Hydraulics & Pneumatics Chapter 9

Fluid power, as the name implies, involves using a fluid to do useful work. Fluid power encompasses two areas: hydraulics when the working fluid is a liquid (usually oil), and pneumatics when the fluid is air. The basic principle behind fluid power is that a fluid under pressure produces an outward force on all surfaces in contact with the fluid. When fluid pressure acts on a movable surface, such as the piston in a cylinder, that force can be harnessed to do work, Fig. 9-1.

One advantage fluid power holds over other technologies is that it can produce a lot of force in a small package. For example, a hydraulic cylinder small enough to be held in one hand can produce enough force to lift a small car!

Fluid power is typically the best way to produce high-force linear motion. Electric motors are usually preferred for rotating applications over fluid motors and rotary fluid actuators. Exceptions are where extremely high torques are required, say the drive wheels of a large excavator, or where safety concerns prevent the use of electricity, such as underwater.

The technique is used in a wide variety of applications. Aircraft, for example, employ hydraulics to control aerodynamic surfaces because a small, lightweight actuator can produce high forces. Construction equipment uses hydraulic devices because they are rugged and extremely powerful. Pneumatics, however, is preferred for industrial applications like stamping presses or pick-and-place robots because the systems are inexpensive, fast-acting, safe, and clean.

Fluid-power mechanisms are also recognized as being extremely durable. Both hydraulic and pneumatic equipment stands up to shock and vibrations, dust and dirt, heat and cold, and requires little maintenance. So they are often used where harsh conditions would quickly destroy other systems. The schematic for a basic fluid-power system is shown in Fig. 9-2. Here's a closer look at the critical components in such a system.

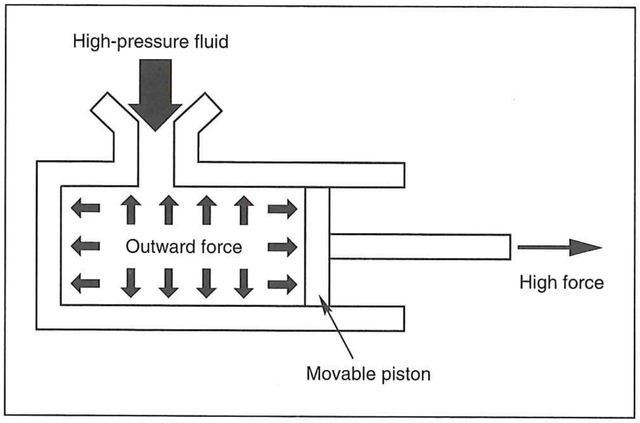

Fig. 9-1 — High-pressure fluid acting on a movable surface can be harnessed to produce force and motion.

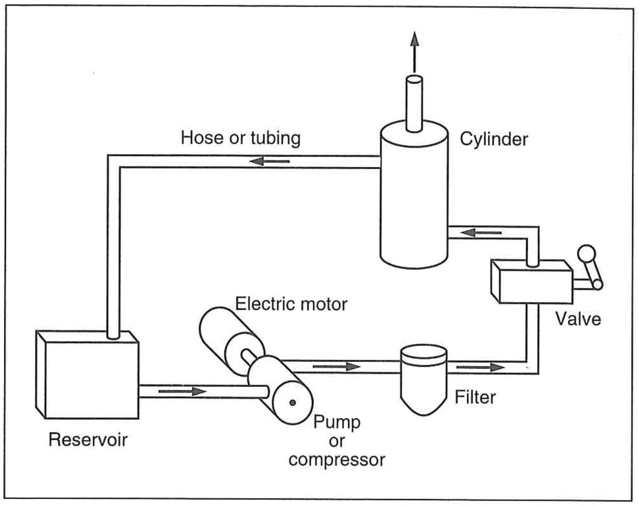

Fig. 9-2 — A typical fluid-power system consists of a pump or compressor to propel the fluid, valves that control where the fluid goes, and actuators that do the work. Hose or tubing carries the fluid from one place to another, and filters keep the fluid clean.

Hydraulic Pumps

A pump, normally driven by an electric motor or internal-combustion engine, is the heart or power source of a hydraulic system. A wide variety of pumps are available that deliver from less than one to many hundreds of gallons per minute (gpm). Output pressures typically range from 500 to about 6,500 psi, although some specially designed pumps produce pressures exceeding 50,000 psi. Pumps are available in three basic designs — gear, vane, and piston.

Gear Pumps

Compact and inexpensive gear pumps feature few moving parts. Two types are widely used — gear-on-gear and gear-within-gear.

Gear-on-gear pumps. These pumps, Fig. 9-3, consist of two gears, usually of equal size, that mesh with each other inside a housing. The driving gear, connected to the drive shaft, drives the second gear. As the gears rotate within the housing, fluid is swept from the inlet to the outlet. Both spur and helical gears are used, but spur gears are the most common. As a spur gear rotates, segments of fluid are released between the

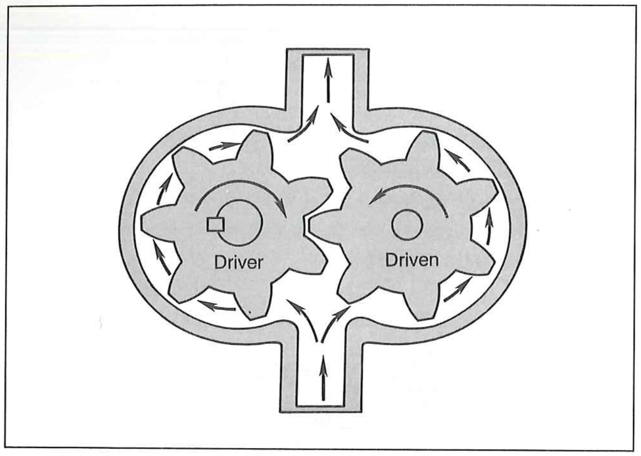

Fig. 9-3 — In gear pumps, the gears rotate within the housing and sweep fluid from the inlet to the outlet.

teeth to the outlet, pulsing or rippling the output pressure. Helical gears release segments of fluid more evenly, minimizing ripple.

Gear-within-gear pumps. This variety, Fig. 9-4, consists of an externally toothed gear that rotates inside and drives a larger internally toothed gear. In one common configuration, the gerotor pump, the inner gear has one tooth less than the outer gear. Here, as the inner gear drives the outer one, the relative motion of the gear teeth creates sliding seal points. As the teeth unmesh, a vacuum forms in the pocket between the teeth, drawing oil from the inlet. When the teeth engage, the action forces the oil out the discharge port.

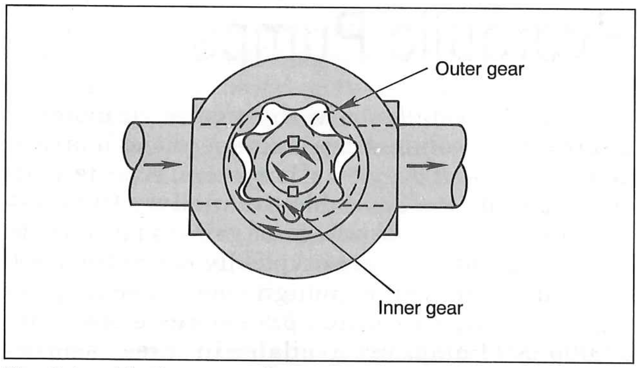

Fig. 9-4 — The inner gear has one tooth less than the outer gear in this gear-within-gear pump. Relative motion between the two causes pumping action.

Vane Pumps

A typical vane pump consists of a circular rotor mounted eccentrically in a circular cavity. As the rotor spins, vanes in the pump extend and retract to seal against the cavity surface, sometimes called a cam ring. Fluid is trapped between the vanes at the inlet, swept along by the vanes, and propelled through the outlet.

Vane pumps are efficient at speeds over about 600 rpm, the minimum rate where vane tips contact the cam ring. Below this speed, leakage is high and efficiency is low. Vane length is adequate to accommodate appreciable wear. The pumps are more sensitive to contaminants than gear pumps but less so than piston pumps.

The basic vane pump is subject to high bearing loads because it is unbalanced. A high-pressure area on one side of the rotor and a low-pressure area on the other forces the rotor and shaft down against the bearings. This drawback is overcome with the balanced vane pump, Fig. 9-5. Here, the rotor is centered inside an elliptical cam ring, and there are two inlet and two outlet ports opposite each other. With this configuration, the two high-pressure zones are 180° apart, balancing out the forces.

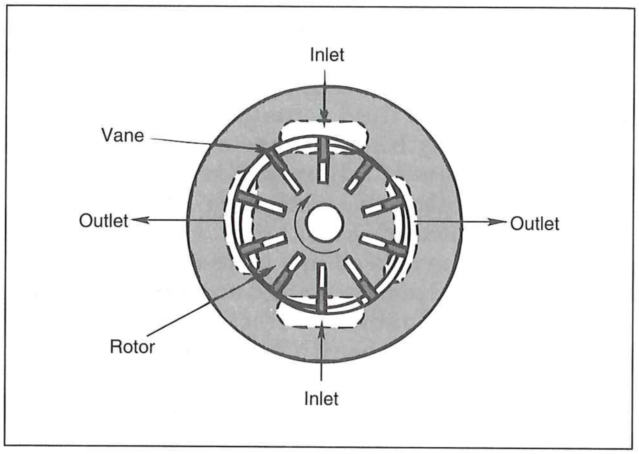

Fig. 9-5 — Two opposing high-pressure zones in this balanced-vane pump equalize forces on the pump shaft.

Piston Pumps

The most efficient of the three pump types, but also the most costly, piston pumps exhibit volumetric efficiencies up to 99%. They convert rotary motion of an input shaft to a reciprocating motion of one or more pistons. Fluid is drawn into and forced out of a chamber by the piston, with valves controlling flow direction. The action is much like that of a piston and cylinder in an automobile engine. Two types are available — axial-piston and radial-piston. The terms indicate the direction of piston motion in relation to the pump shaft.

Axial-piston pumps. These pumps, Fig. 9-6, often use an angled cam or "swashplate" at-

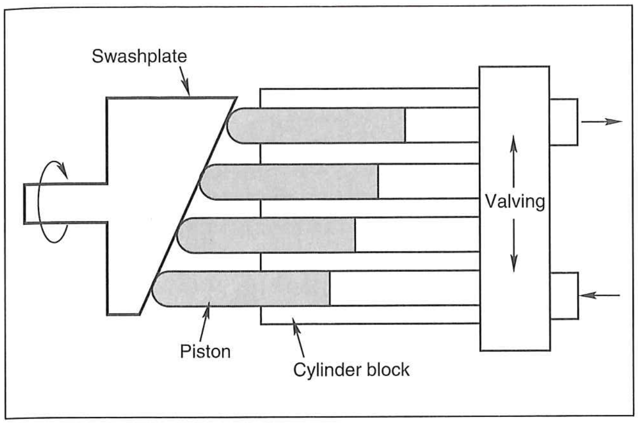

Fig. 9-6 — The pistons reciprocate as the swashplate rotates, taking in fluid while moving toward the thin part of the plate and expelling it while approaching the thick end. Valving controls flow direction.

tached to the pump shaft. As the plate rotates, the pistons reciprocate, taking in fluid while moving toward the thin part of the plate and expelling it while approaching the thick end. An alternative way to reciprocate the pistons is to mount them at an angle in relation to the drive shaft, and allow both the pistons and shaft to rotate. For this design, no swashplate is required because of the angled relationship of the pistons and shafts.

Radial-piston pumps. This design converts rotary shaft motion into a radial reciprocating motion of the pistons. One type is driven by a rotating cam that runs through the center of the pump, driving the pistons.

Variable-Displacement Pumps

Hydraulic applications calling for high power (typically over 15 hp) and flow that varies over a wide range are often best served by variable-displacement pumps. These pumps allow control of output flow, usually between zero and maximum. Vane and piston pumps are usually available with this function. Vane pumps vary displacement by adjusting the position of the cam ring; piston pumps change axis angle or angle of the swashplate. Gear pumps typically change flow only by adjusting drive speed, which generally restricts them to fixed-displacement applications.

The main advantage of a variable-displacement pump is low power consumption. They only use enough power to deliver the required flow — and no more. However, these pumps are generally not as efficient and cost more than fixed-displacement types.

In general, fixed-displacement pumps should be used in applications where:

- Hydraulic horsepower is less than 10 to 15 hp, and energy costs are not an important factor.
- The duty cycle is on-off, and the pump can be unloaded completely when not in use.
- Full flow from the pump is required under most operating conditions, even though the load may vary over a wide range.

Rating Factors

Pressure. The pressure rating is one of the major considerations in determining whether a pump can do a job. The rating is generally limited by the capability of the pump to withstand pressure without undesirable increase in internal leakage, and without damage to the pump parts.

Typically, maximum pressure is approximately 4,500 psi for external gear pumps and from 2,000 to 4,000 psi for vane pumps. Internal-gear units run somewhat lower, with maximums in the range of 1,500 to 2,500 psi. Piston pumps are rated to around 6,500 psi maximum, although some are suitable for pressures exceeding 8,000 psi. A few permit higher pressures for intermittent peak loads

Flow. The second most important consideration in selecting a pump is how much fluid it can deliver, usually expressed as volumetric flow output (gpm), but sometimes called capacity or delivery rate. Flow rating is based on performance under a specific set of conditions. Manufacturer's literature generally states the conditions under which the rating is made.

Speed. A third consideration is the speed rating, which may be a limitation imposed by the ability of the pump to fill without cavitating or by some mechanical factor. The permissible speed range and inlet pressure requirements for pumps are usually clearly defined.

Efficiency. Comparing efficiency is a good way to judge two otherwise similar pumps. But efficiency is defined in three ways. Thus,

Volumetric efficiency is the ratio of actual to theoretical delivery. The difference between actual and theoretical delivery is normally due to internal leakage necessary to lubricate the pump (called "slippage") and other factors. Volumetric efficiency is typically very high, often in the mid to high 90s.

Overall efficiency is the ratio of hydraulic power output to mechanical power input.

Mechanical efficiency is the ratio of overall efficiency to volumetric efficiency. Mechanical losses are due principally to internal friction and fluid compression.

Compressors

The main difference between pumps and compressors is that the fluid delivered by compressors is air. Otherwise compressors are similar in concept and hardware to hydraulic pumps, and selection considerations are much the same.

Inside a plant or factory, numerous pneumatic systems are often powered by a single, large compressor. However, many applications call for individual, small compressors. These units are available in a wide variety of designs. Some of the most common are:

Vane compressors. Like their hydraulic counterparts, vane compressors, Fig. 9-7, are inexpensive, operate at low cost, and demand little starting-torque. They are compact, relatively vibration free, and generate little pulsation in the compressor output. The sliding vanes are closely fitted in the rotor slots and wear little during operation. Vane compressors are available in power ranges from 10 to 500 hp at pressures to 150 psi.

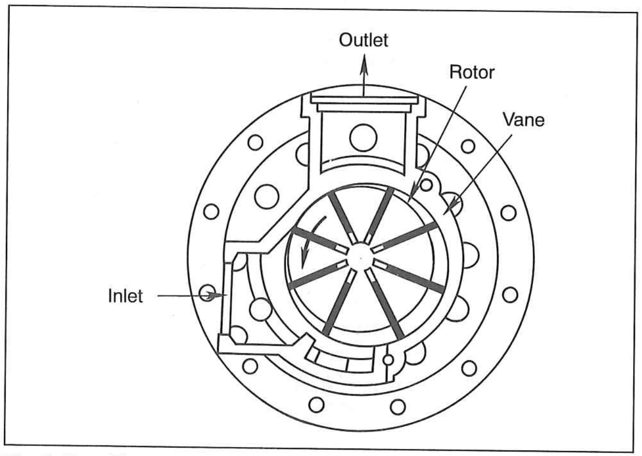

Fig.9-7 — The vanes slide in and out of the slots as the compressor rotates, carrying air from inlet to outlet.

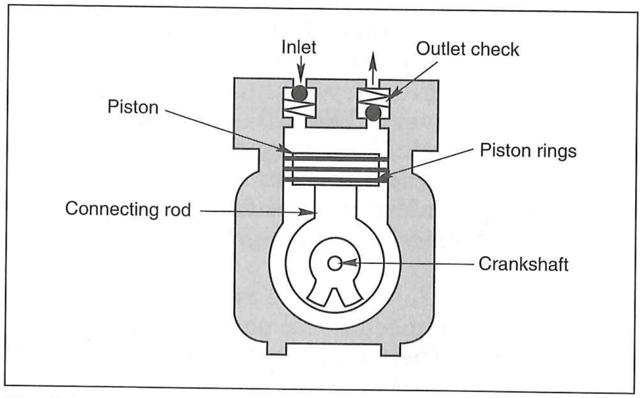

Fig. 9-8 — Check valves control flow direction as the reciprocating piston draws in and expels air.

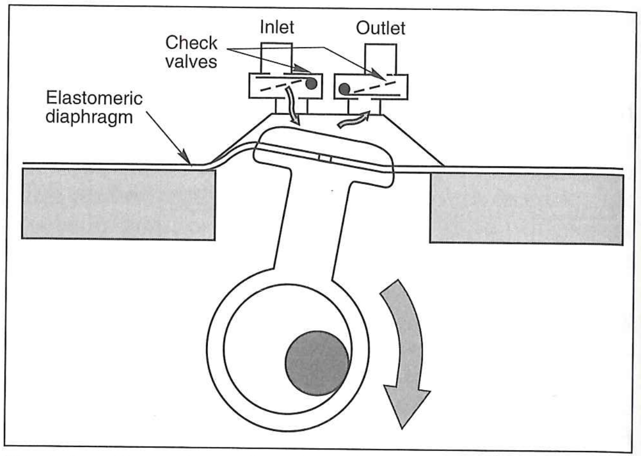

Fig. 9-9 — The reciprocating piston flexes a diaphragm which, in turn, compresses the trapped air.

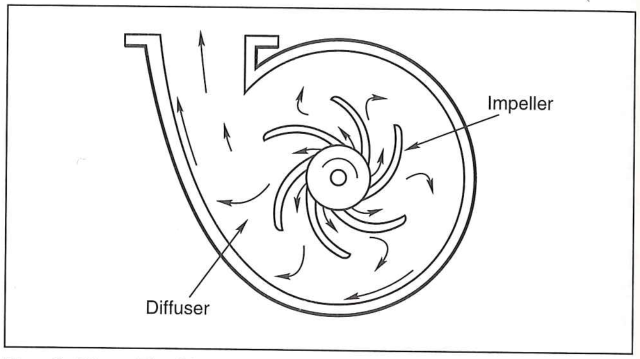

Fig. 9-10 — The high-speed rotating impeller in a centrifugal compressor forces air through a diffuser, where velocity decreases and pressure increases.

Reciprocating compressors. This type of compressor, Fig. 9-8, consists of pistons that compress the air in cylinders and valves that control its inlet and outflow. Sizes range from less than 1 to over 5,000 hp. Reciprocating compressors are efficient and useful for a wide range of operating conditions.

Diaphragm compressors. A modification of the reciprocating compressor, the piston in a diaphragm compressor, Fig. 9-9, flexes a metal or elastomeric diaphragm. This motion compresses air trapped in the cylinder. The diaphragm provides a positive sealing barrier between the air and the compressor's internal parts, so they are often used where clean air is a must.

Centrifugal compressors. Best suited to moving large volumes of air, centrifugal compressors, Fig. 9-10, operate at relatively low pressures. They consist of a high-speed rotating impeller, a diffuser section where air velocity decreases and pressure increases, and a collector section that further reduces velocity and increases pressure. The compressors typically employ multiple stages, supplying from less than 250 to well over 20,000 cfm.

Sizing considerations for compressors are much the same as for hydraulic pumps, with pressure rating and flow of greatest concern. While compressors can be sized to provide only the required pressure and flow, 10 to 25% over-capacity is preferred. Also, inlet filters should be provided to protect the compressor, and outlet filters and dryers should condition the air and protect downstream components.

Valves

Differentiated by the type of control they provide, valves modulate either fluid pressure or the rate of fluid flow. The primary mechanism in a valve is either a spool or a poppet, although slides, rotary devices and diaphragms are sometimes used.

Spool mechanisms. These devices, Fig. 9-11, slide inside a sleeve, controlling flow between two ports. The device is used in both hydraulic and pneumatic valves. The device calls for a short stroke, exhibits low friction, requires little actuation force, and is suitable for high pressures. Because these valves depend on close clearances between spool and bore, low-leakage varieties may be relatively costly and sensitive to contaminants.

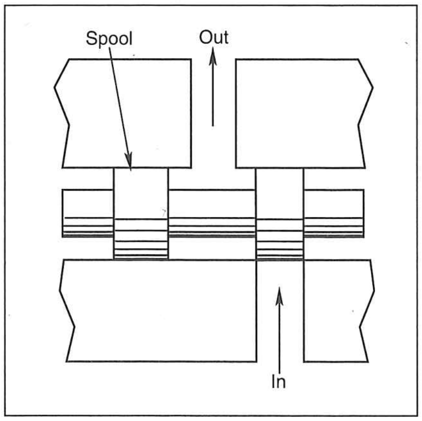

Fig. 9-11 — The spool sliding within the sleeve permits or blocks flow.

Poppet mechanisms. Here, Fig. 9-12, the relative position of the poppet with respect to a seat controls fluid flow. Cartridge valves consist of a poppet, sleeve, and spring that are contained within a machined manifold block. The valves typically are suitable for hefty flows with minimum pressure drop and are relatively insensitive to fluid-borne contaminants.

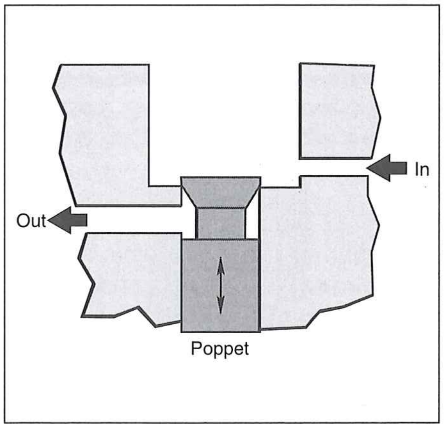

Fig. 9-12 — Poppets seal on the narrow contact area between poppet and seat.

Valves are actuated by various means. Some employ a manually operated lever. Others operate mechanically through a roller, cam, or other mechanism. And pneumatics or hydraulics can be used to operate yet other valves.

Electrically actuated valves are normally powered by small solenoids. The solenoid plunger moves the spool or poppet directly on small valves. On larger valves the solenoid drives a miniature valve that, in turn, directs pressurized fluid to the spool or poppet of the main valve. These are called solenoid-controlled, pilot-operated valves.

Pressure-Control Valves

These valves modulate pressure level in fluid-power circuits. Several types are available, categorized by function.

Relief valves. The most common pressure-control valves, Fig. 9-13, relief valves keep pressure from exceeding a preset level. A spring normally holds the relief valve closed until the pressure level is such that the force acting on the valve seat exceeds the spring force. This opens the valve, permitting flow to the reservoir at low pressure. Maximum pressure rating for relief valves is published by the manufacturer.

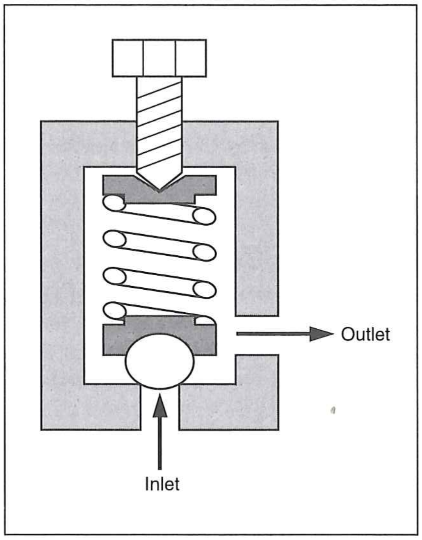

Fig. 9-13 — When pressure force exceeds spring force in this relief valve, the valve opens and allows low-pressure flow to the reservoir.

Reducing valves. These valves limit pressure levels by restricting flow to a branch circuit of a hydraulic system. Here, when the circuit reaches a predetermined pressure, the valve restricts flow and limits the pressure to that level. The spring-positioned spool, Fig. 9-14, is one common configuration.

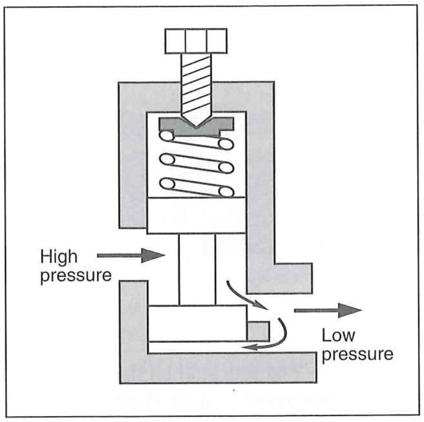

Fig. 9-14 — Reducing valves lower pressure by restricting flow. Spool position is a balance between low-pressure fluid on the spool and spring force.

Sequence valves. Used for machine sequencing, the valves sense pressures other than maximum. These normally closed valves permit flow between inlet and output ports when the pressure reaches preset levels. Sequence valves often have two or more spools or poppets that must be actuated before fluid can pass through the valve. Typically, a certain minimum pressure must develop in one part of the circuit before fluid can pass through another part.

Flow-Control Valves

Fluid flow is controlled by either throttling or diverting it. Throttling limits flow by reducing the size of an orifice. Bypassing routes part of the flow around a circuit so that an actuator receives only the portion needed to perform its task. Where the flow inlet to an actuator is controlled, the circuit is said to be a meter-in system. Where actuator outlet is controlled, it is called a meter-out circuit. When that part of the fluid being diverted to a reservoir or another part of the circuit is controlled, it is said to be a bleed-off system.

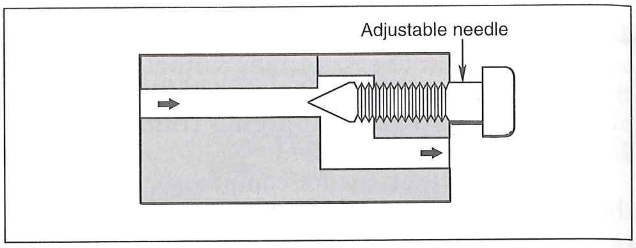

Fig. 9-15 — Needle valves create a restriction that meters flow.

Noncompensated flow controls. These simple valves meter flow by restricting or throttling. The amount of fluid that passes through an orifice and the pressure drop across it are directly related. As pressure increases, valve flow increases.

A common type of noncompensated valve employs an adjustable needle valve, Fig. 9-15.

Pressure-compensated flow controls. To maintain nearly constant flow despite variations in circuit pressure, pressure-compensated valves incorporate a metering orifice like those in noncompensated units. Pressure drop across this orifice shifts a balanced spool against a control spring. This action maintains a constant pressure drop across the orifice which, in turn, maintains a constant flow. Pressure drop through the valve is relatively low.

Directional Control

Directional-control valves determine the fluid's flow path through a circuit. The valves are classified in the following manner:

Port number. This is the number of plumbing connections to the valve. Thus, a three-port valve has one port each for connections to a pump, reservoir, and actuator.

Position. The number of stops the valve can make during operation is referred to as position. For

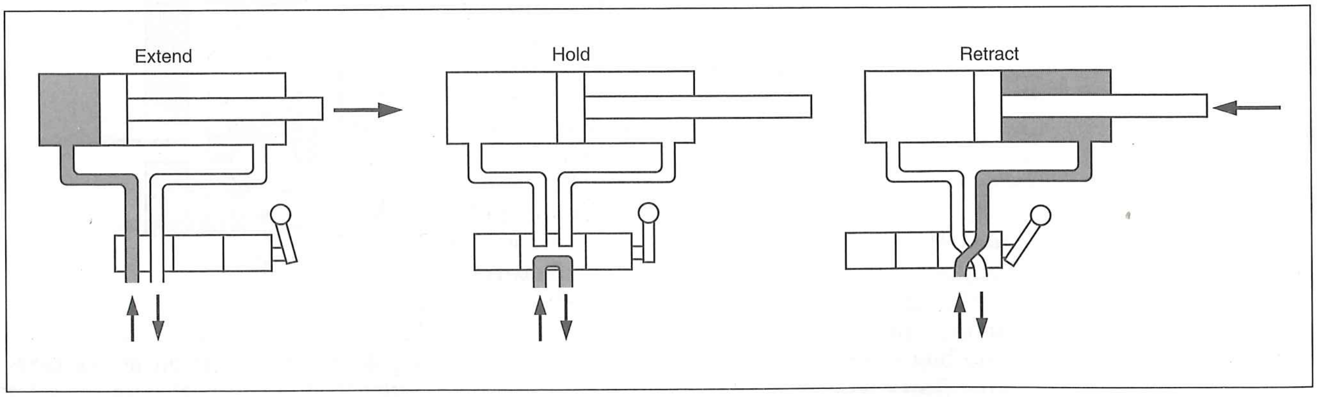

Fig. 9-16 — A three-position, four-way valve can power an actuator to extend the rod; hold a load in an intermediate position; and power the retract stroke.

example, a two-position valve can shift either in one direction or the other, like a light switch. Three-position valves have an intermediate position between the two end stops.

Way. This term refers to the possible flow paths through a valve. A check valve that permits fluid to flow in only one direction is a one-way valve. A two-way valve has two ports and allows flow in either direction. A common directional-control valve is shown in Fig. 9-16.

Proportional and Servovalves

Proportional valves. The performance of proportional valves falls between that of on/off solenoid valves and servovalves. Proportional valves are often modified versions of four-way, on/off solenoid valves in which proportional solenoids replace conventional solenoids. Here, solenoid position (from fully retracted to fully extended) and valve opening (from closed to fully open) is a function of current level in the solenoid. In operation, solenoid force is balanced by spring force to position the spool in proportion to the input current.

The valves are termed proportional because output flow is not exactly linear in relation to current. Despite their nonlinear response, the valves are an inexpensive way to control position, velocity, or force on equipment requiring high-speed response at high flow rates.

Positioning accuracy can be improved by removing the centering springs and adding a positioning sensor to the end of the spool. Electronic feedback results in performance almost as good as that of a servovalve but at a lower cost.

Servovalves. Servovalves offer unsurpassed performance in a fluid-power system. The valves continuously adjust output in response to electrical input signals. They work through closed-loop feedback. The position, velocity, force, or acceleration of an actuator is continuously monitored with sensors, and that information is sent to an electronic controller. The controller compares actual and desired conditions and instantaneously adjusts valve output to compensate for any difference between the two.

Servovalves are available in single and multiple-stage versions that offer a wide range of pressure and flow ratings. Multi-staging is employed in high-flow capacity valves. The first stage typically has an electromechanical actuator, such as a torque motor, force motor, or solenoid that controls a hydraulic metering valve. Sliding spools are generally used for the other stages, with first stage output driving the second stage spool.

Servovalves are precision valves that have high pressure drop across the spool. This ensures precise metering and exacting control. They are used in applications requiring high load stiffness, good stability, precise positioning, good velocity and acceleration control, or predictable dynamic response.

Flow Capacity

Valve size can be related either to size of piping connections or to flow capacity. Valve flow capacity can be expressed as a nominal or maximum rating.

Nominal flow rating. This rating refers to the amount of flow a valve can handle with relatively low pressure drop. The nominal rating quoted by valve makers is often the hydraulic flow that creates a 50 to 60-psi pressure drop through the valve.

Maximum rating. The maximum flow a hydraulic valve can control without malfunction is referred to as the maximum rating. For example, a valve with a 30-gpm nominal rating might have a 50-gpm maximum rating. If subject to higher flow, available pilot pressure may be insufficient to shift the valve. When a valve is used within reasonable limits above its nominal rating, pressure drop increases directly with the square of the flow.

Size ratings. Size ratings are only approximate. A valve designated as $^3\!/_4$ in., for example, is not necessarily limited to use with only $^3\!/_4$-in. pipe. Many valves can handle considerably higher flows.

Flow coefficient. C_v, or flow coefficient ratings for pneumatic valves, are used by many manufacturers. An opening with a C_v of 1.0 is defined as passing 1.0 gpm of water at 1.0 psi pressure drop. Suppliers publish C_v data on their valves, so that if pressures upstream and downstream of the valve are known, flow rate is found from a chart or table. This method provides an accurate indication of steady-flow capacity.

However, the flow coefficient often does not provide enough data for determining whether a specific valve will satisfy a specific circuit response requirement. For instance, valve-shifting time and actuator-exhaust or fill time might be long enough to introduce errors into valve-sizing calculations. A reliable approach is to build and test a prototype system.

Actuators and Motors

Fluid-power actuators are available in a number of forms to provide specific types of action. Cylinders, by far the most common actuators, work through linear extension; motors impart continuous rotary motion to objects; rotary actuators turn an object through only a limited arc.

Generally, all types of actuators are available for both pneumatic or hydraulic operation. Often, the same cylinder can be used for either air or low-pressure oil operation. Air and hydraulic motors, though similar, are usually not interchangeable.

Cylinders

When fluid is pumped into a cylinder, piston and rod are forced to move in or out against a load. Many different types are available, including:

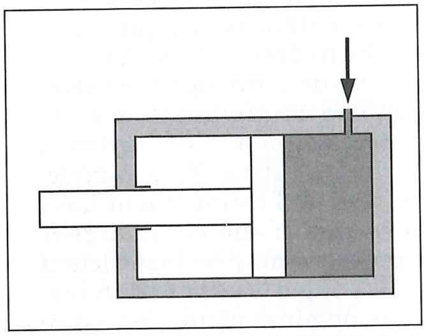

Fig. 9-17 — Single-acting cylinders provide power only to extend the rod.

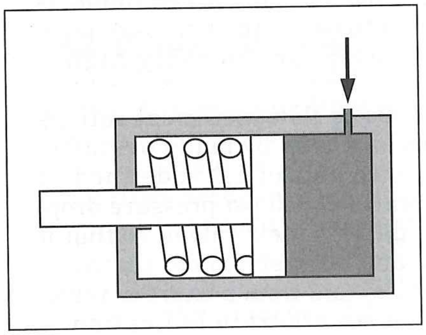

Fig. 9-18 — Spring force retracts the rod in a spring-return cylinder.

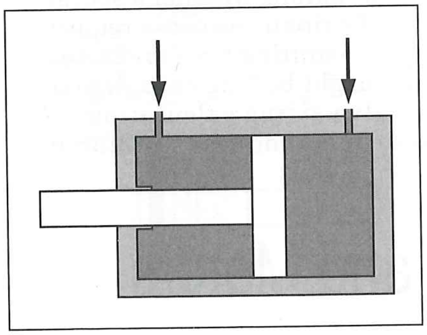

Fig. 9-19 — Fluid pressure can extend and retract the rod in double-acting cylinders.

Single-acting cylinders. The simplest type of cylinder, Fig. 9-17, powers a stroke in only one direction. When the fluid is allowed to drain from the cylinder, some external force, such as gravity, must push the piston back to its starting position.

Spring-return cylinders. Similar to the low-cost single-acting types, spring-return cylinders, Fig. 9-18, have a spring that repositions the piston to its starting point. This type is widely used in both pneumatic and hydraulic service, but sometimes is not suitable for pneumatics. If the spring is heavy enough for speedy piston return, it may require too much force to compress. The cylinder must be about twice as long as the required stroke to include space for the spring. Some cylinders are spring-loaded in the opposite direction, so they extend with spring action and retract pneumatically or hydraulically.

Double-acting cylinders. Double-acting cylinders, Fig. 9-19, contain two fluid chambers so that pressure both extends and retracts the rod. This type of cylinder is by far the most common, and can be used in nearly all types of applications. Effective working area of the rod side of the piston is less than that of the other side, so double-acting cylinders retract faster than they extend, and exert less force on the retraction stroke.

Rodless cylinders. As the name implies, rodless models, Fig 9-20, differ from their more conventional counterparts in that no piston rod extends from the cylinder body. Rather, an internal piston is connected either physically or by magnetic force to an external carriage. Driving the piston by compressed air or other suitable media causes the carriage to traverse between the cylinder end caps. Thus, a major advantage of rodless cylinders is that they require considerably less mounting space — nearly 50% less in some applications — compared with rod-type models.

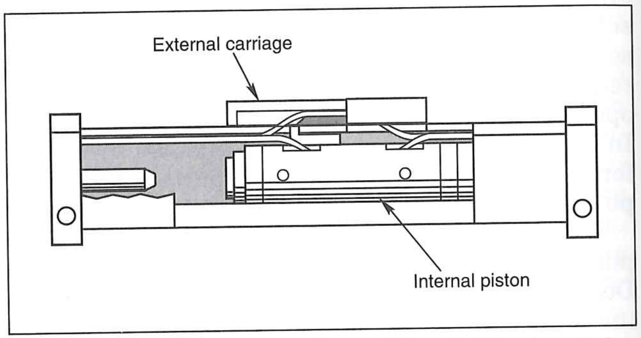

Fig. 9-20 — A carriage coupled to an internal piston travels between the end caps of a rodless cylinder.

Servoactuators. The coupling of electronic and fluid-power technology is becoming increasingly common, especially in electrohydraulic and electropneumatic actuators. Advances in transducers and electronic controls have resulted in cylinders that transmit high forces while allowing computer control of rod velocity, acceleration, and positioning accuracy to less than 0.001 in.

Key to the operation of these actuators is precisely sensing cylinder rod position. One method uses a linear displacement transducer mounted inside a hollowed-out piston rod. The transducer measures position and sends that information to an electronic controller which, in turn, signals a

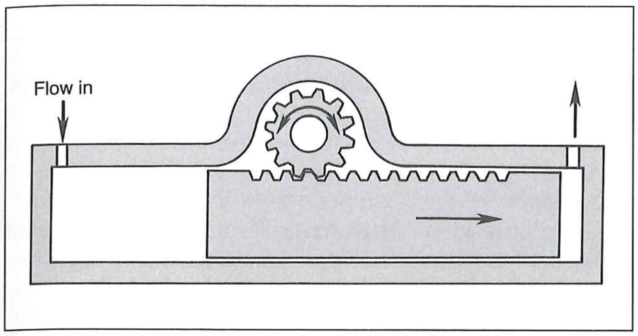

Fig. 9-21 — Fluid pressure slides the rack and rotates the pinion in this rotary actuator.

servo or proportional valve to adjust flow and thus cylinder position accordingly. All this happens in a fraction of a second.

Rotary Actuators

Rotary actuators turn an output shaft through a fixed arc. They are compact, simple, and efficient. The actuators produce high torque instantaneously in either direction, occupy little space, and are simple to mount. Two popular designs are:

Rack-and-pinion actuators. This type of actuator uses fluid pressure to drive a piston connected to a gear rack, which rotates a pinion, Fig. 9-21. Standard units are available that rotate either 90, 180, or 360°. Some actuators have two parallel piston-rack units; this doubles output torque. Outputs exceeding 30 million lb-in. are available.

Vane actuators. These units consist of a shaft mounted in a cylindrical housing, with one or more vanes attached to the shaft, Fig. 9-22. Applying fluid pressure to the vane rotates the shaft. An internal barrier between housing OD and shaft divides the interior volume into two chambers. For this reason, single-vane actuators are normally limited to about 280° of rotation, and double-vane actuators to about 100°. Torque is directly proportional to both vane area and effective fluid pressure. Some vane actuators have torque outputs exceeding 500,000 lb-in.

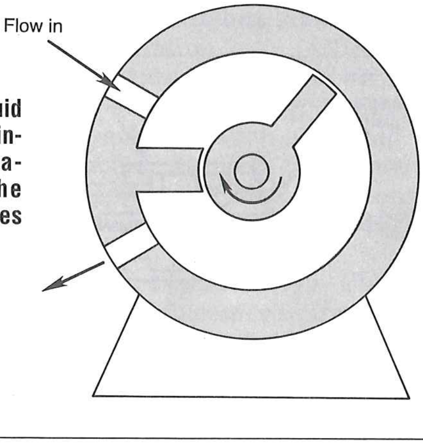

Fig. 9-22 — Fluid pressure in a single-vane actuator moves the vane and rotates the shaft.

Sizing Cylinders

Key considerations when sizing a cylinder are how big and how fast. An oversize cylinder has a healthy extra margin of force that can override a bit of misalignment, binding, or overload. However, extra cylinder size boosts cost, increases weight, and retards actuation.

Force. Cylinder force is a function of piston size and the fluid pressure. Force F in lb is found from the relationship $F = PA$ where P is pressure, psi; and A is the piston area, in.^{2} Area is determined from the piston diameter d_p by $A = (\pi d_p^2)/4$. Thus, a 1-in. diameter cylinder operating at 3,000 psi produces $F = (3{,}000)(\pi)(1^2)/4 = 2{,}356$ lb of force.

Note that double-acting cylinders produce more "push" force than "pull" force. That is because pressure acts on the rod side of the piston when the cylinder retracts, and the rod covers part of the piston surface. Effective piston area A_E is found by subtracting rod area from the total piston area, or $A_E = \pi(d_p^2 - d_r^2)/4$, where d_r is the rod diameter, in.^{2}

Therefore, if the 1-in. diameter cylinder mentioned previously has a 0.5-in. diameter rod, the cylinder produces $F = (3{,}000)(\pi)(1^2 - 0.5^2)/4 = 1{,}767$ lb of retraction force.

Speed. Velocity of a piston is determined jointly by its size and the flow volume into the cylinder. For steady-flow conditions, where flow Q in gpm and piston area A are known, velocity V can be approximated by $V(\text{ips}) = Q(\text{gpm})(231 \text{ in.}^3/\text{gal})/A\ (\text{in.}^2)(60 \text{ sec/min})$. For example, if flow to a 1-in. diameter cylinder is 2 gpm, rod velocity is $V = (2)(231)/(0.785)(60) = 9.8$ ips.

Rod size. The rod must be large enough to withstand the stresses imposed by load and cylinder. Generally, the manufacturer sizes the rod with a healthy margin of safety for the cylinder's maximum pressure rating.

Fluid Motors

Hydraulic and pneumatic motors usually take a back seat to electric motors, but they are useful in specialized applications that include:

- Where very high torque is required
- Where space or weight is limited and high power density is a must.
- Where the motor is subject to stalling and holding loads.
- Where safety considerations prevent use of electricity.

Basic configuration of fluid motors is much the same as the corresponding hydraulic pumps. The difference is that flow causes shaft rotation in a fluid motor. Common designs include:

Axial-piston motors. These contain several pistons that are driven by high-pressure fluid. The pistons are restrained at one end by an angled plate: As they bear against the plate, they generate a rotating force that may either twist the plate or the barrel in which the pistons are rotated. In most designs, the shaft is driven directly from either the barrel or the cam plate; in a few hydraulic motors, the shaft is driven through a differential-gear arrangement that permits low speed and high torque.

Axial-piston motors have high volumetric efficiency at both high and low speeds. In hydraulic designs, typical maximum torque ratings are to 20,000 lb-in. at pressures to 5,000 psi, with maximum speeds to approximately 4,500 rpm.

Radial-piston motors. The motors, Fig. 9-23, have pistons that radiate out from the drive shaft, and are arrayed in a number of ways. They can develop over one million lb-in. torque at pressures exceeding 5,000 psi. Speeds range from 0.1 to 2,000 rpm.

Gear-on-gear motors. This design is one of the most common for hydraulic units. They consist of a pair of matched spur or helical gears enclosed in a case, Fig. 9-24. These units typically develop maximum torques of about 6,000 lb-in. and speeds to 3,000 rpm.

Gear-within-gear motors. Often called gerotors, the motors are very compact for their displacement. An inner gear seals against an outer one to guard against fluid leakage. Tooth velocities and wear are low and power density is high. Gear-within-gear motors deliver torques exceeding 1,500 lb-in. at speeds to over 5,000 rpm.

Vane motors. Used for both pneumatic and hydraulic operation, vane motors consist of a slotted rotor mounted eccentrically within a circuit cam ring. Vanes in the rotor slots are free to move in and out, often spring-loaded to the outward position. As air or fluid enters the motor, it applies force against the vane, turning the rotor and allowing the fluid to sweep from inlet to outlet ports. A typical rating is 4,000 lb-in. torque at 2,500 psi and 4,000 rpm top speed.

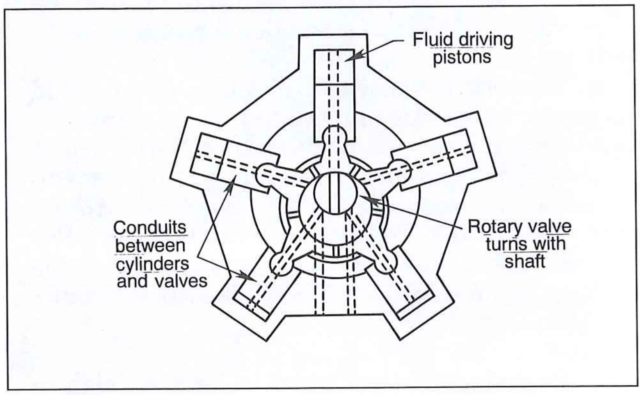

Fig. 9-23 — Reciprocating pistons cause shaft rotation in radial-piston motors.

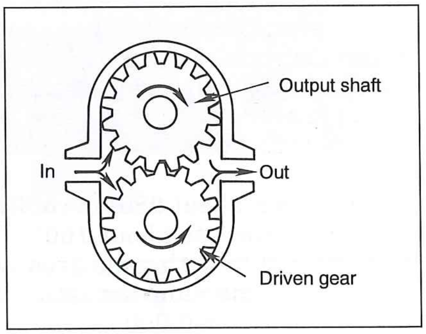

Fig. 9-24 — Fluid flow turns the gears and rotates the shaft in gear-on-gear motors.

Hydrostatic Drives

Hydrostatic drives are widely recognized as an excellent means of power transmission where variable output speed is required. Typically outperforming mechanical and electrical variable-speed drives and gear-type transmissions, they offer fast response, maintain precise speed under varying loads, and allow infinitely variable speed

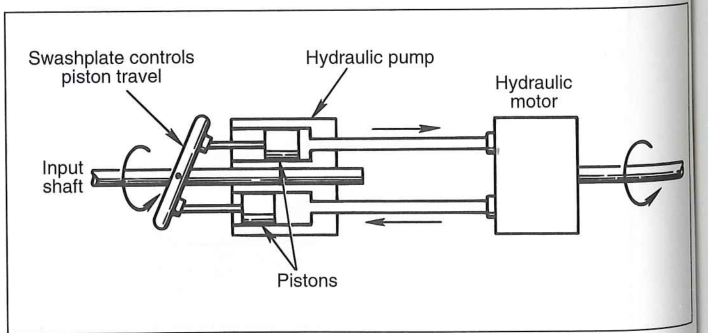

Fig. 9-25 — Adjusting pump flow in a hydrostatic transmission varies hydraulic motor output.

Transmission Sizing

Hydrostatic transmission size is often based on corner horsepower. This is the product of the maximum force and maximum speed required, even though these two conditions rarely occur simultaneously. Corner horsepower for vehicle propulsion is:

$H_c = F_t V/3{,}600\eta$

where

H_c = corner horsepower, kW;

F_t = maximum vehicle tractive force, N

V= maximum vehicle speed, km/h

η = final drive efficiency, %.

Transmission corner horsepower, H_t, is the product of maximum output torque (generally at a specified maximum pressure) and maximum output speed:

$H_t = T\tau N/9{,}550$

where

T = theoretical torque at maximum system pressure, N-m;

τ = torque efficiency, %

N = maximum transmission speed, rpm.

Initial transmission selection is made by comparing the results of these calculations. Selection is refined by considering the effects of duty cycle, final-drive ratio, rolling radius, prime-mover speed, and design life. Light-duty units (less than 20 hp) are used on equipment such as lawn tractors; medium-duty units (25 to 50 hp) on skid-steer loaders and similar vehicles; and heavy-duty transmissions (approximately 60 hp and higher) on large construction equipment.

control from zero to maximum.

A basic hydrostatic transmission is an entire hydraulic system. It contains pump, motor, and all controls in one package. Such a system provides advantages such as stepless adjustment of speed, torque, and power, and smooth, controllable acceleration. It can also be stalled without damage.

A typical hydrostatic transmission, Fig. 9-25, consists of a variable-displacement pump and either a fixed or variable-displacement motor. Adjusting pump flow varies hydraulic motor output. Various configurations produce either constant torque, constant power, or variable torque and power.

There are two types of hydrostatic transmissions — split and close coupled. A split transmission consists of a hydraulic motor mounted where torque is needed but with the hydraulic pump, heat exchanger, filters, valves, and controls mounted on a remote reservoir. Hose or tubing connects the motor and power unit. This arrangement offers flexibility, the most efficient use of space, and the best weight distribution.

Close-coupled, or integrated, transmissions have a hydraulic pump and motor that share a common valving surface. This arrangement provides an extremely short oil-flow path, eliminating potential leak points. A housing provides a self-contained oil reservoir, structural support for the rotating elements, and heat dissipation. The assembly is usually bolted directly to a mechanical differential axle to form a hydrostatic transaxle. Close-coupled transmissions are typically found in light-duty applications where tight space constraints require compact units and high-volume production mandates easy assembly.

Unlike gear transmissions, hydrostatics have a continuous power curve without peaks and valleys, and they can increase available torque without shifting gears. But despite the superior performance of hydrostatics, a major drawback has been higher cost compared to their mechanical counterparts. Manufacturers, however, continue to boost performance levels, produce smaller and lighter packages, and offer advanced electronic controls. These factors now often make hydrostatics an economical choice.

Fluids and Conductors

Constructing a hydraulic or pneumatic system involves the design or selection of numerous components and the determination of how they will all interact. A point often overlooked is that both the fluid and the means for moving it from one location to another are critical.

Fluids

The functions of hydraulic fluid are rather basic: to transmit power efficiently and lubricate moving parts.

Petroleum-based. These fluids are the most widely used for hydraulics because they are relatively inexpensive and perform well with little or no maintenance. They contain a base oil and additives that protect against rust, prevent wear, inhibit foaming, and lengthen life. Tough applications that require wide temperature range, extreme pressure protection, and long life call for premium-grade fluids.

Other fluids typically cost more than petroleum oils, restricting their use to special applications. Nonpetroleum fluids must also be evaluated for compatibility with the metals, seals, and elastomers in a system.

Fire-resistant. These fluids are used when petroleum oils present a hazard, especially when a broken hydraulic line could spray fluid into an ignition source. Among the major types of fire-resistant fluids are phosphate esters, water glycols, invert emulsions, and high-water-content fluids. These tend to be more expensive than petroleum-based fluids and have some performance deficiencies.

Synthetic oils. Generally consisting of esters or synthetic hydrocarbons, synthetic oils are premium hydraulic fluids. Qualities include wide temperature range, resistance to oxidation, and good lubricating properties. However, high price dictates that they be used only where absolutely necessary. They tend to be used where performance requirements are stringent, such as in systems that generate a lot of heat, where start-up temperatures are very low, or long life is a must.

Environmentally acceptable. EA fluids are used where hydraulic oil spilled into water, wetlands, and other sensitive areas can be environmentally damaging. Today's vegetable-oil-based EA fluids are suited for most hydraulic applications with virtually any type of pump or valve.

Conductors

Another basic consideration is getting fluid from pumps to the valves and actuators. Pipe and tubing are used when rigid lines are preferred. Pipe generally costs less than tubing, and is normally used where disassembly is very infrequent, large volumes of fluid must be handled, or where the line is long and straight. Tubing is stronger and neater than pipe, bends easily, and has a wider variety of fittings. Steel tubing is the only type recommended for high-pressure hydraulic service. Copper, aluminum, and plastic tubing are generally suitable for low-pressure applications and pneumatic circuits.

Hose is widely used in applications where lines must flex and bend. Hose construction has been standardized by SAE International under SAE J517, better known as 100R-series hoses. Reinforcement, construction, and dimensions vary among these designs, providing different pressure ratings and other specific performance features. For example, SAE 100R1 is a rubber hose with one layer of braided-wire reinforcement between a rubber inner tube and outer cover. Working pressures range from 375 to 3,000 psi, depending on the hose ID, and temperature range is from -40 to 200°F. This hose is commonly used on lower-pressure hydraulic lines.

Line Sizing

Pipe and tubing must be large enough to carry the required flow, and they must be strong enough to withstand internal pressures. Line size can be determined from the amount of fluid that must be carried and the maximum velocities at which the fluid may travel. Normally, good design practice dictates that fluid velocities should not exceed 10 to 15 fps in pressure lines and 2 to 5 fps in inlet or suction lines.

Average pipeline velocity can be approximated by:

$$Q = 2.45d^2V$$

where

Q is flow rate in gpm
d is the tube internal diameter, in.
V is velocity in fps.

To determine the required wall thickness of pipe and tubing, apply this basic equation:

$$T_t = pd_oM/2S,$$

where

p = pressure, psi
d_o = outside diameter, in.
M = safety factor
S = material tensile strength, psi.

Sizes are designated in 16ths of an inch by using a "dash" equivalent to the numerator of the fraction. Thus, "—10" is $^{10}/_{16}$ (or $^{5}/_{8}$) in. size. These dash sizes are marked on the hose.

Connectors

Connectors fill the gap between the hose or pipe and the mating port on a pump, valve, or actuator. Among the most common types are:

Pipe threads. The threads seal by metal-to-metal interference between fitting and housing, Fig. 9-26. They are widely used, inexpensive, and suitable for low-pressure service.

JIC 37°. The fittings, Fig. 9-27, seal by conical, metal-to-metal contact between mating male and female seats. They are the most widely used con-

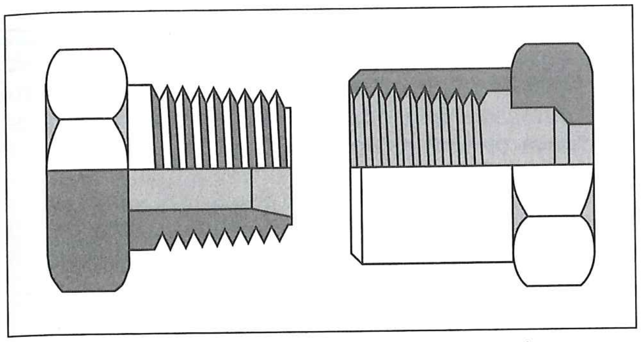

Fig. 9-26 — Pipe threads seal by metal-to metal interference.

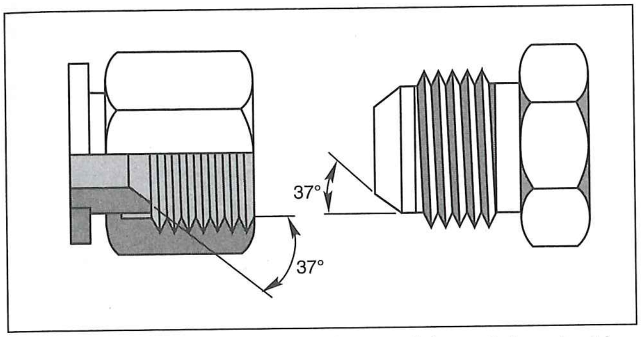

Fig. 9-27 — JIC couplings seal by metal-to-metal contact between mating seats.

nector in the U.S. Simple and inexpensive, JIC couplings perform well at low-to-moderate pressures.

Flat-face O-ring. These connectors have a recessed O-ring seal held in a circular groove on the male connector, Fig. 9-28. It mates with a flat, finished surface on the female end when assembled. These are suitable for 6,000 psi service.

SAE flange. The couplings are available in two domestic styles: Code 61 for 3,000 to 5,000 psi service (depending on size) and Code 62 for 6,000 psi service. In both, an elastomeric O-ring set in a groove on the flange mates with the flat machined surface of a pump, valve, or housing, Fig. 9-29. Four small mounting bolts attach the flange to the port.

SAE straight-thread. This port, Fig. 9-30, seals with an O-ring between threads and wrench flats. It is the best "leak-free" port for smaller sizes, suitable for 6,000 psi service.

Hydraulic and Pneumatic Filters

Filters are a must in air and hydraulic systems because dirty fluids have a short life, accelerate component wear, and lead to premature failure.

Typically a hydraulic system is cleaned by a single filter. Often this filter is located on the inlet line in front of the pump, to protect the pump and downstream components. So used, it is occasionally called a suction filter. Many pump manufacturers object to this filter location, claiming that it starves the pump inlet. In this case, the filter may be located at other points in the circuit, such as on the return line or in a pressure line.

Filtration for pneumatic systems is handled quite differently. In most industrial settings, compressed air is supplied from a single compressor to a large number of operating systems. Individual filters are used on the separate systems. Often the filters are combined with regulators and sometimes lubricators, forming a filter-regulator-lubri-

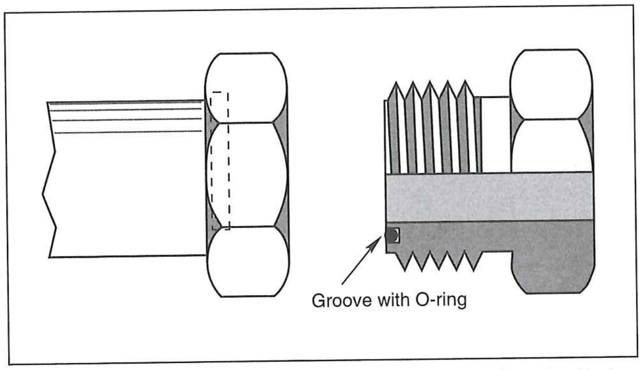

Fig. 9-28 — Flat-face O-ring fittings seal by pressing the O-ring against a finished metal surface.

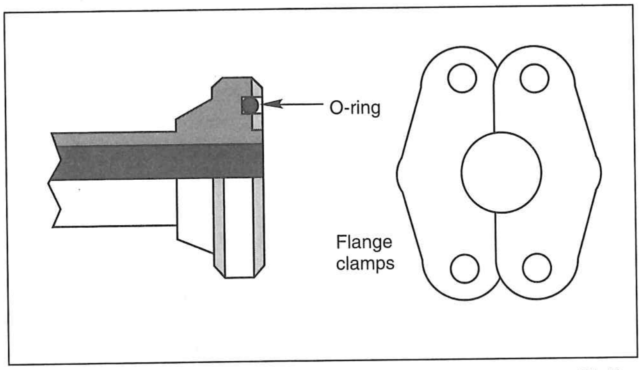

Fig. 9-29. An elastomeric O-ring in a flange fitting mates with the flat machined surface of a pump, valve, or housing.

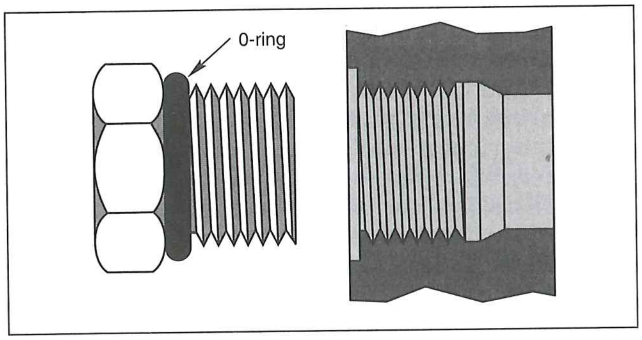

Fig. 9-30 — The straight-thread port seals with an O-ring between threads and wrench flats.

Filter Performance

The Beta ratio, a system for rating filter performance, is expressed by:

$\beta_x = N_u / N_d$

where

β_x = Beta filtration rating for particles larger than x microns,

N_u = number of particles larger than x microns upstream of the filter, and

N_d = number of particles larger than x microns downstream of the filter.

The Beta filtration rating can also be converted into an efficiency rating, E_x. Efficiency rating is expressed as a percentage of the filter medium's ability to remove particles larger than x microns:

$E_x = ((\beta - 1)/\beta) \times 100\%$.

A filter with a reported rating of $\beta_3 > 100$ removes a minimum of 99% of all particles larger than 3 μm. Similarly, a filter rated at $\beta_{10} > 20$ captures a minimum of 95% of all particles larger than 10 μm. Clearly, the element rated at $\beta_3 > 100$ removes many more small particles than the element rated at $\beta_{10} > 20$, especially in the 3 to 10-μm range.

cator (FRL) for the system.

Filters are rated on the ability to retain contaminants of certain size levels.

Beta rating. A widely used rating system for filter-media performance, the Beta rating is a standard that attempts to give both users and manufacturers an accurate means of comparing filters. The rating is a ratio that compares the number of particles of a given size or greater in the fluid upstream of the filter to the number of particles of the same size or greater in the downstream fluid.

Absolute rating. The diameter of the largest hard, spherical particle that passes through a filter under controlled conditions determines the absolute filtration rating. The rating is also an indication of the largest opening through a filter.

Nominal rating. Determined by the filter manufacturer, nominal filtration rating is an arbitrary value. The rating system refers more to the types and sizes of holes in the filter medium than actual filter performance. Nominal filter ratings have many limitations. First, they do not present a clear indication of the largest-size particle that can pass through a filter. Second, it is a nonstandard system that lacks consistency from one manufacturer to another.

Fluid-power Standards

Today, U.S. standards still dominate the American fluid-power industry, covering virtually every component and aspect, from cylinder dimensions to valve configurations. The central clearinghouse for these standards is the National Fluid Power Association.

International Standards Organization (ISO) standards, widespread in Europe, are gaining importance here with the influx of off-shore machinery to the U.S. Also, many domestic manufacturers now offer fluid-power components made to ISO standards.

Hose and connectors are most often made to SAE standards. However, a note of caution is in order here. With a lot of foreign-made machinery being imported to the U.S., a problem that has surfaced in recent years is the proliferation of hydraulic connectors from suppliers around the world. This dramatically increases the possibility of mismatching threads and seats, guaranteeing leakage. Some couplings, though made to different standards, fit close enough to be assembled, although they should not be used interchangeably. When dealing with off-shore couplings, check styles and dimensions. Most manufacturers and distributors of connectors have kits to measure threads, seats, and angles, and these are a good investment.

For more information:

National Fluid Power Association
3333 North Mayfair Road
Milwaukee, WI 53222
414-778-3344

SAE International
400 Commonwealth Drive
Warrendale, PA 15096
412-776-4841