions as illustrated in Figure 10.23. In the **locked step mode,** the rotor decelerates and may even come to rest between each step. Within this region, the motor can be instantaneously started, stopped, or reversed without losing step integrity. In the **slewing mode,** the speed is too fast to allow instantaneous starting, stopping, or reversing. The rotor must be gradually accelerated to enter this mode and gradually decelerated to leave the mode. While in slewing mode, the rotor is in synch with the stator field rotation and does not settle between steps. The curve between the regions in the figure indicates the maximum torques that the stepper can provide at different speeds without slewing. The curve bordering the outside of the slewing mode region represents the absolute maximum torques the stepper can provide at different speeds.

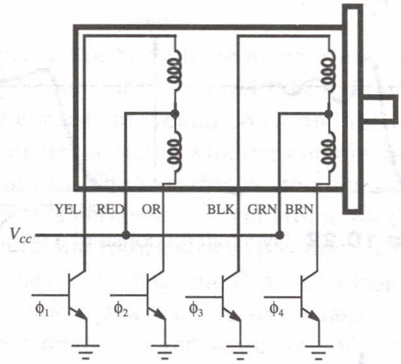


Figure 10.24 Standard unipolar stepper motor field coil schematic.

Figure 10.24 illustrates a unipolar stepper motor field coil schematic with external power transistors that must be switched on and off to produce the controlled sequence of stator polarities to cause rotation. The schematic in Figure 10.24 shows six wires connected to the motor. Because the second and fifth wires are usually connected externally as shown, manufacturers sometimes connect them inside the motor, in which case the motor only has five external wires. The wires are usually color coded by the manufacturers to help the user make a correspondence to the schematic. Figure 10.24 includes a common color scheme used for a six-wire unipolar stepper motor: yellow (coil 1), red (1/2 common), orange (coil 2), black (coil 3), green (3/4 common), brown (coil 4). Another common six-wire color scheme is green (coil 1), white (1/2 common), blue (coil 2), red (coil 3), white (3/4 common), black (coil 4). A common color scheme for a five-wire unipolar stepper is red (coil 1), green (coil 2), black (common), brown (coil 3), white (coil 4). If you come across a motor for which you have no documentation and the color scheme is unknown, there is a testing procedure you can follow to determine the wire identities (e.g., see Internet Link 10.3).

Internet Link

10.3 How to identify the different wires of a stepper motor

Figure 10.25 illustrates the construction of and stepping sequence for a four-phase unipolar stepper motor. It consists of a two-pole permanent magnet rotor and a four-pole stator, with each pole wound by two complementary windings (e.g., ϕ_1 and ϕ_2 wound in opposite directions on the top left pole). Table 10.1 lists the phase sequence required to step the motor in full steps, where two of the four phases are energized (ON) and each stator pole is polarized. Table 10.2 lists the phase sequence for half-stepping, where between each full step only one phase is energized (ON) and only two stator poles are polarized. The resolution or number of steps of the motor is twice as large in the half-step mode (8 steps/rev at 45°) than in the full-step mode (4 steps/rev at 90°), but the holding torque and drive torque change between two values on alternate cycles in half-step mode. Another technique for increasing the number of steps is called **micro-stepping,** where the phase currents are controlled by fractional amounts, rather than just ON and OFF, resulting in more magnetic equilibrium

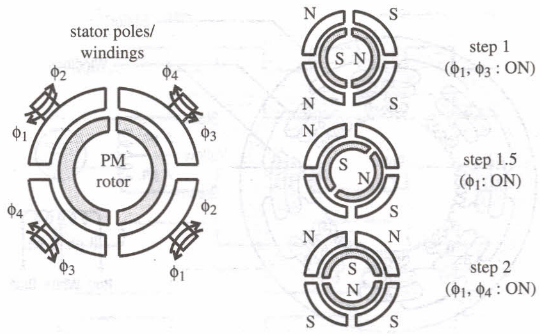


Figure 10.25 Example of a unipolar stepper motor.

Table 10.1 Unipolar full-step phase sequence

	Step	ϕ_1	ϕ_2	ϕ_3	ϕ_4
CW	1	ON	OFF	ON	OFF
↓	2	ON	OFF	OFF	ON
CCW	3	OFF	ON	OFF	ON
↑	4	OFF	ON	ON	OFF

Table 10.2 Unipolar half-step phase sequence

	Step	ϕ_1	ϕ_2	ϕ_3	ϕ_4
CW	1	ON	OFF	ON	OFF
↓	1.5	ON	OFF	OFF	OFF
	2	ON	OFF	OFF	ON
	2.5	OFF	OFF	OFF	ON
CCW	3	OFF	ON	OFF	ON
↑	3.5	OFF	ON	OFF	OFF
	4	OFF	ON	ON	OFF
	4.5	OFF	OFF	ON	OFF

positions between the poles. In effect, discretized sine waves are applied to the phases instead of square waves. The most common commercially available stepper motors have 200 steps/rev in full-step mode and are sometimes referred to as 1.8° (360°/200) steppers. In micro-stepping mode, 10,000 or more steps per revolution can be achieved.

Figure 10.26 illustrates the structure, pole geometry, and coil connections of an actual stepper motor in more detail. This particular stepper motor can be wired as a four-phase unipolar motor or a two-phase bipolar motor. Figure 10.27 shows the 50-tooth split rotor with one side having north polarity and the other having south polarity.

See Internet Link 10.4 for links to many resources and manufacturers for various stepper motor products.

Internet Link

10.4 Stepper motor online resource

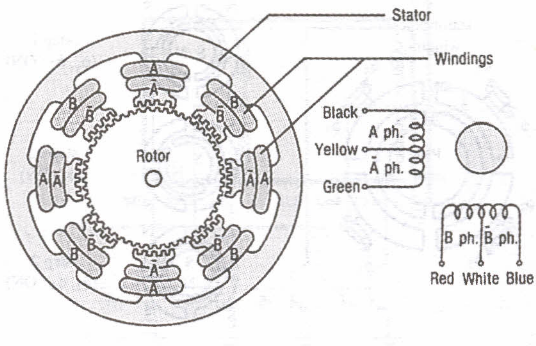


Figure 10.26 Typical stepper motor rotor and stator configuration. *(Courtesy of Oriental Motor, Torrance, CA)*

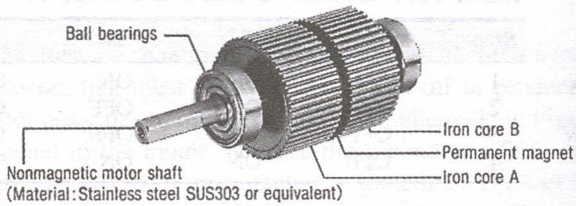


Figure 10.27 Actual stepper motor rotor. *(Courtesy of Oriental Motor, Torrance, CA)*

10.6.1 Stepper Motor Drive Circuits

A drive circuit for properly phasing the signals applied to the poles of the unipolar stepper motor for rotation in full-step mode is easily and economically produced using the components illustrated in Figure 10.28. A similar drive circuit can be purchased as a single monolithic IC (e.g., E-Lab's EDE1200, Signetics' SAA1027, or Allegro Microsystems' UCN 5804B). The discrete circuit includes 7414 Schmitt trigger buffers, a 74191 up-down counter, and 7486 Exclusive OR gates. The Schmitt triggers (see Section 6.12.2) produce well-defined control signals with sharp rise and fall times in the presence of noise or fluctuations. The hysteresis of

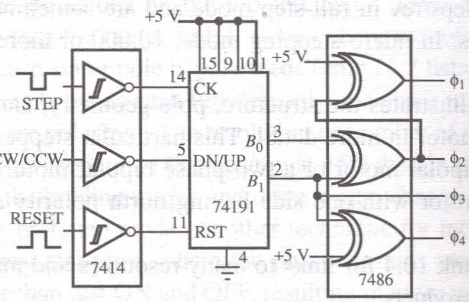


Figure 10.28 Unipolar stepper motor full-step drive circuit.

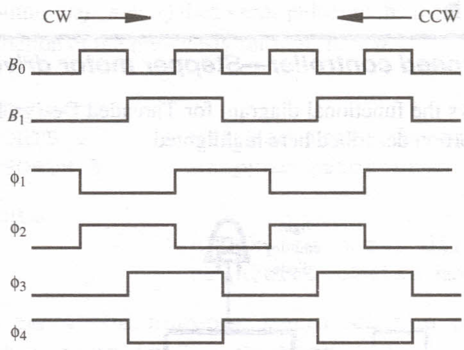


Figure 10.29 Timing diagram for full-step unipolar stepper motor drive circuit.

the Schmitt triggers provides sharp square-wave signals for the direction (CW/CCW), initialization (RESET), and single-step (STEP) inputs. The up-down counter and the XOR gates in turn create four properly phased motor drive signals. These four digital signals (ϕ_1, ϕ_2, ϕ_3, ϕ_4) are coupled to the bases of power transistors that sequentially energize the respective motor coils connected to the DC motor supply, resulting in shaft rotation. Each square-wave pulse received at the STEP input causes the motor to rotate a full step in the direction determined by the CW/CCW input.

The timing diagram for the two least significant output bits B_0 and B_1 of the counter and the phase control signals is shown in Figure 10.29. Compare the signals to the sequence in Table 10.1. They are in agreement. Boolean expressions that produce the four desired phased outputs from the two counter bits can be represented in both AND-OR-NOT and XOR forms:

$$\begin{aligned} \phi_1 &= \overline{\phi_2} = \phi_2 \oplus 1 \\ \phi_2 &= (B_0 \cdot \overline{B_1}) + (\overline{B_0} \cdot B_1) = B_0 \oplus B_1 \\ \phi_3 &= B_1 \\ \phi_4 &= \overline{B_1} = B_1 \oplus 1 \end{aligned} \tag{10.18}$$

These expressions can be verified by checking the signal values at different times in the timing diagram shown in Figure 10.29 (see Class Discussion Item 10.5). The purpose for representing the Boolean expressions in XOR form is to allow the logic to be executed using a single IC (the quad XOR 7486); otherwise, three ICs would be required for the AND, OR, and NOT representation.

■ CLASS DISCUSSION ITEM 10.5

Stepper Motor Logic

Construct a truth table for the timing diagram in Figure 10.29 and verify that Equations 10.18 are correct. Also, show that the sum-of-product and product-of-sum results for ϕ_2 are equivalent.

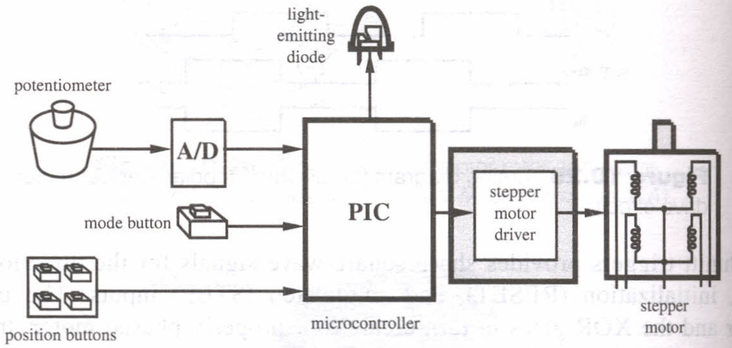
THREADED DESIGN EXAMPLE

B.3 Stepper motor position and speed controller—Stepper motor driver

Video Demo

1.7 Stepper motor position and speed controller

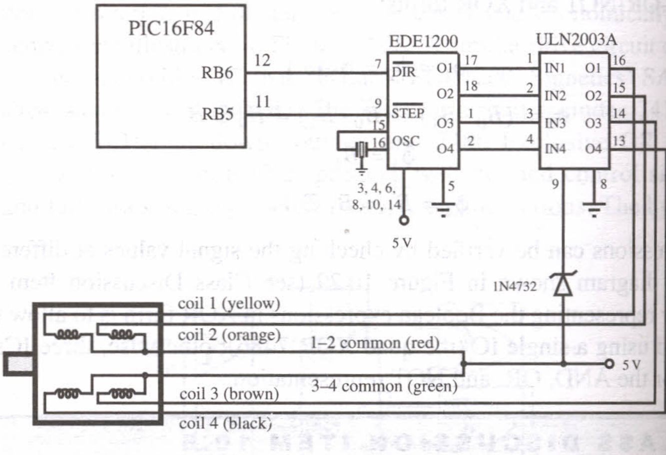
The figure below shows the functional diagram for Threaded Design Example B (see Video Demo 1.7), with the portion described here highlighted.



Internet Link

7.16 EDE1200 unipolar stepper motor driver

The figure below shows all components and interconnections required to drive a stepper motor from a PIC. A commercially available stepper motor driver IC, the E-Lab EDE1200, is the main component in the design. Detailed information about this component can be found in the data sheet at Internet Link 7.16. Only two signals from the PIC are required to drive the motor: a direction line and a step line. Each time a pulse is sent out on the step line, the stepper motor rotates a single step either clockwise or counterclockwise, as indicated by the direction line. The ULN2003A is required with the EDE1200 to provide enough current to drive typical stepper motor coils. Refer to the EDE1200 data sheet for more information.



The code required to move the motor follows. The *move* subroutine first determines the required direction and magnitude of the motion, based on the user-selected *new_motor_pos* value. This value is compared to the current motor position (*motor_pos*) to determine and set the motion direction and to calculate the required number of steps. The subroutine *move_steps* (with the help of subroutine *step_motor*) then sends pulses to the motor causing rotation. The rotational speed is a function of the previously set *step_period.*

```
' Define I/O pin names
motor_dir Var PORTB.6       ' stepper motor direction bit (0:CW 1:CCW)
motor_step Var PORTB.5      ' stepper motor step driver (1 pulse = 1 step)
' Define Constants
CW Con 0                    ' clockwise motor direction
CCW Con 1                   ' counterclockwise motor direction

' Subroutine to move the stepper motor to the position indicated by motor_pos
' (the motor step size is 7.5 degrees)
move:
  ' Set the correct motor direction and determine the required displacement
  If (new_motor_pos > motor_pos) Then
     motor_dir = CW
     delta = new_motor_pos - motor_pos
  Else
     motor_dir = CCW
     delta = motor_pos - new_motor_pos
  EndIf

  ' Determine the required number of steps (given 7.5 degrees per step)
  num_steps = 10*delta / 75

  ' Step the motor the appropriate number of steps
  Gosub move_steps

  ' Update the current motor position
  motor_pos = new_motor_pos
Return

' Subroutine to move the motor a given number of steps (indicated by num_steps)
move_steps:
  For i = 1 to num_steps
     Gosub step_motor
  Next
Return

' Subroutine to step the motor a single step (7.5 degrees) in the motor_dir
'  direction
step_motor:
  Pulsout motor_step, 100*step_period   ' (100 * 10microsec = 1 millisec)
  Pause step_period
  ' Equivalent code:
  ' High motor_step
  ' Pause step_period
  ' Low motor_step
  ' Pause step_period
Return
```

10.7 SELECTING A MOTOR

When selecting a motor for a specific mechatronics application, the designer must consider many factors and specifications, including speed range, torque-speed variations, reversibility, operating duty cycle, starting torque, and power required. These and other factors are described here in a list of questions that a designer must consider when selecting and sizing a motor in consultation with a motor manufacturer. As we will see, the torque-speed curve provides important information, helping to answer many questions about a motor's performance. Recall that the torque-speed curve displays the torques the motor can deliver at different speeds at rated voltage. Figure 10.30 shows an example of a torque-speed curve for a stepper motor, and Figure 10.31 shows an example of a torque-speed curve for a servomotor. These figures are examples from motor manufacturer specification sheets.

Some of the salient questions a designer may need to consider when choosing a motor for an application include the following:

- *Will the motor start and will it accelerate fast enough?* The torque at zero speed, called the *starting torque,* is the torque the motor can deliver when rotation begins. For the system to be self-starting, the motor must generate torque sufficient to overcome friction and any load torques.

  The acceleration of the motor and load at any instant is given by

  $$\alpha = (T_{motor} - T_{load})/J \tag{10.19}$$

  where α is the angular acceleration in rad/sec^2, T_{motor} is the torque produced by the motor, T_{load} is the torque dissipated by the load, and J is the total polar moment of inertia of the motor rotor and the load. The difference between motor and load torques determines the acceleration of the system. When the motor torque is equal to the load torque, the system is at a steady state operating speed.
- *What is the maximum speed the motor can produce?* The zero torque point on the torque-speed curve determines the maximum speed a motor can reach. Note that the motor cannot deliver any torque to the load at this speed. When the motor is loaded, the maximum no-load speed cannot be achieved.
- *What is the operating duty cycle?* When a motor is not operated continuously, one must consider the operating cycle of the system. The **duty cycle** is defined as the ratio of the time the motor is on with respect to the total elapsed time. If a load requires a low duty cycle, a lower-power motor may be selected that can operate above rated levels but still perform adequately without overheating during repeated on-off cycles.
- *How much power does the load require?* The power rating is a very important specification for a motor. Knowing the power requirements of the load, a designer should choose a motor with adequate power based on the duty cycle.
- *What power source is available?* Whether the motor is AC or DC might be a critical decision. Also, if battery power is to be used, the battery characteristics must match the load requirements.

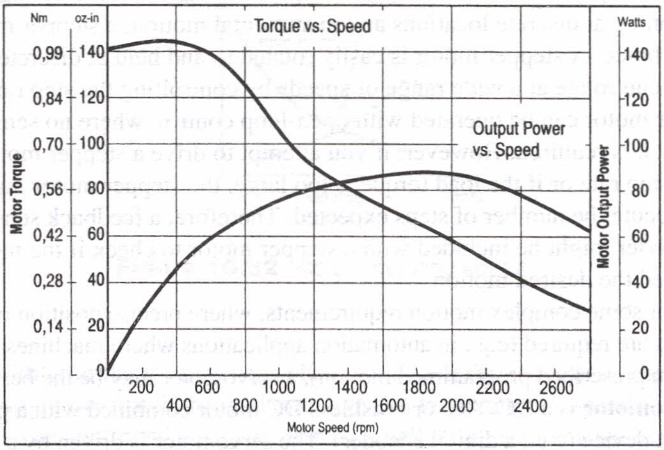


Figure 10.30 Typical stepper motor performance curves.
(Courtesy of Aerotech, Pittsburgh, PA)

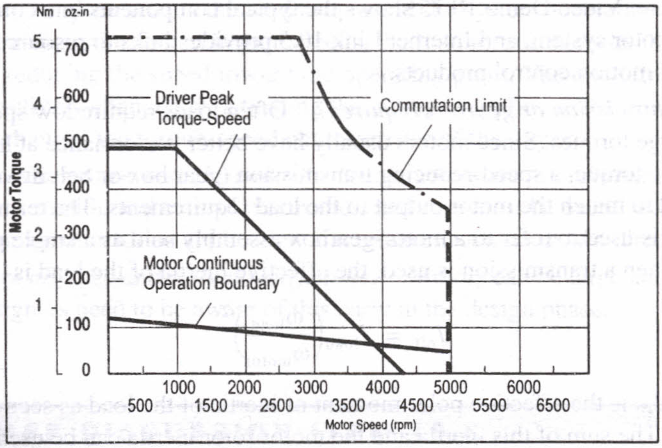


Figure 10.31 Typical servomotor performance curves.
(Courtesy of Aerotech, Pittsburgh, PA)

- *What is the load inertia?* As Equation 10.19 implies, for fast dynamic response, it is desirable to have low motor rotor and load inertia *J*. When the load inertia is large, the only way to achieve high acceleration is to size the motor so it can produce much larger torques than the load requires.
- *Is the load to be driven at constant speed?* The simplest method to achieve constant speed is to select an AC synchronous motor or a DC shunt motor which runs at a relatively constant speed over a significant range of load torques.

- *Is accurate position or speed control required?* In the cases of angular positioning at discrete locations and incremental motion, a stepper motor is a good choice. A stepper motor is easily rotated to and held at discrete positions. It also can rotate at a wide range of speeds by controlling the step rate. The stepper motor can be operated with open-loop control, where no sensor feedback is required. However, if you attempt to drive a stepper motor at too fast a step rate or if the load torque is too large, the stepper motor may slip and not execute the number of steps expected. Therefore, a feedback sensor such as an encoder might be included with a stepper motor to check if the motor has achieved the desired motion.

  For some complex motion requirements, where precise position or speed profiles are required (e.g., in automation applications where machines need to perform prescribed programmed motion), a servomotor may be the best choice. A **servomotor** is a DC, AC, or brushless DC motor combined with a position sensing device (e.g., a digital encoder). The servomotor is driven by a programmable controller that processes the sensor input and generates amplified voltages and currents to the motor to achieve specified motion profiles. This is called **closed-loop control,** since it includes sensor feedback. A servomotor is typically more expensive than a stepper motor, but it can have a much faster response. Video Demo 10.15 shows the typical components in a commercial servomotor system, and Internet Link 10.5 provides links to resources and vendors of motion control products.

Video Demo

10.15 Servomotor system

Internet Link

10.5 Motor and motion controller online resources and vendors

- *Is a transmission or gearbox required?* Often loads require low speeds and large torques. Since motors usually have better performance at high speed and low torque, a speed-reducing transmission (gear box or belt drive) is often needed to match the motor output to the load requirements. The term **gear motor** is used to refer to a motor-gearbox assembly sold as a single package.

  When a transmission is used, the effective inertia of the load is

$$J_{eff} = J_{load}\left(\frac{\omega_{load}}{\omega_{motor}}\right)^2 \tag{10.20}$$

  where J_{eff} is the effective polar moment of inertia of the load as seen by the motor. The sum of this inertia and the motor rotor inertia can be used in Equation 10.19 to calculate acceleration. The speed ratio in Equation 10.20 is called the **gear ratio** of the transmission. It is often specified as a ratio of two numbers, where one or both numbers are integers (which is always the case when using meshing gears, which have integer numbers of teeth). So a gear ratio is sometimes written $N : M$, which can be read as: N to M gear reduction. This means N turns of the motor are required to create M turns of the load, so for an $N : M$ gear ratio, the speeds are related by

$$\omega_{load} = (M/N)\omega_{motor} \tag{10.21}$$

- *Is the motor torque-speed curve well matched to the load?* If the load has a well-defined torque-speed relation, called a **load line,** it is wise to select a

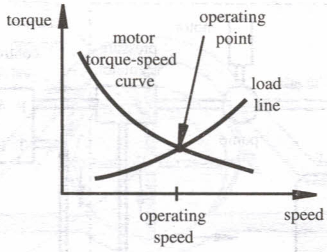


Figure 10.32 Motor operating speed.

motor with a similar torque-speed characteristic. If this is the case, the motor torque can match the load torque over a large range of speeds, and the speed can be controlled easily by making small changes in voltage to the motor.

- *For a given motor torque-speed curve and load line, what will the operating speed be?* As Figure 10.32 illustrates, for a given motor torque-speed curve and a well-defined load line, the system settles at a fixed speed operating point. Furthermore, the operating point is self-regulating. At lower speeds, the motor torque exceeds the load torque and the system accelerates toward the operating point, but at higher speeds, the load torque exceeds the motor torque, reducing the speed toward the operating point. The operating speed can be actively changed by adjusting the voltage supplied to the motor, which in turn changes the torque-speed characteristic of the motor.
- *Is it necessary to reverse the motor?* Some motors are not reversible due to their construction and control electronics, and care must be exercised when selecting a motor for an application that requires rotation in two directions.
- *Are there any size and weight restrictions?* Motors can be large and heavy, and designers need to be aware of this early in the design phase.

■ CLASS DISCUSSION ITEM 10.6
Motor Sizing

Why is it important not to oversize a motor for a particular application?

■ CLASS DISCUSSION ITEM 10.7
Examples of Electric Motors

Make a list of the different types of electric motors found in household devices and automobiles. Describe the reasons why you think the particular type of motor is used for each example you cite.

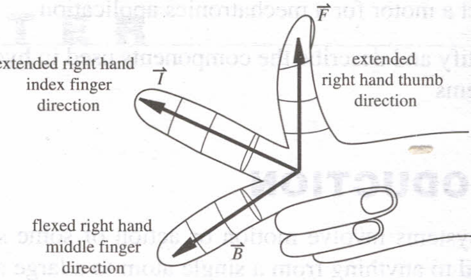


Figure 10.1 Right-hand rule for magnetic force.

Another electromagnetic effect important to actuator design is field intensification within a coil. Recall that, when discussing inductors in Chapter 2, we stated that the magnetic flux through a coil is proportional to the current through the coil and the number of windings. The proportionality constant is a function of the permeability of the material within the coil. The permeability of a material characterizes how easily magnetic flux penetrates the material. Iron has a permeability a few hundred times that of air; therefore, a coil wound around an iron core can produce a magnetic flux a few hundred times that of the same coil with no core. Most electromagnetic devices we will present use iron cores of one form or another to enhance the magnetic flux. Cores are usually laminated (made up of insulated layers of iron stacked parallel to the coil-axis direction) to reduce the eddy currents induced when the cores experience changing magnetic fields. Eddy currents, which are a result of Faraday's law of induction, result in inefficiencies and undesirable core heating.

10.3 SOLENOIDS AND RELAYS

As illustrated in Figure 10.2, a **solenoid** consists of a coil and a movable iron core called the **armature.** When the coil is energized with current, the core moves to increase the flux linkage by closing the air gap between the cores. The movable core is usually spring-loaded to allow the core to retract when the current is switched off. The force generated is approximately proportional to the square of the current and inversely proportional to the square of the width of the air gap. Solenoids are inexpensive, and their use is limited primarily to on-off applications such as latching, locking, and triggering. They are frequently used in home appliances (e.g., washing machine valves), automobiles (e.g., door latches and the starter solenoid), pinball machines (e.g., plungers and bumpers), and factory automation.

An electromechanical **relay** is a solenoid used to make or break mechanical contact between electrical leads. A small voltage input to the solenoid controls a potentially large current through the relay contacts. Applications include power switches and electromechanical control elements. A relay performs a function similar to a power transistor switch circuit but has the capability to switch much larger currents. Also, the input circuit of a relay is electrically isolated from the output circuit, unlike the common-emitter transistor circuit, where there is a common ground between the input and output. Because the relay is electrically isolated, noise,

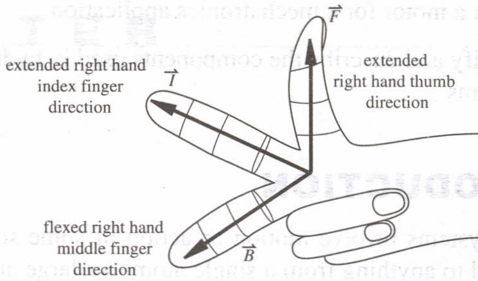


Figure 10.1 Right-hand rule for magnetic force.

Another electromagnetic effect important to actuator design is field intensification within a coil. Recall that, when discussing inductors in Chapter 2, we stated that the magnetic flux through a coil is proportional to the current through the coil and the number of windings. The proportionality constant is a function of the permeability of the material within the coil. The permeability of a material characterizes how easily magnetic flux penetrates the material. Iron has a permeability a few hundred times that of air; therefore, a coil wound around an iron core can produce a magnetic flux a few hundred times that of the same coil with no core. Most electromagnetic devices we will present use iron cores of one form or another to enhance the magnetic flux. Cores are usually laminated (made up of insulated layers of iron stacked parallel to the coil-axis direction) to reduce the eddy currents induced when the cores experience changing magnetic fields. Eddy currents, which are a result of Faraday's law of induction, result in inefficiencies and undesirable core heating.

10.3 SOLENOIDS AND RELAYS

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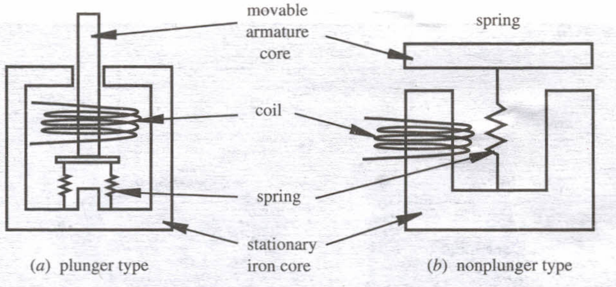

Figure 10.2 Solenoids.

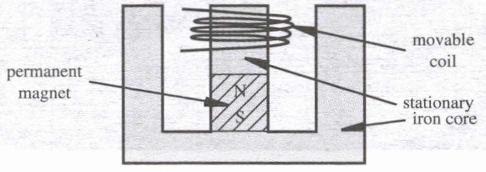

Figure 10.3 Voice coil.

induced voltages, and ground faults occurring in the output circuit have minimal impact on the input circuit. One disadvantage of relays is that they have slower switching times than transistors. Video Demo 10.1 demonstrates how relays and transistors respond to different switching speeds.

As illustrated in Figure 10.3, a **voice coil** consists of a coil that moves in a magnetic field produced by a permanent magnet and intensified by an iron core. Figure 10.4 shows the coil and iron core of a commercially available voice coil, which can be used as either a sensor or an actuator. When used as an actuator, the force on the coil is directly proportional to the current in the coil. The coil is usually attached to a movable load such as the diaphragm of an audio speaker, the spool of a hydraulic proportional valve, or the read-write head of a computer disk drive. The linear response and bidirectional capability make voice coils more attractive than solenoids for control applications.

Video Demos 10.2 and 10.3 show how a computer disk drive functions, where a voice coil is used to provide the pivoting motion of the read-write head. Video Demo 10.4 shows a super-slow-motion clip, filmed with a special high-speed camera, which dramatically demonstrates the accuracy and speed of the voice coil motion. The read-write head comes to a complete stop on one track before moving to another. In real-time (e.g., in Video Demo 10.3), this motion is a total blur.

Video Demo

10.1 Relay and transistor switching circuit comparison

10.2 Computer hard-drive with voice coil

10.3 Computer hard-drive track seeking demonstration

10.4 Computer hard-drive super-slow-motion video of track finding

■ CLASS DISCUSSION ITEM 10.1
Examples of Solenoids, Voice Coils, and Relays

Make a list of common household and automobile devices that contain solenoids, voice coils, and relays. Describe why you think the particular component was selected for each of the devices you cite.

vents to the atmosphere, or back to the sump. This can be used a pressure relief valve to safeguard a system against excessi pressures.

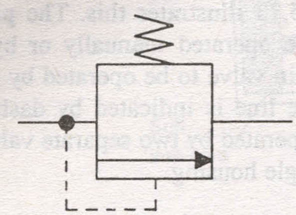

Fig. 5.16 Pressure sequence valve

5.4.2 Pressure sequence valve

With the pressure limiting valve of Figure 5.15, the limitin pressure is set by the pressure at the inlet to the valve. We ca adapt such a valve to give a sequence valve. This can be used t allow flow to occur to some part of the system when the pressur has risen to the required level. For example, in an automati machine we might require some operation to start when th clamping pressure applied to a workpiece is at some particula value. Figure 5.16 shows the symbol for a sequence valve, th valve switching on when the inlet pressure reaches a particula value and allowing the pressure to be applied to the system tha follows.

Figure 5.17 shows a system where such a sequential valve is used. When the 4/3 valve first operates, the pressure is applied to cylinder 1 and its ram moves to the right. While this is happening the pressure is too low to operate the sequence valve and so no pressure is applied to cylinder 2. When the ram of cylinder 1 reaches the end stop, then the pressure in the system rises and, at an appropriate level, triggers the sequence valve to open and so apply pressure to cylinder 2 to start its ram in motion.

5.5 Cylinders

The *hydraulic* or *pneumatic cylinder* is an example of a linear actuator. The principles and form are the same for both hydraulic and pneumatic versions, differences being purely a matter of size as a consequence of the higher pressures used with hydraulics. The cylinder consists of a cylindrical tube along which a piston/ ram can slide.

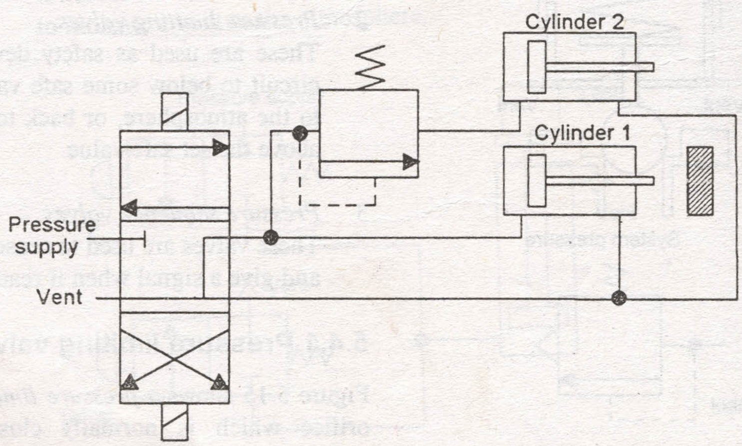

Fig. 5.17 Sequential system

vents to the atmosphere, or back to the sump. This can be used as a pressure relief valve to safeguard a system against excessive pressures.

5.4.2 Pressure sequence valve

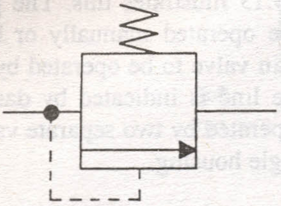

Fig. 5.16 Pressure sequence valve

With the pressure limiting valve of Figure 5.15, the limiting pressure is set by the pressure at the inlet to the valve. We can adapt such a valve to give a sequence valve. This can be used to allow flow to occur to some part of the system when the pressure has risen to the required level. For example, in an automatic machine we might require some operation to start when the clamping pressure applied to a workpiece is at some particular value. Figure 5.16 shows the symbol for a sequence valve, the valve switching on when the inlet pressure reaches a particular value and allowing the pressure to be applied to the system that follows.

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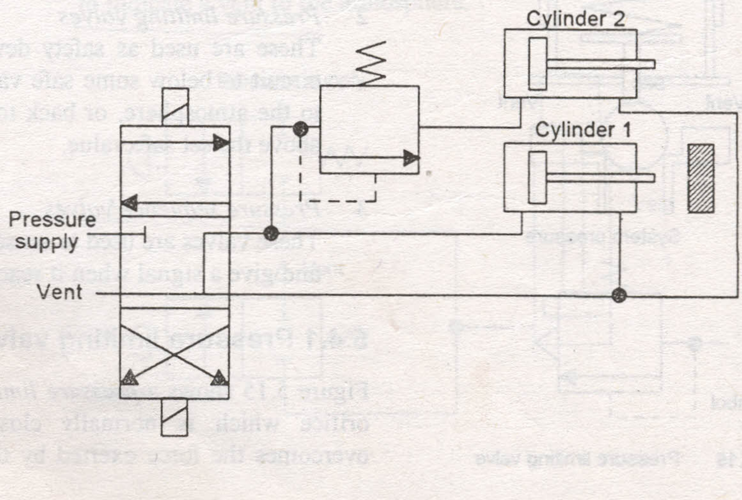


Fig. 5.17 Sequential system

The term *single acting* is used when the control pressure is applied to just one side of the piston, a spring often being used to provide the opposition to the movement of the piston. For the single-acting cylinder shown in Figure 5.18, when a current passes through the solenoid, the valve switches position and pressure is applied to move the piston along the cylinder. When the current through the solenoid ceases, the valve reverts to its initial position and the air is vented from the cylinder. As a consequence the spring returns the piston back along the cylinder.

The term *double acting* is used when the control pressures are applied to each side of the piston. A difference in pressure between the two sides then results in motion of the piston, the piston being able to move in either direction along the cylinder as a result of high pressure signals. For the double-acting cylinder shown in Figure 5.19, current through one solenoid causes the piston to move in one direction with current through the other solenoid reversing the direction of motion.

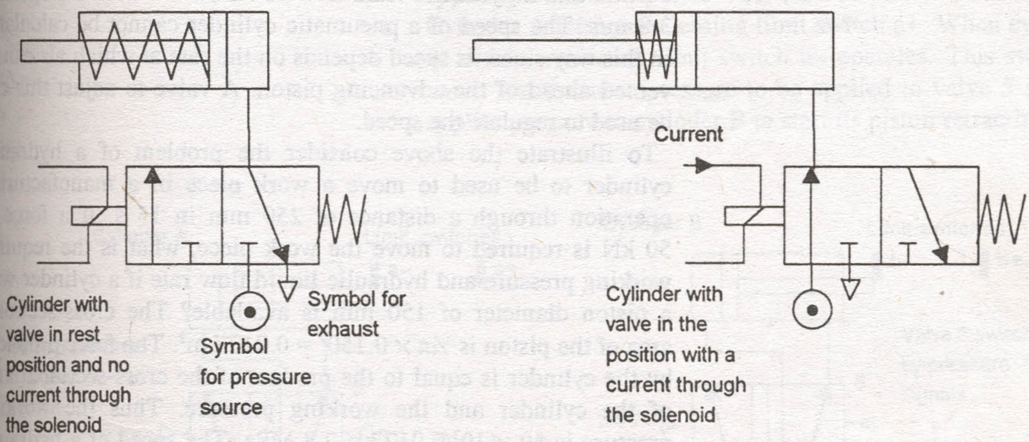


Fig. 5.18 Control of a single-acting cylinder

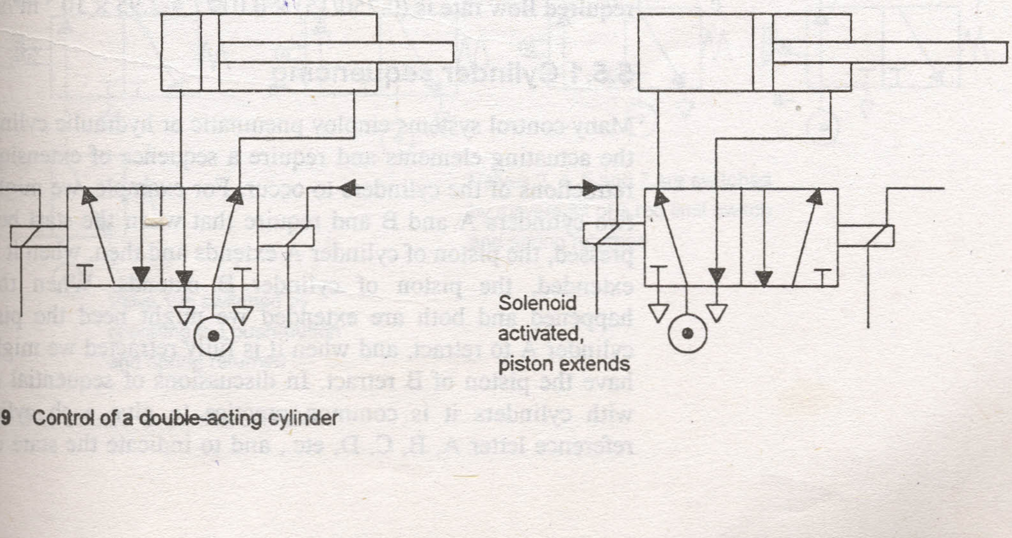


Fig. 5.19 Control of a double-acting cylinder

The choice of cylinder is determined by the force required to move the load and the speed required. Hydraulic cylinders are capable of much larger forces than pneumatic cylinders. However, pneumatic cylinders are capable of greater speeds. The force produced by a cylinder is equal to the cross-sectional area of the cylinder multiplied by the working pressure, i.e. the pressure difference between the two sides of the piston, in the cylinder. A cylinder for use with a working pneumatic pressure of 500 kPa and having a diameter of 50 mm will thus give a force of 982 N. A hydraulic cylinder with the same diameter and a working pressure of 15 000 kPa will give a force of 29.5 kN.

If the flow rate of hydraulic liquid into a cylinder is a volume of Q per second, then the volume swept out by the piston in a time of 1 s must be Q. But for a piston of cross-sectional area A this is a movement through a distance of v in 1 s, where we have $Q = Av$. Thus the speed v of a hydraulic cylinder is equal to the flow rate of liquid Q through the cylinder divided by the cross-sectional area A of the cylinder. Thus for a hydraulic cylinder of diameter 50 mm and a hydraulic fluid flow of 7.5×10^{-3} m^3/s the speed is 3.8 m/s. The speed of a pneumatic cylinder cannot be calculated in this way since its speed depends on the rate at which air can be vented ahead of the advancing piston. A valve to adjust this can be used to regulate the speed.

To illustrate the above consider the problem of a hydraulic cylinder to be used to move a work piece in a manufacturing operation through a distance of 250 mm in 15 s. If a force of 50 kN is required to move the work piece, what is the required working pressure and hydraulic liquid flow rate if a cylinder with a piston diameter of 150 mm is available? The cross-sectional area of the piston is $\frac{1}{4}\pi \times 0.150^2 = 0.0177$ m^2. The force produced by the cylinder is equal to the product of the cross-sectional area of the cylinder and the working pressure. Thus the working pressure is $50 \times 10^3/0.0177 = 2.8$ MPa. The speed of a hydraulic cylinder is equal to the flow rate of liquid through the cylinder divided by the cross-sectional area of the cylinder. Thus the required flow rate is $(0.250/15) \times 0.0177 = 2.95 \times 10^{-4}$ m^3/s.

5.5.1 Cylinder sequencing

Many control systems employ pneumatic or hydraulic cylinders as the actuating elements and require a sequence of extensions and retractions of the cylinders to occur. For example, we might have two cylinders A and B and require that when the start button is pressed, the piston of cylinder A extends and then, when it is fully extended, the piston of cylinder B extends. When this has happened and both are extended we might need the piston of cylinder A to retract, and when it is fully retracted we might then have the piston of B retract. In discussions of sequential control with cylinders it is common practice to give each cylinder a reference letter A, B, C, D, etc., and to indicate the state of each

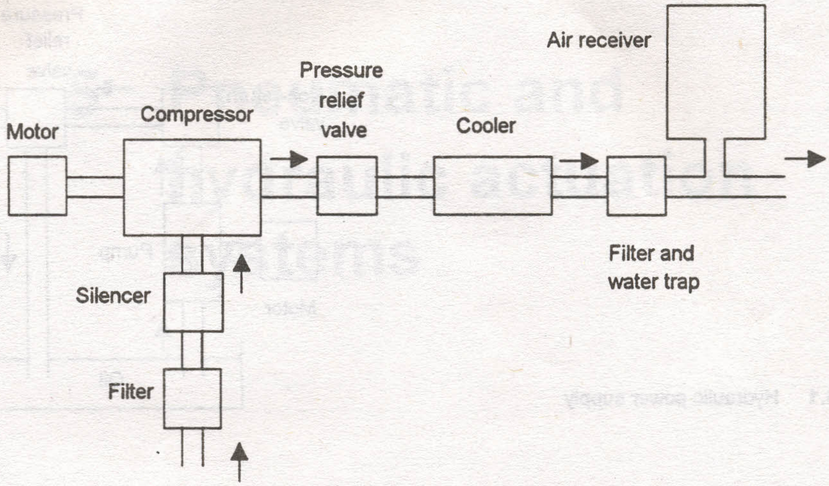


Fig. 5.3 Pneumatic power supply

5.3 Directional control valves

Pneumatic and hydraulic systems use directional control valves to direct the flow of fluid through a system. They are not intended to vary the rate of flow of fluid but are either completely open or completely closed, i.e. on/off devices. Such on/off valves are widely used to develop sequenced control systems (see later in this chapter). They might be activated to switch the fluid flow direction by means of mechanical, electrical or fluid pressure signals.

A common type of directional control valve is the *spool valve*. A spool moves horizontally within the valve body to control the flow. Figure 5.4 shows a particular form. In (a) the air supply is connected to port 1 and port 3 is closed. Thus the device connected to port 2 can be pressurised. When the spool is moved to the left (Fig. 5.4(b)) the air supply is cut off and port 2 is connected to port 3. Port 3 is a vent to the atmosphere and so the air pressure in the system attached to port 2 is vented. Thus the movement of the spool has allowed the air to firstly flow into the system and then be reversed and flow out of the system. *Rotary spool valves* have a rotating spool which, when it rotates, opens and closes ports in a similar way.

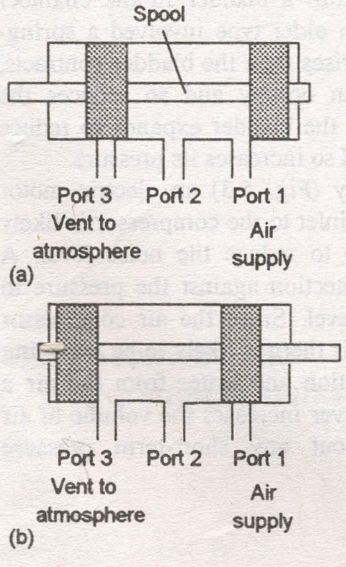


Fig. 5.4 Spool valve

Another common form of directional control valve is the *poppet valve*. Figure 5.5 shows one form. This valve is normally in the closed condition, there being no connection between port 1 to which the pressure supply is connected and port 2 to which the system is connected. In poppet valves, balls, discs or cones are used in conjunction with valve seats to control the flow. In the figure a ball is shown. When the push-button is depressed, the ball is pushed out of its seat and flow occurs as a result of port 1 being connected to port 2. When the button is released, the spring forces the ball back up against its seat and so closes off the flow.

5.3.1 Valve symbols

The symbol used for control valves consists of a square for each of its switching positions. Thus for the poppet valve shown in Figure 5.5, there are two positions: one with the button not pressed and one with it pressed. Thus a two-position valve will have two squares, a three-position valve three squares. Arrow-headed lines (Fig. 5.6(a)) are used to indicate the directions of flow in each of the positions, with blocked-off lines closed flow lines (Fig. 5.6(b)). The initial position of the valve has the connections (Fig. 5.6(c)) to the ports shown; in Fig. 5.6(c) the valve has four ports. Ports are labelled by a number or a letter according to their function. The ports are labelled 1 (or P) for pressure supply, 3 (or T) for hydraulic return port, 3 or 5 (or R or S) for pneumatic exhaust ports, and 2 or 5 (or B or A) for output ports.

Figure 5.7 shows examples of some of the symbols which are used to indicate the various ways the valves can be actuated. More than one of these symbols might be used with the valve symbol.

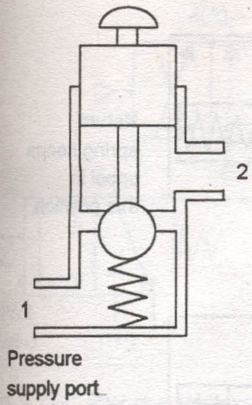


Fig. 5.5 Poppet valve

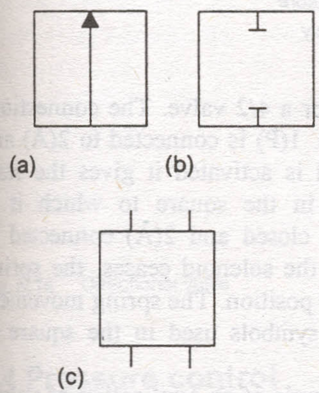


Fig. 5.6 (a) Flow path, (b) flow shut-off, (c) initial connections

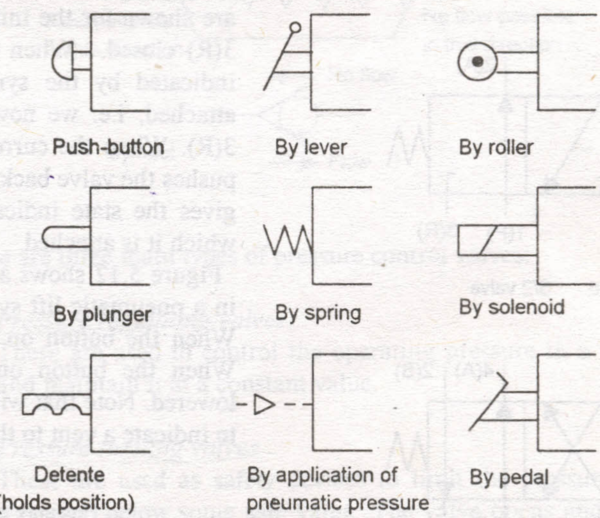


Fig. 5.7 Valve actuation symbols

As an illustration of how these various symbols can be combined to describe how a valve operates, Figure 5.8 shows the symbol for the 2 port 2 position poppet valve of Figure 5.6. Note that a 2 port 2 position valve would be described as a 2/2 valve, the first number indicating the number of ports and the second number the number of positions.

As a further illustration, Figure 5.9 shows a solenoid operated spool valve and Figure 5.10 its symbol. The valve is actuated by a current passing through a solenoid and returned to its original position by a spring.

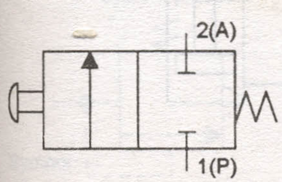


Fig. 5.8 2/2 valve

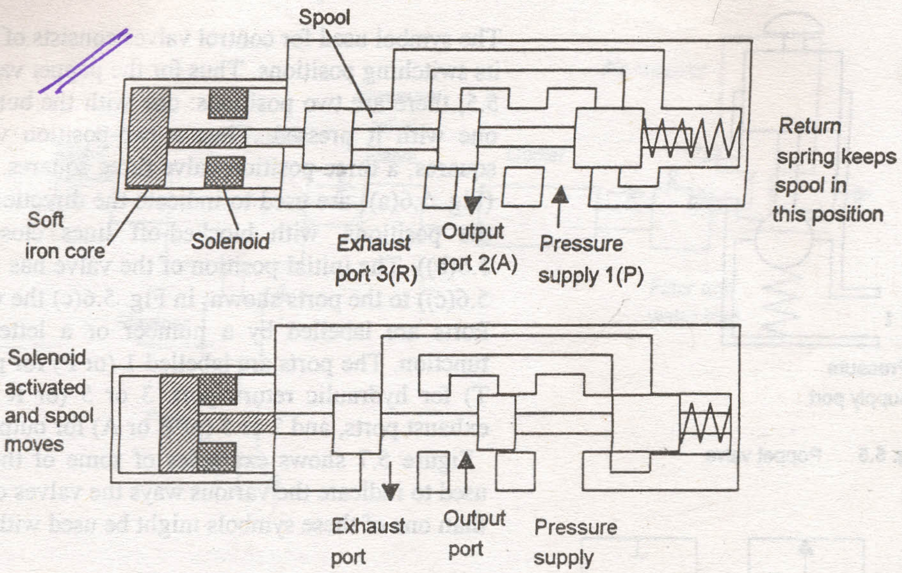


Fig. 5.9 Single-solenoid valve

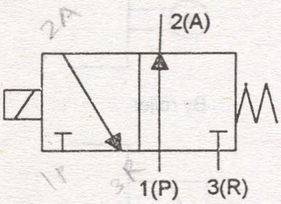


Fig. 5.10 3/2 valve

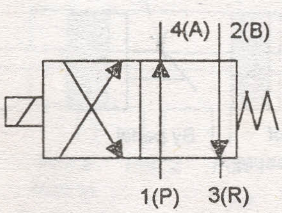


Fig. 5.11 4/2 valve

Figure 5.11 shows the symbol for a 4/2 valve. The connections are shown for the initial state, i.e. 1(P) is connected to 2(A) and 3(R) closed. When the solenoid is activated it gives the state indicated by the symbols used in the square to which it is attached, i.e. we now have 1(P) closed and 2(A) connected to 3(R). When the current through the solenoid ceases, the spring pushes the valve back to its initial position. The spring movement gives the state indicated by the symbols used in the square to which it is attached.

Figure 5.12 shows a simple example of an application of valves in a pneumatic lift system. Two push-button 2/2 valves are used. When the button on the up valve is pressed, the load is lifted. When the button on the down valve is pressed, the load is lowered. Note that with pneumatic systems an open arrow is used to indicate a vent to the atmosphere.

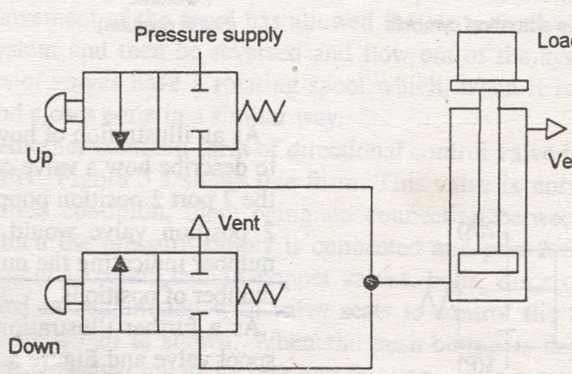


Fig. 5.12 Lift system

5.3.2 Pilot-operated valves

The force required to move the ball or shuttle in a valve can often be too large for manual or solenoid operation. To overcome this problem a *pilot-operated system* is used where one valve is used to control a second valve. Figure 5.13 illustrates this. The pilot valve is small capacity and can be operated manually or by a solenoid. It is used to allow the main valve to be operated by the system pressure. The pilot pressure line is indicated by dashes. The pilot and main valves can be operated by two separate valves but they are often combined in a single housing.

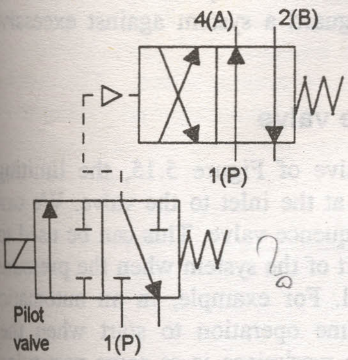


Fig. 5.13 Pilot-operated system

5.3.3 Directional valves

Figure 5.14 shows a simple *directional valve* and its symbol. Free flow can only occur in one direction through the valve, that which results in the ball being pressed against the spring. Flow in the other direction is blocked by the spring forcing the ball against its seat.

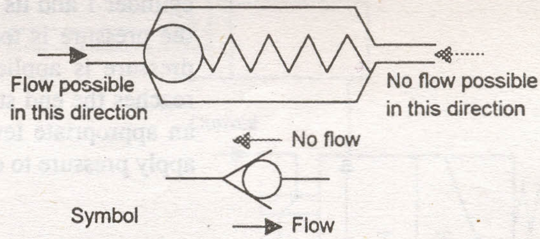


Fig. 5.14 Directional valve

5.4 Pressure control valves

There are three main types of pressure control valves:

1 *Pressure regulating valves*
These are used to control the operating pressure in a circuit and maintain it at a constant value.

2 *Pressure limiting valves*
These are used as safety devices to limit the pressure in a circuit to below some safe value. The valve opens and vents to the atmosphere, or back to the sump, if the pressure rises above the set safe value.

3 *Pressure sequence valves*
These valves are used to sense the pressure of an external line and give a signal when it reaches some preset value.

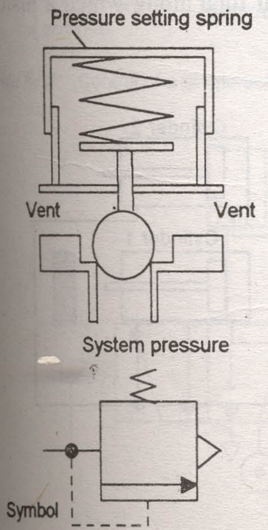


Fig. 5.15 Pressure limiting valve

5.4.1 Pressure limiting valve

Figure 5.15 shows a *pressure limiting/relief valve* which has one orifice which is normally closed. When the inlet pressure overcomes the force exerted by the spring, the valve opens and

5

RADIO FREQUENCY CABLES : Conducting and Insulating Materials

5.1 INTRODUCTION

The radio frequency cables are used to carry radio frequency power of signals from some distance. The choice of a suitable r. f. cable depends on its application, r.f. TV, radio transmission, r. f. carrier telephone equipment. The choice must take into account the circumstances in which the equipment is used. The standard cables are used. Plugs and sockets are also standardised so that replacement is easy.

5.1.1 Co-Axial or Twin Cables

There are mainly two types of cables. (i) Co-axial; (ii) twin core. For almost all applications, co-axial cables are better than twin core cables. For a given attentuation and power rating, the size of the co-axial cable is about half that of twin core cable. Characteristic impendance, attenuation and electrical length are stable. Twin core cable is used at low frequency where the screening of balanced twisted pair is better than that of a co-axial cable; and in simple applications where balanced transformer is to be connected such as a dipole.

5.2 CHARACTERISTICS OF CABLES

5.2.1 Characteristics Impendance of Cable

The internationally accepted standards are 50 ohms and 75 ohms. The cable with 50 ohms impedance gives a good compromise between the requirement of a power rating and attenuation. The cable with 75 ohms impedance is used where a low attenuation is required. In applications where very low capacitance cables are required, characteristic impedances of 100 ohms and 125 ohms are used.

5.2.2 Size of Cable

Size of cable is chosen mainly by consideration of attenuation and power or voltage handling capacity. The attenuation decreases linearly with cable diameter. The power and voltage ratings increase linearly with the cable diameter. The weight and cost increase as square of the diameter. To keep the cost lower, size should be small. But from mechanical consideration, it should be large. Standard sizes should be used so that standard fittings are available and maintenance is easy. Non-standard fittings are costly.

5.3 CONSTRUCTION OF R. F. CABLES

5.3.1 Single or Stranded Inner Conductors

Single conductors are more likely to break than stranded ones. In stranded conductors, however, there are greater losses and lower voltage ratings. The best solution is thus to use copper clad steel conductor or barylium copper conductors. Fig. 5.1 shows different shapes of conductor fittings.

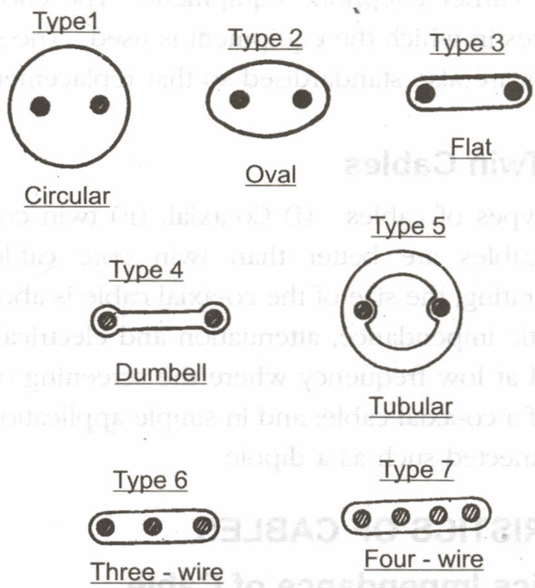


Fig. 5.1 Shapes of conductor fittings

5.3.2 Type of Dielectric

Air spaced or semi-air spaced dielectric gives minimum attenuation and capacitance, e.g. dielectric formed by polythene threads and tubes. These have disadvantage that they change their characteristics due to moisture absorption and can be easily crushed. Solid polythene dielectrics are robust and not susceptible to moisture. These can be used in ordinary applications.

5.3.3 Outer Conductors

Pipes of lead, aluminium, copper give the best screening and offer lowest loss. Lead sheathed cable is much heavier but is more stable. Braided wire or tape outer conductors are flexible, light weight but more costly. Silver plating wires gives reduction in attenuation at frequencies in the band 5,000 to 10,000 MHz.

5.3.4 Outer Sheaths

The material used for outer sheaths are P V C polythelene and nylon. P V C is the most popular and is available in three grades : (i) General purpose grade. This is flexible. (ii) Artic grade : This is used in cables to be flexed in temperatures between -30C to -40C. (iii) Non-contaminating grade : This is recommended for cable operating above 600 MHz. Polythene sheaths have good electrical and mechanical properties but sometimes present fire hazards. Nylon sheaths are tough and used for cables installed in fuel oil tanks.

5.3.5 Armour

The armour gives protection against rough treatment. There are three types of armours used. (i) braid. (ii) tape and (iii) wire armour. Braid armour is formed of steel or aluminium alloy wire and is light and flexible. It gives protection against abration. Steel tape gives protection against crushing. Steel wire armour gives tensile strength to the cable.

5.3.6 Protective Servings

Paper impregnated with bituminous compounds are used over outer conductors. These give protection from corrosion. P V C sheath gives better overall protection and is clean for handling.

5.3.7 Anti-Termite Protection

Various poisons are introduced into P V C sheathing compound.

5.4 HIGH TEMPERATURE CABLES

There are two types of high temperature cables.

(i) with P T F E

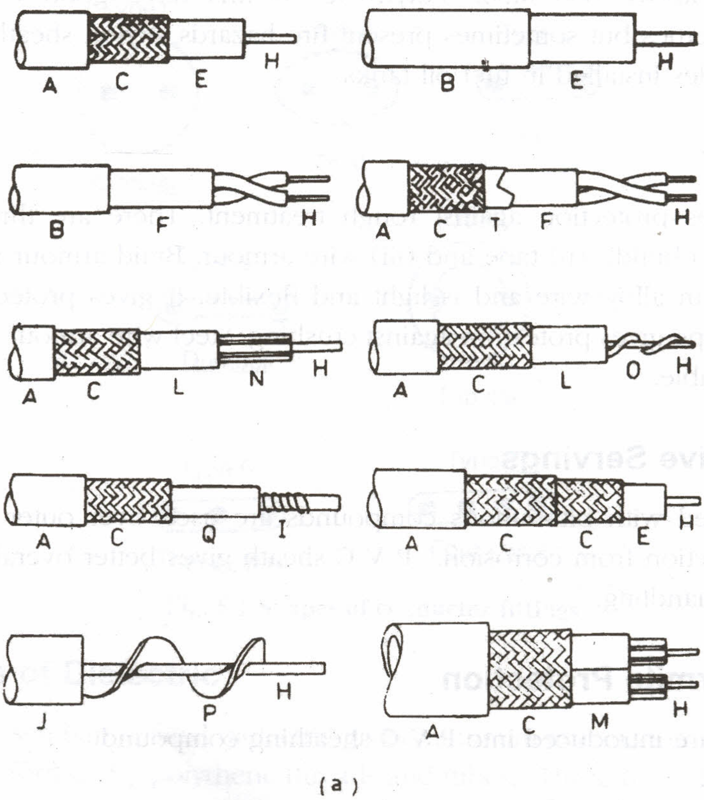
(ii) with mineral insulation

(i) are light, flexible and suitable for use in temperature upto 200°C.

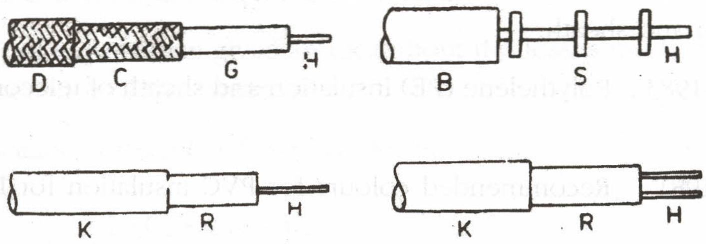
(ii) are heavy and rigid and can be used at temperature upto 400C. These cannot be used at frequencies above 200 MHz because they have irregular local impedance.

5.5 LOW IMPEDANCE CABLES

Low impedance cables with 14 ohms impedance are used in matching stubs. This is achieved by larger inner conductor formed by a wire braid over plastic wire. Their characteristics are sensitive to small changes in conductor diameter. Thus, two or three small cables of 50 ohms or 75 ohms can be used in parallel. Fig. 5.2 shows some types of cables.



(a)



(b)

Fig. 5.2 Some types of cables

A. PVC sheath; B. Lead sheath; C. Wire braid; D. Glass fibre braid; E. Polythene core; F. Polythene cores filled to circular sector, G. P T F E Core; H. Inner conductor; I. Helical inner conductor; J. Aluminium tube; K. Copper tube; L. Polythene tube; M. Polythene tube and fin cores; N. Polythene star; O. Polythene thread; P. Polythene helix; Q. Polythene insulation; R. Mineral insulation; S. Plastics spacers; T. Metallized paper tape.

5.6 STANDARDISATION OF CABLES

5.6.1 International Standardisation

I E C standardisation for characteristic impedance and diameter of r. f. cables are given in the standard. For military purposes, the standardisation is by N A T O.

5.6.2 National Standardisation

Indian standards Institute has prepared standards for cables and wires for LF and RF. The following standards give the information :

IS 9943-1981 Co-axial cables radio frequency, characteristic impedances and dimensions.

Flexible co-axial, radio frequency cables with characteristic impedance 50 ohms: IS 5801 (Part 1, 2, 3) 1970.

IS 5802 (Part 1, 2) 1970 : Flexible co-axial ratio frequency cables with characteristic impedance of 75 ohms.

IS 5026 (Part 1) 1969 : General requirements and tests for radio frequency cables.

IS 5608 (Part 1 to 6) 1970 : Low frequency wires and cables with P V C insulation and sheath.

IS 10579-1983 : Polythelene (PE) insulation and sheath of telecommunication cables.

IS 9938-1981 : Recommended colours for PVC insulation for LF wires and cables.

IS 8080-1976 Silver coated copper wire.

IS 9567-1980 Tin or Tin lead coated copper wire.

5.7 MEASUREMENT OF TEST PARAMETERS

5.7.1 In Line Spark Test

At the time of insulation covering, the cable is passed through a high voltage system, comprising of fine link mesh which can detect any electrically weak points on insulation sheath.

5.7.2 Voltage Test on Dielectric

High voltage as per specification is applied between the inner conductor and screen for a specified time. The cable should withstand it without any breakdown. The frequency of voltage applied is 40 to 60 cycles/sec. And the rate of increase of test voltage should not exceed 2 kV second. Unscreened cables are immersed in water for 1 hour and test voltage is applied between conductor and water.

5.7.3 Insulation Resistance

A direct voltage of 500 V ± 50 V is applied between conductor and insulation system for 1 minute ± 5 sec. Then insulation resistance is measured between inner conductor and outer conductor. For co-axial cables, this should not be less than 750,000 ohms per 30 metres at room temperature.

5.7.4 Conductor Resistance

Resistance of each inner conductor should be measured with direct current and its value corrected to a temperature of 20°C.

5.7.5 Capacitance Measured at 1 KHz

Measurement of capacitance gives an idea about the losses in r.f. cables and also to calculate impedance of the system.

Capacitance of screened twin cables is

$$C = \frac{2\,(C_a + C_b) - C_c}{4} \qquad (5.1)$$

Where C_a = Capacitance per unit length between conductor A and conductor B connected to screen.

C_b = Capacitance per unit length between conductor B and conductor A connected to screen.

C1 = Capacitance between conductors A and B connected to screen.

5.7.6 Corona Discharge Test

Corona

When altering potential between two parallel conductors increase beyond a certain limit, a point is reached when a pale violet glow appears on the conductor surface. This phenomenon is termed 'Corona' and is accompanied by hissing noise. The luminous envelope surrounding the conductors is composed of air which has become ionised and become conducting due to effect of high electrostatic stress. The breakdown occurs at the surface of the conductors and the effect of corona is equivalent to increasing the effective diameter of the conductors. Corona is accompanied by power loss and there is flow of current due to corona.

A specimen of 1 metre length is subjected to gradually increasing voltage until corona is detected. This voltage reading is known as inception voltage. Similarly, voltage is decreased until corona extinction voltage is observed. Test voltage = 300 V and the rate of increase of voltage is 50 V sec.

5.7.7 Attenuation Measurement at 200 MHz and 400 MHz

The test set up is shown in Fig. 5.3

V H F oscillator is used as a signal generator. Low pass filter is used at the output of V H F oscillator to filter the harmonics from passing through the cable. V H F oscillator is used to generate exactly 30 MHz. Mixer is used to hyterodyne, the above two frequencies, to give a beat frequency of 30 MHz. The output of mixer is given to input of I F amplifier. I F amplifier is tuned to 30 MHz to give maximum deflection. The connections are done as shown in the Figure. A certain reading is obtained on I F amplifier without inserting cable. The cable is inserted and the new reading is obtained. The difference between new and previous reading is attenuation loss in *db*.

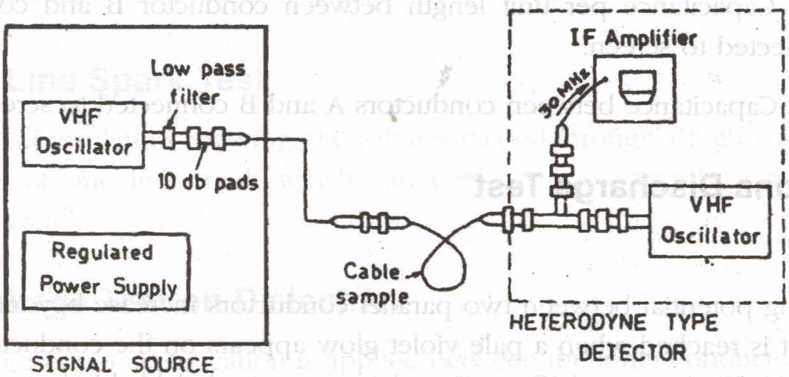


Fig. 5.3 Attenuation measurement set up

5.7.8 Mean Characteristic Impedance

The characteristic impedance is defined as the impedance seen at the input of an infinite cable. Mean characteristic impedance is the arithmetic mean of local characteristic impedance along the length of cable.

$$Z_m = \frac{1017}{\frac{V}{c} \times C} \text{ ohms}$$

Where $\frac{V}{c}$ = velocity ratio; C = Capacitance in farads.

5.7.9 IS for Radio Frequency Cables

Part I General requirements and tests

IS 5026 (Part I) 1969

Electrical tests

Resistivity of inner conductor(s)

Dielectric strength of core

Insulation resistance

Spark test

Discharge test (Corona test)

5.7.10

The characteristics of flexible polyethylene co-axial cables and Teflon cables are shown in Fig. 5.4 for the following sizes :

RG - 178 Teflon

RG - 188 Teflon

RG - 122 Type

RG - 58 Type

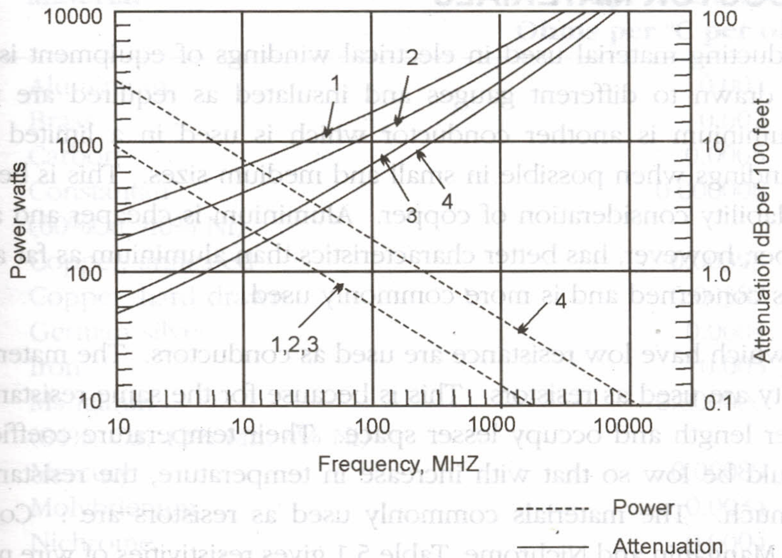


Fig. 5.4 Power rating and attenuation of flexible polyethylene co-axial cables

5.8 APPLICATIONS OF R.F. CABLES

1. Low attenuation, low capacitance cables are used in transmission of R.F. power or reception of weak R.F. signals.
2. Gas filled cables are used to avoid moisture and increase attenuation for high power transmission.
3. Low noise cables are used in space craft signal conditioner.
4. Used for smooth radio transmission and reception in underground mines.
5. Used in application as multiplexed teledata acquisition.

5.8.1 Future Developments in R.F. Cables

1. Polythene cables which are light weight, cheaper and have improved performance.
2. Extruded PTFE cables used for S H F equipments.
3. Miniature cables used for airborne equipment.
4. Optical fibre cable used for R F communication which is lossless and saves space.

5.9 CONDUCTOR MATERIALS

The main conducting material used in electrical windings of equipment is copper. Copper wires drawn to different gauges and insulated as required are used for windings. Aluminium is another conductor which is used in a limited way for transformer windings when possible in small and medium sizes. This is because of costs and availability consideration of copper. Aluminium is cheaper and available in India. Copper,. however, has better characteristics than aluminium as far as its use as conductor is concerned and is more commonly used.

The materials which have low resistance are used as conductors. The materials with higher resistivity are used as resistors. This is because for the same resistance, they will need lesser length and occupy lesser space. Their temperature coefficients of resistance should be low so that with increase in temperature, the resistance does not increase much. The materials commonly used as resistors are : Constantan German silver, Manganin and Nichrome. Table 5.1 gives resistivities of wire materials. Table 5.2 temperature coefficients of resistance of conductor materials.

Table 5.1

Resistivities of Wire Materials

Material	Resistivity ^{p} ohm-meter at 20°C
Aluminium	2.83×10^{-8}
Brass	7×10^{-8}
Constantan (40% Ni, 60% Cu)	49×10^{-8}
Copper, hard drawn	1.77×10^{-8}
Copper, annealed	1.724×10^{-8}
German silver (18% Ni)	33×10^{-8}
Lead	$22\ 10^{-8}$
Manganin (84% Cu, 12% Mn, 4% Ni)	44×10^{-8}
Nichrome	100×10^{-8}
Nickel	7.8×10^{-8}
Platinum	10×10^{-8}
Silver	1.64×10^{-8}
Tungsten	5.5×10^{-8}

Table 5.2

Resistivities of Wire Materials

Material	Temperature coefficient ^{p} Ohms per °C per ohm at 20 °C
Aluminium	0.004
Brass	0.002
Carbon	0.0005
Constantan (60%Cu, 40% Ni)	0.000008
Copper, annealed	0.00393
Copper, hard drawn	0.00382
German silver	0.0004
Iron	0.005
Manganin (84%, Cu, 12% Mn, 4% Ni)	0.000006
Mercury	0.00089
Molybdenum	0.0034
Nichrome	0.0004
Nickel	0.006

Platinum	0.003
Silver (99.98% pure)	0.0038
Steel, soft	0.0042
Tin	0.0042
Tungsten	0.0045

5.10 INSULATING MATERIALS : CLASSIFICATION

The insulating materials are grouped into the following classes. This is mainly on the temperature that the types of insulating materials will withstand or it is thermal classification. This is done as per 1.S. 1271-1958 and is given in Table 5.3.

Class Y insulation consists of materials or combinations of materials, such as cotton, silk and paper without impregnation.

Class A insulation consists of materials or combinations of materials such as cotton, silk and paper when suitably impregnated or coated or when immersed in a dielectric liquid such as oil.

Class E insulation consists of materials or combinations of materials which by experience or accepted tests can be shown to be capable of operation at class E temperatures, i.e. 15C higher than class A materials.

Table 5.3

Thermal classification of Insulating Materials

Class	Temperature
Y	90°C
A	105°C
E	120°C
B	130°C
F	155°C
H	180°C
C	Abover 180°C

Class B insulation consists of materials or combinations of materials such as mica, glass fibre, asbestos, etc. with suitable binding substance.

Class F insulation consists of materials or combinations of materials such as mica, glass fibre, asbestos, etc. with suitable binding substances as well as other materials, not necessarily inorganic, which by experience or accepted tests can be shown to be capable of operation at class F (25°C higher than Class B materials).

Class H insulation consists of materials such as silicone elastomer and combinations of materials such as glass, fibre, mica, asbestos, etc. with suitable binding substances, such as appropriate silicon resins.

Class C insulation consists of materials or combinations of materials such as mica, poreclain, glass and quartz with or without an inorganic binder.

5.10.1 Insulation Requirements

(i) The insulation must have a 'galvanic separation' from the apparatus components at varying potentials. This must be achieved under high temperature fluctuations without influence from humidity, dirt or corrosive chemical surroundings.

(ii) The insulation must withstand mechanical stresses.

(iii) The insulation should be as thin as possible so that active copper and core materials in the equipment could be put to use in the best way.

(iv) The insulation should be able to conduct heat generated in the apparatus for proper dissipation.

(v) The insulation should be as non-hygroscopic as possible.

(vi) The insulation must be able to withstand the transient high voltage surge subjected on power supply.

5.10.2 Phenolic Materials

(i) Bakelite

They consist of a solution of reaction product of phenol and formal dehyde in a solvent. They are low cost non-hazardous and non-toxic. They are used in laminates for copper clad PCB. They are attacked by strong alkalies, but acids have no effect. They have poor arc resistance. They are made with good resistance to moisture absorption but of lower order compared to epoxy laminates.

(ii) Paper phenolic

Insulation resistance	35 x 10^6 Magohms
Volume resistivity	10^4 to 10^7 Megohms
Dielectric strength	10-32 kV/mm
Dielectric constant at 1 MHz	3 to 6
Dissipation factor at 1 MHz	0.02 to 0.08
Arc resistance	4 to 75 sec.

(iii) Epoxy resins

Epichlorohydrin and bivalent phenol is reacted to give the base resin. It has low shrinkage, toughness, good adhesion, good mechanical properties, high alkali and acid resistance, high dielectric strength, arc and tracking resistance and excellent resistance to water absorption. They are hard to machine. Combination of glass with epoxy gives high mechanical strength.

5.11 WIRES

5.11.1 Wire Conductors

Wires are needed for (I) wiring various electronic components; (ii) R F cables (iii) winding or magnet wires and (iv) resistance wires

Conductors used for wires are of copper because of its low resistivity, ductility, uniformity and reasonable cost. In certain applications, aluminium may be used as conductors. Such applications are large busbars and high gauged enamelled wires. The main disadvantage of aluminium is that it cannot be soldered easily with soldering gun. Therefore, joint between two wires is loose and may introduce noise. Special ultrasonic guns are used for soldering aluminium. Table 5.4 shows comparison of copper and aluminium.

Table 5.4

Comparison of Copper and Aluminium

	Copper	Aluminium
Density gm/cm3 at 20°C	8.89	2.703
Melting point °C	1083	657
Thermal conductivity Cal/cm-sec. deg. C	0.923	0.503
Coefficient of linear expansion (covers range of 0 to 150°C)	0.000017 per deg. C	23 x 10-6 per deg. C at 20°C
Electrical resistivity micro-ohms-cm at 20°C	1.724	2.8
Temperature coefficient of resistance per deg. C at 20°C.	0.0039	0.004

Pure aluminium is more resistant to acid and gases while copper gets corroded. Tensile strength of aluminium is low. Aluminium wires are available upto 40 gauge. For fine gauge wires and for high speed machines, copper is used. The resistivity of aluminium is more, so more space is required for aluminium windings. The cost of aluminium is 1/3 that of copper. The aluminium can be rolled, drawn and annealed in the same way as copper.

The conductors used are single strand or multistrand. Single stranded conductors are used as hook up wires or in transformer windings. Multistrand conductors are used for general purpose chasis wiring. Multistrand conductors are of two types. (I) Twisted type : A number of wires are twisted. (ii) Concentric stranding : A straight wire is used as a core and a number of layers of wires are twisted round it. Multistrand wires are used in applications where vibrations or shocks are present. If puncture occurs in one strand, the other strands complete the circuit.

5.11.2 Resistance Wires

Alloys used for resistance wires are Nickel, Chromium, Copper-Nickel. These metals are alloyed with small percentage of iron, aluminium, cobalt, manganese to obtain better stability and tensile strength. Desired properties are high resistivity for large cores section, stability of resistance with temperature, chemical and physical inertness, high tensile strength in small diameters, low thermoelectric effect, when connected with other metals. Cross sections are in form of strip, ribbon, round and rectangular.

Insulations available are oxidised surface, Oleo-resinous enamel, wrapped silk and cotton, fibre glass, glass fibre, ceramic, etc.

Applications

Precision resistors : Temperatures stable alloys are used for high values and Cu-Ni alloys are used for lower values.

H F Types : Thin film resistors, strip line assemblies are used at h.f.

High Power : Ceramic composition type is used.

Ballast resistance : Positive temperature coefficient resistance is used for protection of circuits.

High purity Ni-iron is used in protecting voltage regulator circuits.

5.12 OTHER MATERIALS

(i) Carbon : Carbon is used in microphones. Its resistance decreases when compressed. The temperature coefficient of carbon is negative. It is used in making welding electrodes.

(ii) Lead : Lead sheaths are used to protect insulation of cable from moisture. It is also used in plates of lead acid accumulator.

(iii) Tin : It is used for low current fuses.

(iv) Electrical Contact materials : Copper, molybdenum, nickel, palladium, platinum, silver and tungsten are the different contact materials used. Silver offers low contact resistance. Addition of copper reduces its cost. Addition of tungsten gives high thermal and electrical conductivity, low contact resistance and high resistance to oxidation, high melting point and high resistance to electrical corrosion.

Such contacts are used in relays, generator cutouts, etc. Silver and gold is used for end connection of ICs and PCBs. Internal connections of ICS are connected to external pins which are of 0.024 mm. diameters. This is connection by gold or aluminium bonding wire. Gold wire permits ball bonding. Aluminium wires are used in ultrasonic and thermal compensation wire bonding.

(v) Phosphorus : These can be excited by electrons, ions or optically. These are class II or IV compounds.

The screen of TV is coated with phosphorous. When excited with high speed electrons, they are visible. Various lights are available depending upon spectral wave-length, i.e. violet, green, yellow, etc. P 4 type of screen is used in TV picture tubes. Persistance is medium or short. Delay time 1/2 sec. Fluorescence is white. Phosphoruscence is white or blue-white. Saturation, brightness, uniformity factor, resolution, writing speed, erase time, viewing time, shades provided are the important parameters of phosphorus used in TV.

5.13 WIRES : MANUFACTURING

5.13.1 Process of Manufacturing

Copper bars are hot-rolled to reduce its cross section to a suitable size. IT is then dipped in sulphuric acid to remove oxide, passed through neutralising bath and finally water-washed. Next, the rod is inserted in drawing dies and pulled to reduce diameter. Such 13 or more dies may be used successively. Annealing means slow heating upto 400°C in an inert atmosphere and slow cooling in normal atmosphere. This process of annealing is necessary after each drawing for removing internal stresses and springy nature of wire. A wire 3/22 means wire with three strands each of 22 gauge.

5.13.2 Current Carrying Capacity of Wires

The cross-sectional area of conduction decides its current carrying capacity. When current I flows through a wire, its power dissipation is I2R. If this power is not propagated to atmosphere because of low cross section, the temperature of wire rises. It may also damage the covering.

5.13.3 Twin Core-Multicore Wires

In applications where a number of connections are to be connected, it is convenient to use multicore wires. The examples of such connections are supply plug wire connection, CRO cables, communication receiver cables.

5.14 WIRE COVERINGS

For general purpose flexible wires, rubber insulating covers are used. The winding magnet wires are covered with Oleo resinous enamels. PVC, teflon coverings are used to give high insulation and thus low loss.

5.14.1 Process of Manufacturing : Rubber Coverings

The basic material is mixed with the necessary plasticizers and pigments in a suitable mixer and resultant mix is put into a pre-heating mixer. Then it is fed into a heated hopper of the extruder and then forced along the barrel of the machine by a worm or screw drive. The wire to be covered is pulled through the extruder and heated material impinges on it at right angles to its direction of movement. The wire covering is then covered with french chalk and rolled on drums.

Winding Wire Coverings

The Oleo resinous enamels are applied by successively applying the resin and then backing thermostatically controlled oven.

5.15 WIRE SLEEVINGS

Single stranded conductors may sometimes be used with sleeves. Two or more wires may be used with their covers and additional sleeves to provide screening. Wire sleevings are of three types :

(i) Silk, (ii) Glass and (iii) High temperature ceramic coverings.

(i) Silk

Silk is suitably impregnated and cut into 90 cm. strips. The strip is rolled on a mandrel of size equal to internal diameter required. The rolled tube on mandrel is heated and then cooled. Mixed colours can be obtained by mixing initial fabrics

(ii) Glass

Glass is melted in platinum crucible. The base of crucible has a number of holes thus molten glass coming out forms fibres when cooled. These fibres are passed through rollers to remove tension. The glass sleeving is manufactured by passing glass fibre on multi-spindle machines. Then they are cooled with varnishes.

(iii) High temperature ceramic coverings

In high temperature and flame-proof applications, ceramic sleevings are used. Powder of magnesium oxide is moulded into cylinders under great pressure. This cylinder has as many holes as the number of sleeves required. These cylinders are then dehydrated in a furnace. Solid uncoated copper rods are then inserted in the holes. The ends of copper are sealed. The assembly undergoes successive drawing and annealing.

5.16 MANUFACTURING OF RESISTANCE WIRE

The material used for resistance wire is nickel-chromium or copper-nickel alloy. It is manufactured by drawing a small diameter rod by passing through a series of dies. While passing through each die, diameter reduces and length increases. The drawing process hardens the core and reduces ductility. Annealing in reducing atmosphere is then carried out.

5.17 WIRE TABLES

IS : 4800 (Part I) 1968 gives specifications for enamelled round winding wires.

Copper conductor shall be of high conductivity annealed copper. The IS standard gives details of the various copper and aluminium round conductors normally used. The sizes covered are for conductors of 0.020 mm. diameter to 5 mm. diameter. Table 5.5 shows some conductors and their resistance for illustration.

Aluminium conductors used are from 0.2 mm. diameter to 5 mm. diameter. Material for aluminium conductor shall be electrolytic high conductivity annealed aluminium. The physical properties of copper and aluminium are already mentioned in Table 5.4.