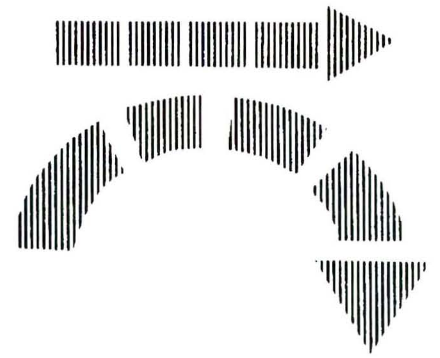
CHAPTER 6

Hydraulic Actuators

Hydraulic actuators convert hydraulic working energy into mechanical working energy. They are the points where all visible activity takes place and one of the first things to be considered in the design of a machine.



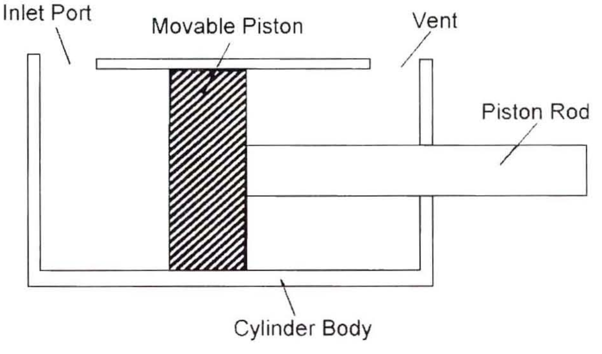
Hydraulic actuators can be divided into basically two types: linear and rotary.

cylinders

Hydraulic cylinders transform hydraulic working energy into a straight-line or linear mechanical energy which is applied to a movable resisting object to perform work.

what cylinders consist of

Cylinders have been briefly touched on earlier. It was shown that a cylinder basically consists of a cylinder body, a closure at each end, and a movable piston attached to a piston rod. At one end, the cylinder body has an inlet port by which fluid enters the body, the other end is vented.



cylinder force

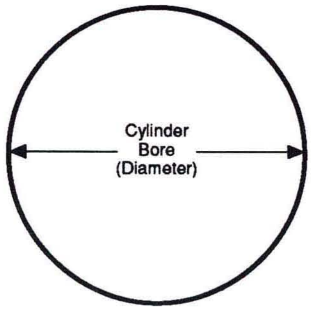
Through the stroke of a cylinder, hydraulic working energy is applied to the area of its movable piston. The pressure component of working energy applied to the piston will be no more than the resistance which a load offers.

Many times it is required to know what the pressure must be at a certain size cylinder to develop a particular output force. To determine this pressure, the following formula is used: (neglecting friction)

$$\text{pressure} = \frac{\text{force}}{\text{area}}$$

[P = F/A]

When the formula was used previously, the area and pressure, or the area and force were given. But, many times just the bore (diameter) of the cylinder is known, and the area must be calculated. This calculation is as easy to make as the calculation for the area of a square.

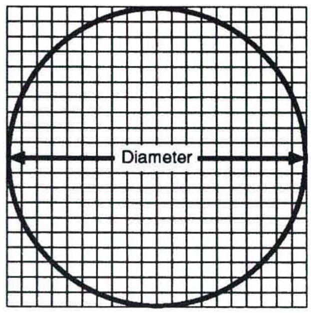


area of a circle

It is a fact that the area of a circle is exactly 78.54% of the area of a square whose sides are the length of its diameter (D).

To determine the area of a circle, multiply the circle diameter by itself and by .7854.

$$\text{circle area} = \text{diameter}^2 \times .7854$$



Another commonly used formula is:

$$\text{circle area} = \frac{(\pi)(D^2)}{4}$$

cylinder stroke

The distance through which working energy is applied determines how much work is done. This distance is the cylinder stroke.

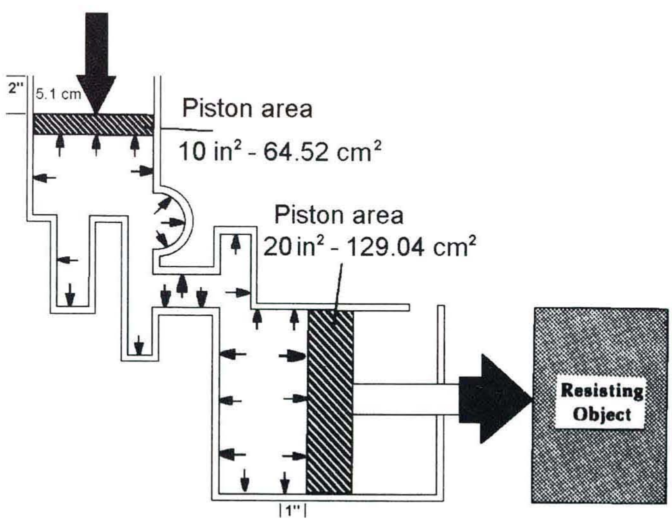
It has been illustrated that a cylinder can be used to multiply a force by the action of hydraulic pressure acting on a piston area.

When multiplying a force hydraulically, it appeared that something was received for nothing. It appeared that a smaller force could generate a larger force under the right circumstances, and nothing was sacrificed. This is relatively true in a static system. But if the force were to be multiplied and moved at the same time, something would be sacrificed — distance.

cylinder volume

Each cylinder has a volume (displacement) which is calculated by multiplying its stroke in inches by the square inch area of the piston. This will give a volume of so many cubic inches (cubic centimeters).

cylinder volume	= piston area	x stroke
(in^3)	(in^2)	(in.)
(cm^3)	(cm^2)	(cm)



In the illustration, the top piston must move through a distance of 2" (5.08 cm) to make the cylinder piston move 1" (2.54 cm). In both instances, the work done is the same. The top piston displaces 20 in^3 (327.8 cm^3) of liquid, and the lower cylinder piston is displaced by 20 in^3 (327.8 cm^3) of liquid.

piston rod speed

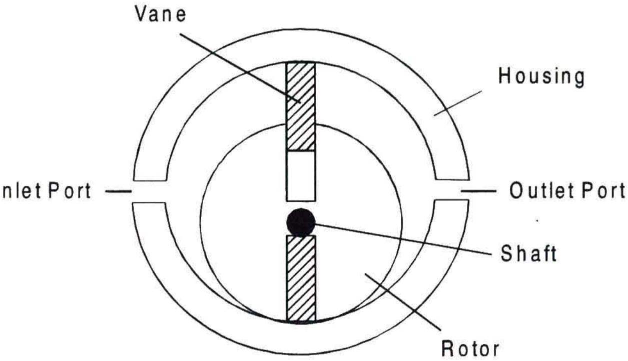
The rod speed of a cylinder is determined by how quickly the volume behind the piston can be filled with liquid. The expression which describes piston rod speed is:

$$\text{rod speed (in./min.)} = \frac{\text{gpm} \times 231}{\text{piston area (in}^2\text{)}}$$

$$\text{rod speed (m/sec)} = \frac{\text{lpm} \times .1667}{\text{cm}^2}$$

hydraulic motors

Hydraulic motors transform hydraulic working energy into rotary mechanical energy, which is applied to a resisting object by means of a shaft.

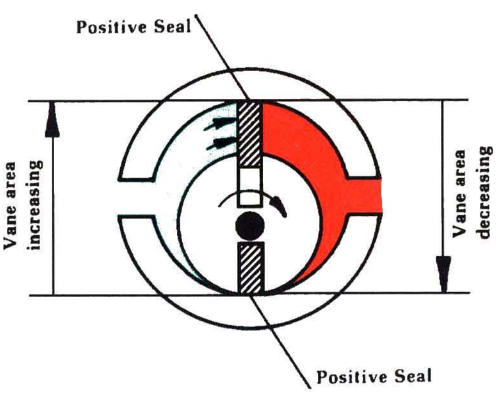


what motors consist of

All motors basically consist of a housing with inlet and outlet ports and a rotating group attached to a shaft. The rotating group in the particular vane type motor illustrated consists of a rotor and vanes which are free to slide in and out.

how motors operate

The rotating group of the motor is positioned off-center to the housing. The shaft in the rotor is connected to an object which offers a resistance. As fluid enters the inlet port, hydraulic working energy acts on any part of a vane exposed to the inlet port. Since the top vane has more area exposed to pressure, the force on the rotor is unbalanced and the rotor turns.

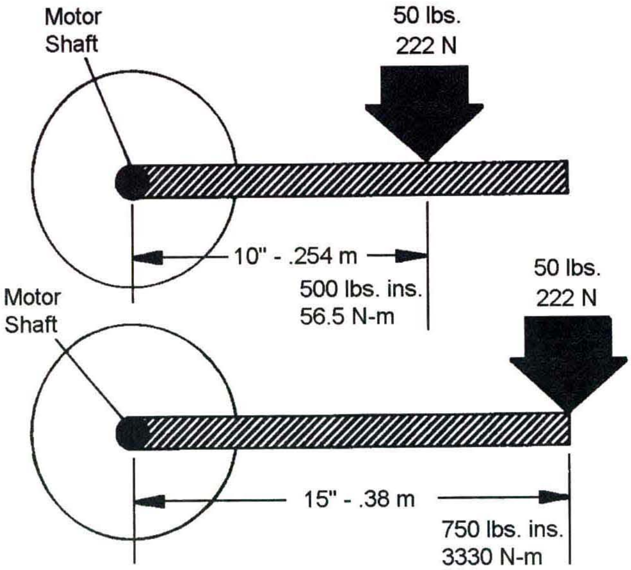


As the liquid reaches the outlet port where a decreasing volume is present, the liquid exits.

NOTE: Before a motor of this type will operate, the vanes must be previously extended and a positive seal must exist between vanes and housing. Centrifugal force cannot be depended on as in a pump. The manner in which these vanes are extended will be dealt with in a following section.

torque

Torque is a rotary or turning effort. Torque indicates a force is present at a distance from a motor shaft. One unit for measuring torque is a lb. in. (Newton-meter).



description of torque

Torque tells us where a force is in relation to the motor shaft. The expression which describes torque is:

torque	=	force	x	distance from shaft
(lb.in.)		(lb.)		(in.)
(N-m)		(N)		(m)

In the illustration, a force of 50 lbs. (222 N) is positioned on a bar which is attached to a motor shaft. The distance between the shaft and the force is 10 inches (0.254 m). This results in a torque or turning effort at the shaft of 500 lbs. in. (56.5 N-m).

If the 50 lbs. (222 N) were located 15 inches (0.38 m) along the bar, the turning effort generated at the shaft would be equal to a twisting effort of 750 lbs. in. (3330 N).

From these examples, we can see that the farther the force is from the shaft, the larger the torque at the shaft. It will also be noted that torque does not involve any movement.

A resisting object attached to a motor shaft generates a torque as described above. This, of course, is a resistance for the motor which must be overcome by hydraulic pressure acting on a motor's rotating group.

The expression used to describe the torque developed by a hydraulic motor is:

$$\underset{(\text{lb.in.})}{\text{torque}} = \frac{\text{psi} \times \text{motor displacement (in}^3)}{2\pi}$$

$$\underset{(\text{N-m})}{\text{torque}} = \frac{\text{bar} \times \text{motor displacement (cm}^3)}{20\pi}$$

motor shaft speed

The speed at which the shaft of a hydraulic motor turns is determined by how quickly it is filled with fluid.

The expression which describes motor shaft speed is:

$$\underset{(\text{rpm})}{\text{motor shaft speed}} = \frac{\text{gpm} \times 231}{\text{motor displacement (in}^3/\text{rev.)}}$$

$$\underset{(\text{rpm})}{\text{motor shaft speed}} = \frac{\text{lpm} \times 1000}{\text{motor displacement (cm}^3/\text{rev.)}}$$

power

We have seen earlier that the speed or rate of doing work is power. Power = ft.lbs./time or Joule/time= Watts.

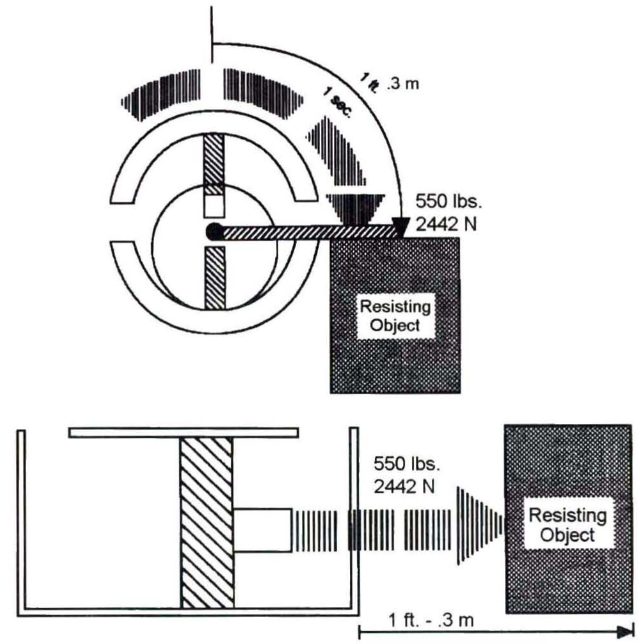
The machine which performs its required work in three seconds produces more power than a machine which performs the same work in three minutes.

mechanical horsepower

We have also seen that horsepower, or watts, may be the unit of measure for power.

If a cylinder or hydraulic motor applies a mechanical force of 550 lbs. (2442 N) against a resisting object through a distance of one foot (0.30 m) in a time lapse of one second, one horsepower (746 W) is used.

If the same work (550 ft. lbs./746 J) were completed in a half second, the work would be done at twice the rate, or two horsepower (1490 W).



One Horsepower

hydraulic horsepower

The mechanical horsepower transmitted by the cylinder or motor to the resisting object will also be the hydraulic horsepower requirement at the cylinder or motor.

A hydraulic system doing work at the rate of 550 ft. lbs. (746 J) per second is one hydraulic horsepower (746 W). However, instead of using the terms of "foot" (meter) and "lb" (Newton) found in the mechanical horsepower expression, these terms are converted to hydraulic terms of "psi" (bar) and "gpm" (lpm). Also, in the hydraulic horsepower formula, a conversion factor is used which shows the relationship between gpm, psi, feet, and lbs. (lpm, bar, meter and Newtons).

GPM X PSI

system and cylinder horsepower calculation

To calculate horsepower developed by a hydraulic cylinder or the total hydraulic system, the following expression is used:

horsepower = gpm x psi x .000583
watts = horsepower x 746
watts = 5/3 lpm x bar

.000583

63,025

To calculate horsepower developed by a hydraulic motor, the following expression is used:

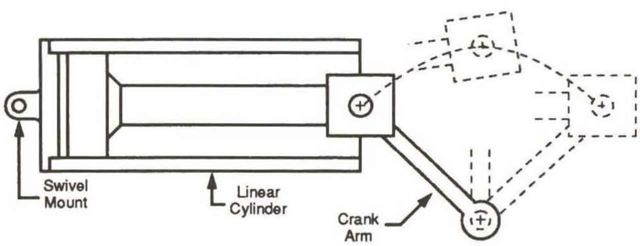
$$\text{horsepower} = \frac{\text{rpm} \times \text{Torque (lb.in.)}}{63{,}025}$$

$$\text{Kilowatt} = \frac{\text{rpm} \times \text{Torque (N-m)}}{9543}$$

rotary actuators

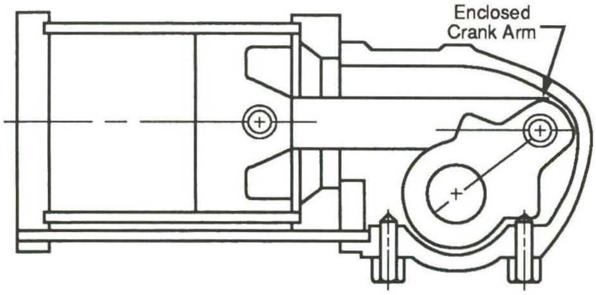
Up to this point we have discussed rotary output of motors and straight line motion of cylinders. Now we are going to discuss actuators that have a limited degree of rotation. These devices, known as rotary actuators, are compact, simple, and efficient. They produce high torque and require small space and simple mounting.

Common applications for rotary actuators would be such things as machine tool indexing, bending operations, lifting or rotating heavy objects, rollover function, positioning, machining fixtures, ship rudder positioning, actuating valves, etc.



There are many types of rotary actuators. Perhaps the simplest of the rotary actuators is the linear cylinder. It is just a simple cylinder swivel-mounted at one end. The rod is attached to a crank arm that drives the shaft. The cylinder is controlled by a four-way directional valve that controls the direction of the cylinder. There are limits at the end of the drive stroke.

As with all mechanical devices, there are basic characteristics. One characteristic is that this cylinder based rotary actuator can be built up from commercially available components. This allows for design flexibility. It is inexpensive and repair parts are readily available.



There are other characteristics that are not as favorable: the rod is unprotected and left exposed to the surrounding environment; the mechanism, the crank arm, is typically unshielded, and therefore is an unsafe condition. Also, tremendous side-loadings or sideward thrust is generally applied to the shaft causing premature failure, excess wear, and galling.

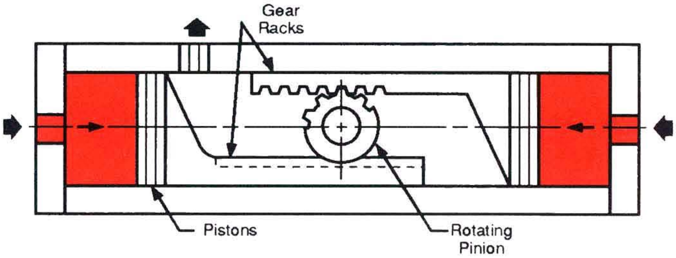
With this particular type of rotary actuator the cylinder must be free to move. Therefore, flexible lines must be used as fluid conductors. With this type of rotary actuator the torque is not constant throughout the entire stroke of the cylinder.

The shrouded cylinder type of rotary actuator is very similar to the linear cylinder actuator. The shrouded cylinder has a shrouded enclosure around the cylinder rod and crank arm. Also, in this particular type there is generally additional bearing support to prevent the extreme side loading that may occur.

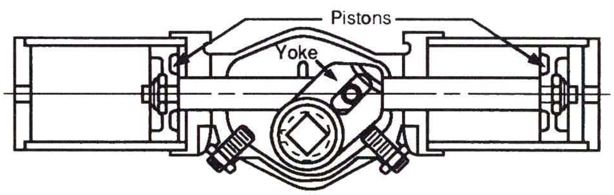
These particular types of rotary actuators can be equipped with solenoid operated valves, positioners or limit switches. Ordinarily their stroke is adjustable from a range of about 85 to 100 degrees.

Still another type of rotary actuator is called a "spring return" cylinder. This particular type uses a spring loaded cylinder to return the shaft to its normal position. The spring return actuators are available with torque outputs of up to 5000 pound inches (565 N-m).

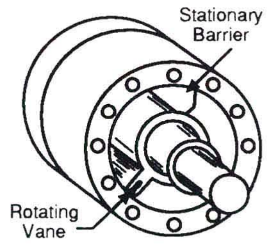
A very common type of rotary actuator is called the rack-and-pinion. This particular type of rotary actuator gives uniform torque in both directions and throughout the range of rotation. In this device fluid pressure will drive a piston which in turn is connected to a gear rack which rotates a pinion shaft. Standard rack-and-pinion units are available in rotations of 90°, 180°, 360°, or more. Variations of the rack-and-pinion actuators can produce units with torque outputs of as much as fifty-two million pound-inches (5,876,000 N-m).



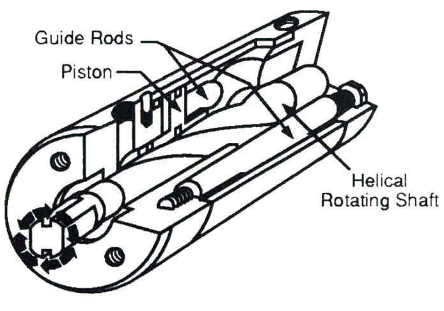
There is still another rotary actuator called a skotch yoke actuator. This type is very similar to two cylinders with a common rod. These are typically double acting or can be single acting; they could even be provided with a spring return. These actuators are rather large, with torque ranges as high as forty-five million pound-inches (5,085,000 N-m). These are limited to driving through very short arcs, generally 90° or less.



Vane type rotary actuators are also available. They can be single or multiple vanes. They can have rotations of 280° with single vane or 200° with dual vanes. The dual vanes would give twice the torque of the single vane. These have torque ratings of as high as five hundred thousand pound-inches (56,500 N-m).



There is still another type rotary actuator that produces torque through the aid of a helical spline. Variation in length and pitch of the helix permit the rotation to be varied over a wide range. It consists



GPM Determines Actuator Speed

$$\text{Rod Speed (in./min.)} = \frac{\text{gpm} \times 231}{\text{piston area (in}^2\text{)}}$$

$$\text{(m/s)} = [\text{l/min/cm}^2]\ (.1667)$$

$$\text{Shaft Speed (rpm)} = \frac{\text{gpm} \times 231}{\text{motor displacement (in}^3\text{/rev.)}}$$

$$\text{(rpm)} = \frac{\text{l/min} \times 1000}{\text{cc/rev}}$$

PSI Determines Actuator Output Force

$$\text{cylinder force (lb.)} = \text{psi} \times \text{piston area (in}^2\text{)}$$

$$\text{(N)} = 10 \times \text{bar} \times \text{piston area (cm}^2\text{)}$$

$$\text{motor torque (lb. in.)} = \frac{\text{psi} \times \text{motor displacement(in}^3\text{)}}{2\pi}$$

$$\text{(N-m)} = \frac{\text{bar} \times \text{motor displacement (cm}^3\text{)}}{20\pi}$$

Actuator Speed Multiplied By Actuator Output Force Equals Horsepower

$$\text{cylinder horsepower} = \text{gpm} \times \text{psi} \times .000583$$

$$\text{watts} = 5/3\ \text{(l/min) (bar)}$$

$$\text{motor horsepower} = \frac{\text{rpm} \times \text{torque (lb. in.)}}{63025}$$

$$\text{kWatt} = \frac{\text{torque (N-m)} \times \text{rpm}}{9543}$$

of a helical splined shaft that rotates when a piston sleeve, which is restrained from rotating by sliders, moves within a cylinder. This particular type rotary actuator usually has 90°, 180°, 270°, or 360° rotation and output torques of up to one million pound-inches (13,000 N-m).

The sprocket type rotary actuator uses a drive piston, chain, and sprocket to rotate the shaft. In this type of actuator there is typically a large piston that acts as a driver or pulls the chain and a smaller piston that provides a seal to prevent fluid leakage past the return side of an endless chain. This type of rotary actuator will have torque outputs to about 23 thousand pound-inches (2599 N-m). Shaft rotations with this type can be as high as five complete turns or 1800°.

Choosing the best rotary actuator for a particular application involves matching torques, speed and operating modes for that task. The actual choices of a rotary actuator will be covered in another text. In addition, deciding whether it is single or double acting, closed positioning, cushioned, and frequency or cycle rate will also be examined.

generalizations about hydraulic actuators

Actuator **speed** is a function of flow **gpm [l/min]**. The **speed** at which a cylinder's piston rod travels is determined by how quickly the flow **gpm [l/min]** from the pump fills the volume behind the cylinder piston.

The **speed** at which the shaft of a hydraulic motor revolves is dependent on the rate at which the **gpm [l/min]** from the pump fills the hydraulic motor.

Actuator output **force** is a function of pressure **psi/bar.** The output **force** at the shaft of a hydraulic motor is determined by the amount of hydraulic **pressure** acting on the exposed area of the motor's rotating group.

The horsepower developed by an actuator is a function of actuator speed multiplied by actuator output force.

For a cylinder, the output force is expressed by psi. The rod speed is denoted by gpm. The constant .000583 gives the relationship between psi, gpm, and horsepower.

For a hydraulic motor, the output force is expressed by torque. The motor's operating speed is denoted by rpm. The constant 63,025 give the relationship between rpm, torque, and horsepower.

exercise
hydraulic actuators
25 points

Instructions: Solve the following problems:

1. A cylinder with a 3" (7.62 cm) bore and a stroke of 16" (40.64 cm) receives 18 gpm (68.22 lpm). What is the piston rod velocity?

2. Calculate how much output torque a motor will produce if it has a displacement of 13 in^3 (213 cm^3) and is subjected to 240 psi (16.55 bar)?

3. A cylinder with an 8" (20.32 cm) bore and a 36" (.9 m) stroke must extend in one minute. How much flow is required?

4. A hydraulic motor develops 200 lb.ins. (2.25 N-m) of torque at 800 rpm. What is the horsepower?

5. A cylinder with a 10" (25.4 cm) bore and a 24" (.609 m) stroke must move a 78,540 lb. (348717.6 N) load through its stroke in three seconds. How much hydraulic horsepower must be delivered to the cylinder?