Pneumatics and hydraulics

Hydraulic motors

Dr. Ahmad Al-Mahasneh

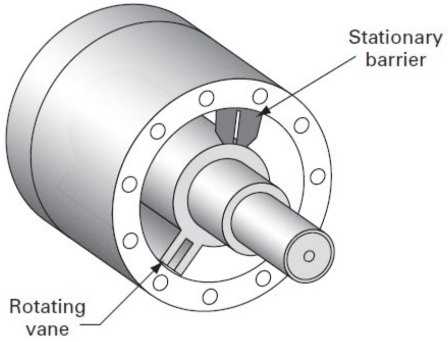
Introduction

- Hydraulic motors extract energy from a fluid and convert it to mechanical energy to perform useful work.
- Hydraulic motors can be of the limited rotation or the continuous rotation type.
- A limited rotation motor, which is also called a rotary actuator or an oscillating motor, can rotate clockwise and counterclockwise but through less than one complete revolution.
- A continuous rotation hydraulic motor, which is simply called a hydraulic motor, can rotate continuously at an rpm that is determined by the motor's input flow rate.
- In reality, hydraulic motors are pumps that have been redesigned to withstand the different forces that are involved in motor applications.
- As a result, hydraulic motors are typically of the gear, vane, or piston configuration.

Figure 7-1. Hydraulic impact wrench. *(Courtesy of Greenlee Textron, Inc., Rockford, Illinois.)*

LIMITED ROTATION HYDRAULIC MOTORS

- A limited rotation hydraulic motor (also called *oscillation motor* or *rotary actuator*) provides rotary output motion over a finite angle.
- This device produces high instantaneous torque in either direction and requires only a small space and simple mountings.
- Rotary actuators consist of a chamber or chambers containing the working fluid and a movable surface against which the fluid acts.
- The movable surface is connected to an output shaft to produce the output motion.
- In a direct acting vane-type actuator fluid under pressure is directed to one side of the moving vane, causing it to rotate.
- This type provides about 280° of rotation.
- Vane unit capacity ranges from 3 to 1 million in · lb.
- Rotary actuators are available with working pressures up to 5000 psi.
- They are typically mounted by foot, flange, and end mounts.
- Cushioning devices are available in most designs.
- An actual rotary actuator contains two vanes, the maximum angle of rotation is reduced to about 100°. However, the torque-carrying capacity is twice that obtained by a single-vane design.
- This particular unit can operate with either air or oil at pressures up to 1000 psi.



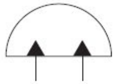


Figure 7-2. Rotary actuator. *(Courtesy of Rexnord Inc., Hydraulic Components Division, Racine, Wisconsin.)*

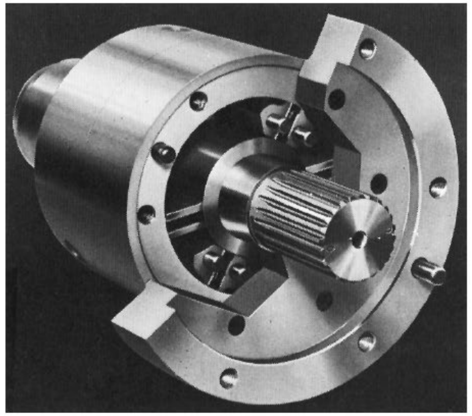


Figure 7-3. Rotary actuator. *(Courtesy of Ex-Cell-O Corp., Troy, Michigan.)*

Analysis of Torque Capacity

The following nomenclature and analysis are applicable to a limited rotation hydraulic motor containing a single rotating vane:

R_R = outer radius of rotor (in, m)

R_V = outer radius of vane (in, m)

L = width of vane (in, m)

p = hydraulic pressure (psi, Pa)

F = hydraulic force acting on vane (lb, N)

A = surface area of vane in contact with oil (in^2, m^2)

T = torque capacity (in · lb, N · m)

The force on the vane equals the pressure times the vane surface area:

$$F = pA = p(R_V - R_R)L$$

The torque equals the vane force times the mean radius of the vane:

$$T = p(R_V - R_R)L\frac{(R_V + R_R)}{2}$$

On rearranging, we have

$$T = \frac{pL}{2}(R_V^2 - R_R^2) \qquad \textbf{(7-1)}$$

Analysis of Torque Capacity

A second equation for torque can be developed by noting the following relationship for volumetric displacement V_D:

$$V_D = \pi(R_V^2 - R_R^2)L \qquad \textbf{(7-2)}$$

Combining Eqs. (7-1) and (7-2) yields

$$T = \frac{pV_D}{2\pi} \qquad \textbf{(7-3)}$$

Observe from Eq. (7-3) that torque capacity can be increased by increasing the pressure or volumetric displacement or both.

Analysis of Torque Capacity

EXAMPLE 7-1

A single-vane rotary actuator has the following physical data:

$$\text{outer radius of rotor} = 0.5 \text{ in}$$
$$\text{outer radius of vane} = 1.5 \text{ in}$$
$$\text{width of vane} = 1 \text{ in}$$

If the torque load is 1000 in · lb, what pressure must be developed to overcome the load?

Solution Use Eq. (7-2) to solve for the volumetric displacement:

$$V_D = \pi(1.5^2 - 0.5^2)(1) = 6.28 \text{ in}^3$$

Then use Eq. (7-3) to solve for the pressure:

$$p = \frac{2\pi T}{V_D} = \frac{2\pi(1000)}{6.28} = 1000 \text{ psi}$$

Applications of rotary actuators

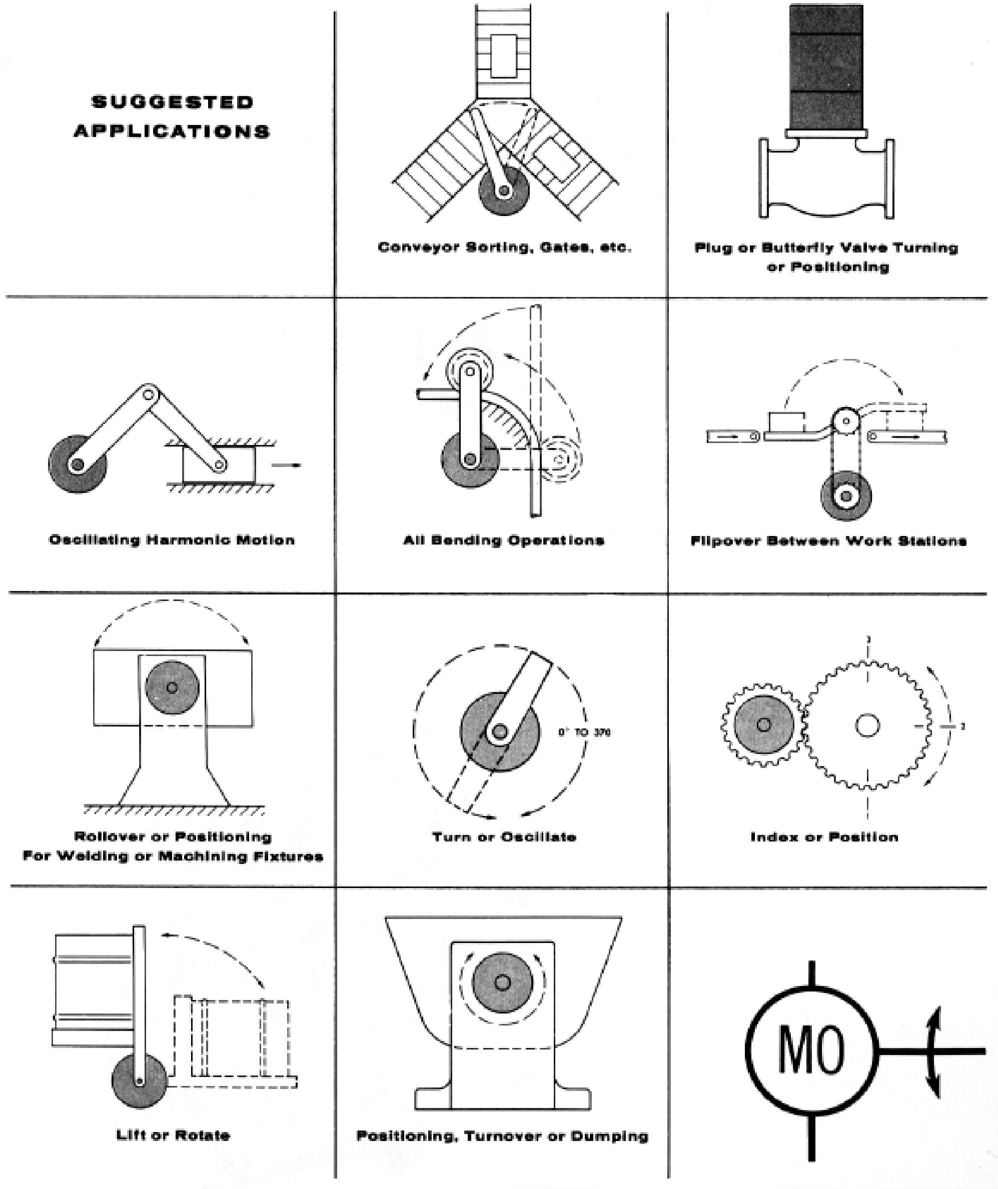
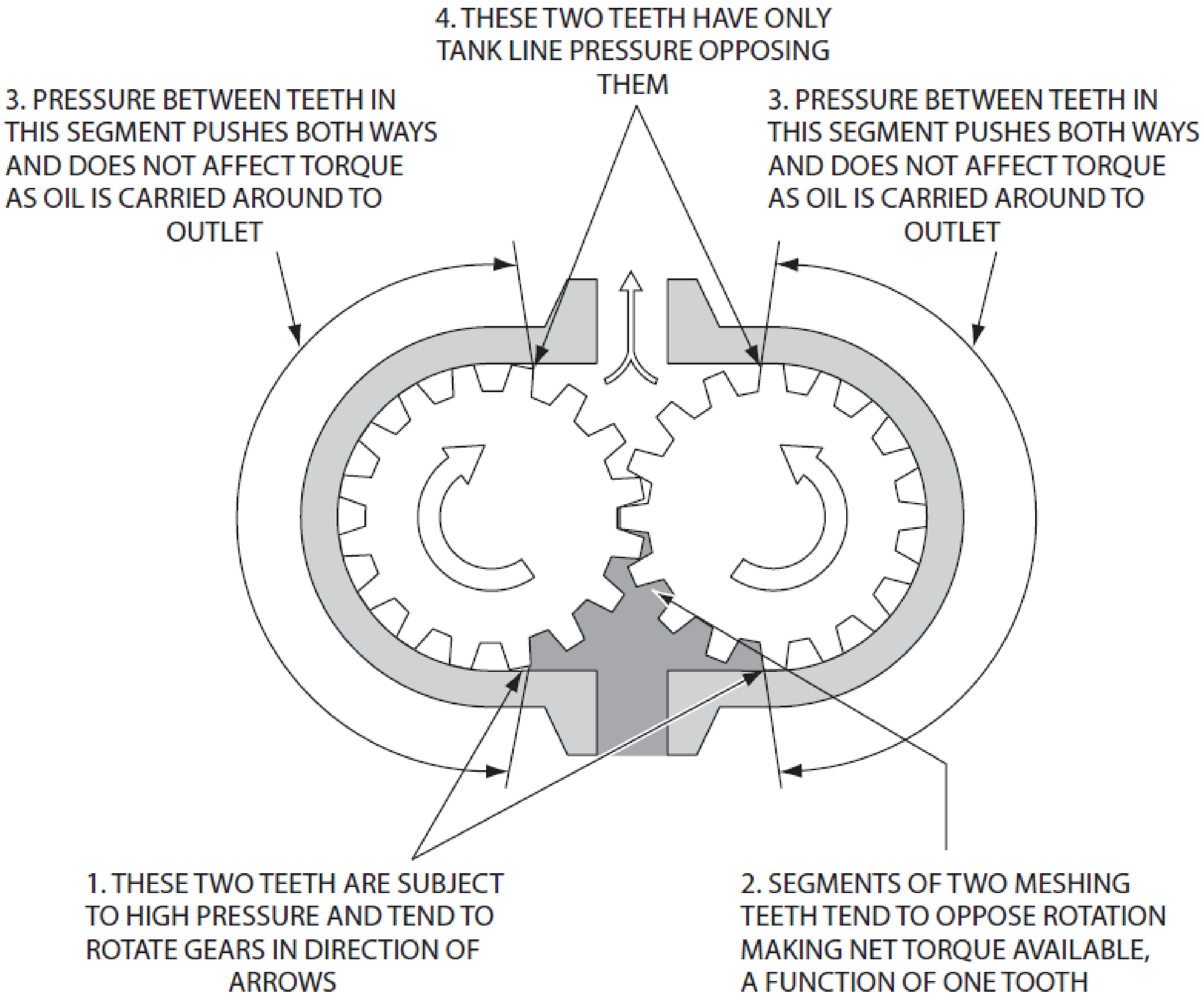


Figure 7-4. Applications of rotary actuators. *(Courtesy of Carter Controls, Inc., Lansing, Illinois.)*

GEAR MOTORS



- Gear motors are normally limited to 2000-psi operating pressures and 2400 rpm operating speeds.
- They are available with a maximum flow capacity of 150 gpm.
- The main advantages of a gear motor are its simple design and subsequent low cost.

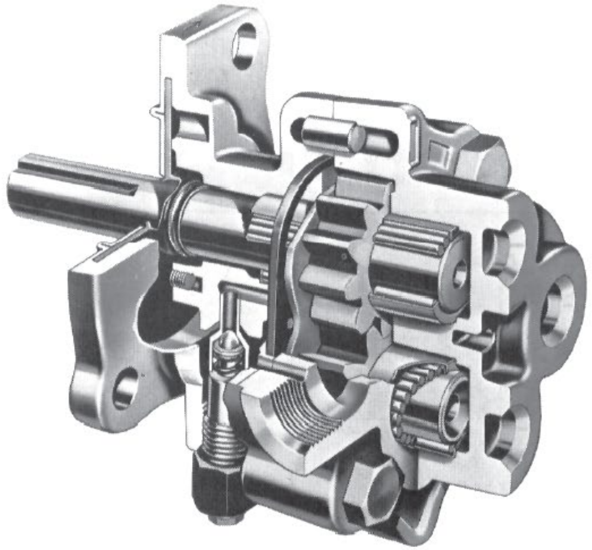
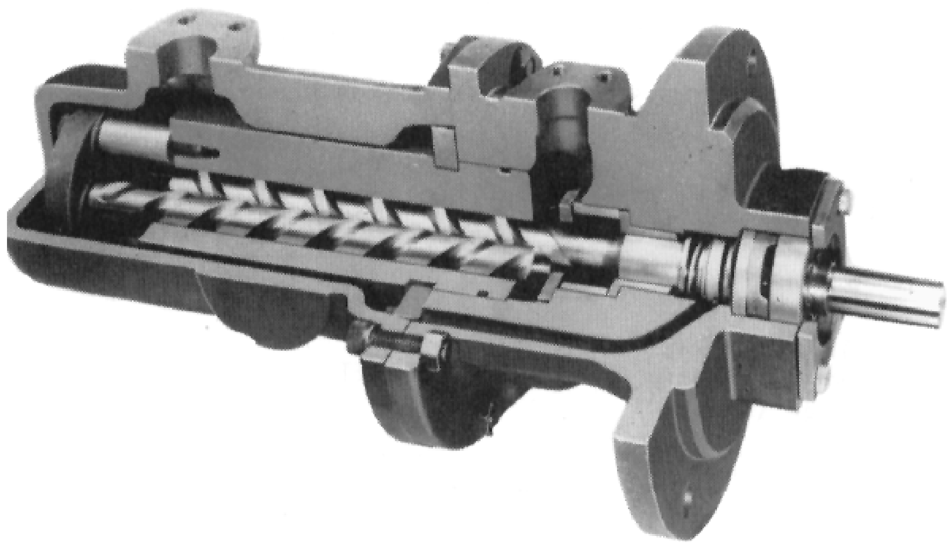


Figure 7-6. External gear motor. *(Courtesy of Webster Electric Company, Inc., subsidiary of STA-RITE Industries, Inc., Racine, Wisconsin.)*

GEAR MOTORS

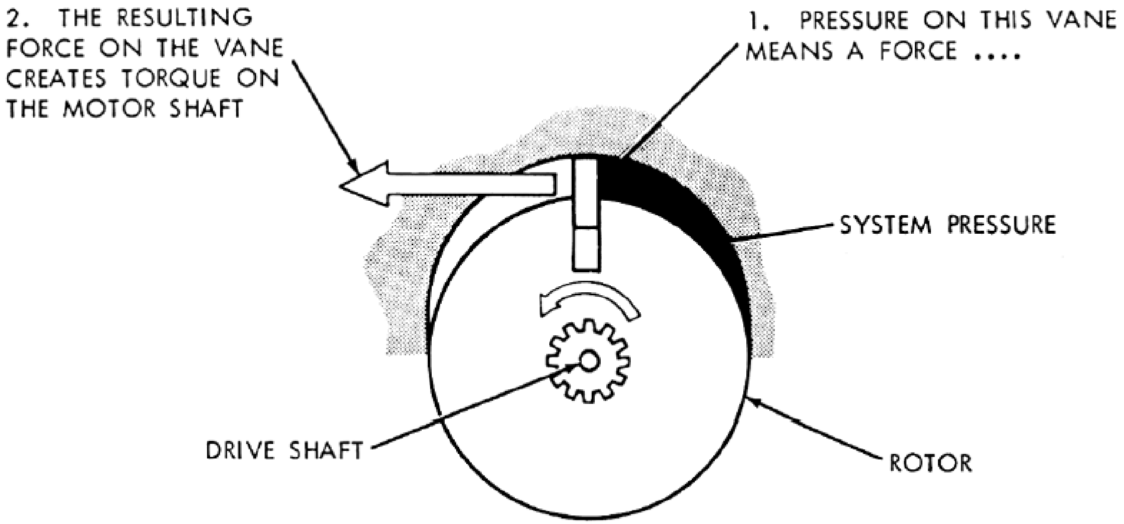
- Hydraulic motors can also be of the internal gear design.
- This type can operate at higher pressures and speeds and also has greater displacements than the external gear motor.

- screw-type hydraulic motors exist using three meshing screws (a power rotor and two idler rotors).
- The rolling screw set results in extremely quiet operation.
- Torque is developed by differential pressure acting on the thread area of the screw set.
- Motor torque is proportional to differential pressure across the screw set.
- This particular motor can operate at pressures up to 3000 psi and can possess volumetric displacements up to 13.9 in3.

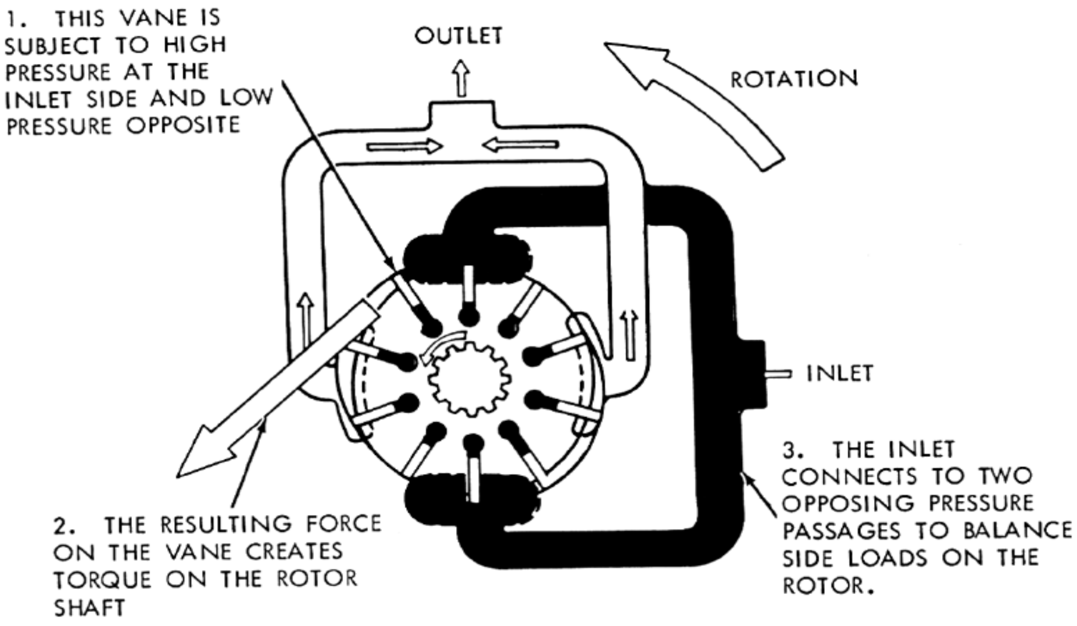


VANE MOTORS

- Vane motors develop torque by the hydraulic pressure acting on the exposed surfaces of the vanes, which slide in and out of the rotor connected to the drive shaft
- As the rotor revolves, the vanes follow the surface of the cam ring because springs (not shown in Figure 7-8) are used to force the vanes radially outward.
- No centrifugal force exists until the rotor starts to revolve.
- Therefore, the vanes must have some means other than centrifugal force to hold them against the cam ring.
- Some designs use springs, whereas other types use pressure-loaded vanes.
- The sliding action of the vanes forms sealed chambers, which carry the fluid from the inlet to the outlet.
- Pressure buildup at either port is directed to two interconnected cavities located 180° apart.
- The side loads that are created are therefore canceled out.
- Since vane motors are hydraulically balanced, they are fixed displacement units.
- This type of motor is available to operate at pressures up to 2500 psi and at speeds up to 4000 rpm.
- The maximum flow delivery is 250 gpm.



VIEW A BASIC OPERATION



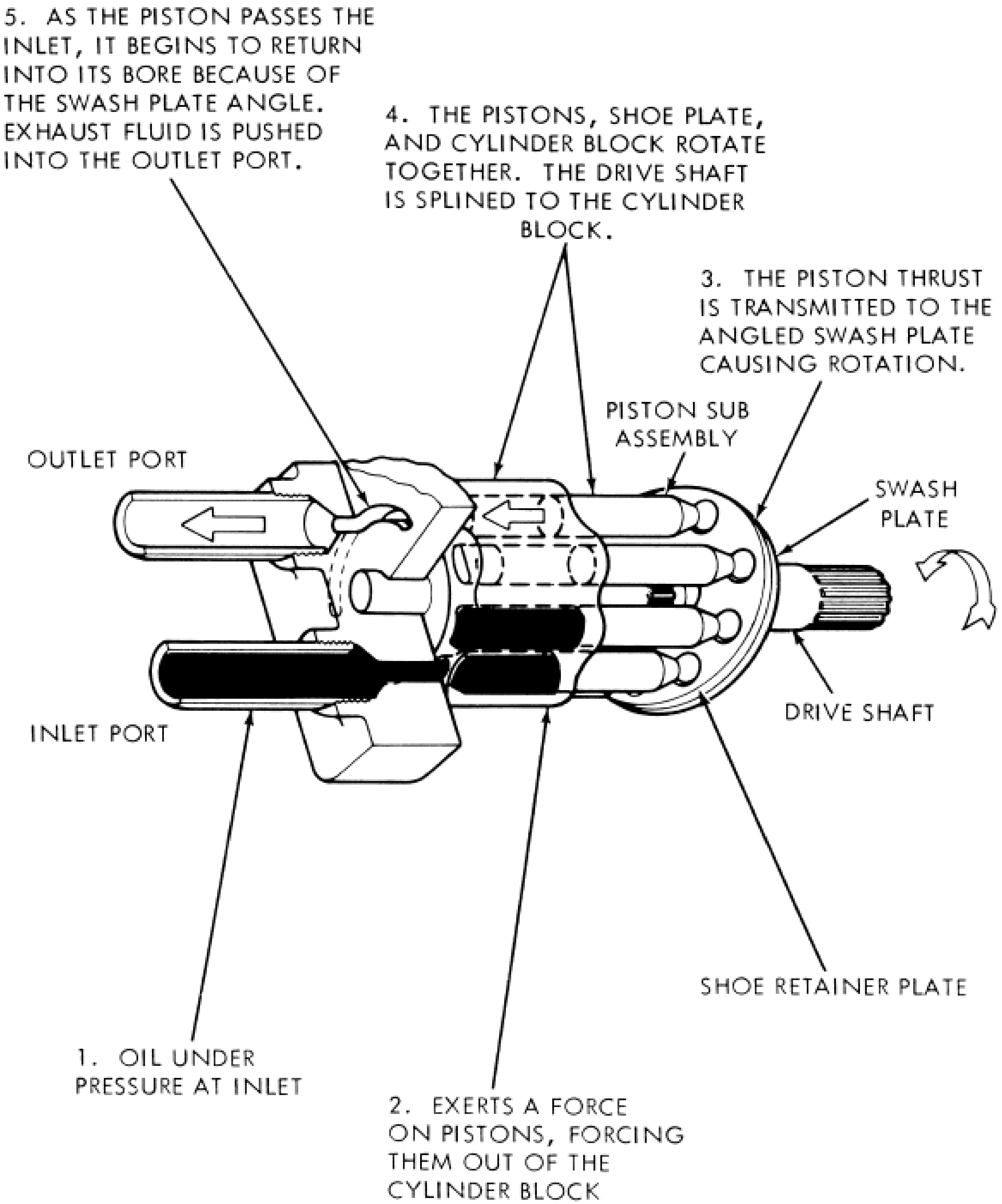
VIEW B BALANCED DESIGN

PISTON MOTORS

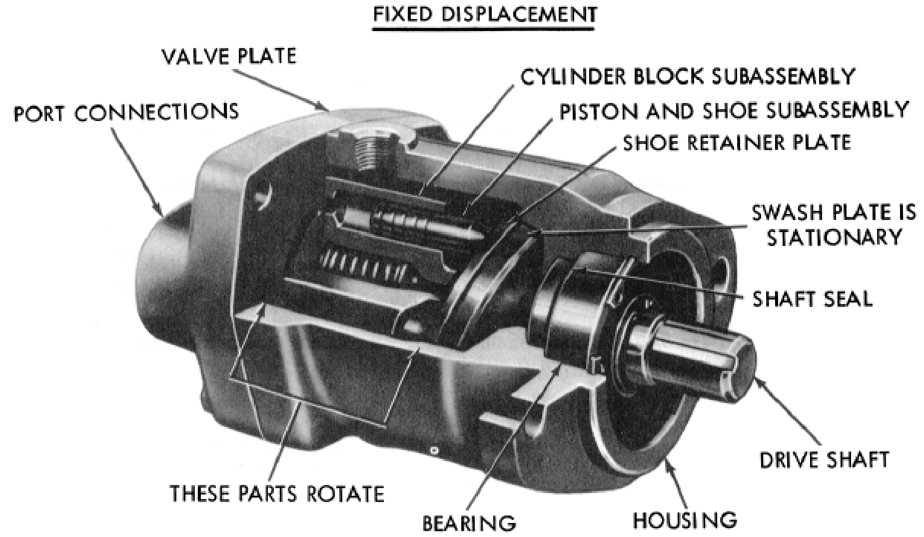
- Piston motors can be either fixed or variable displacement units.
- They generate torque by pressure acting on the ends of pistons reciprocating inside a cylinder block.

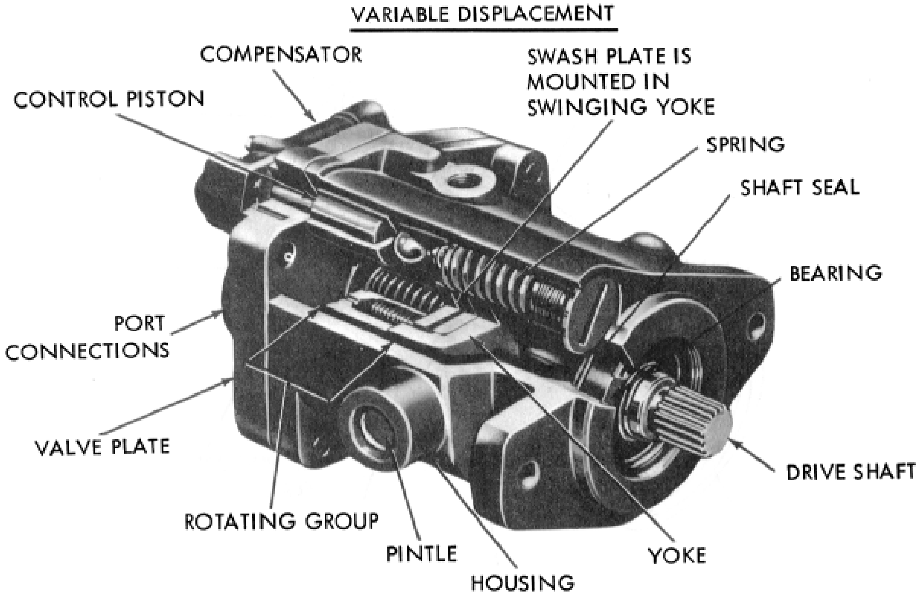
1. In-Line Piston Motor (Swash Plate Design)
2. Axial Piston Motor (Bent-Axis Design)

- Piston motors are the most efficient of the three basic types and are capable of operating at the highest speeds and pressures.
- Operating speeds of 12,000 rpm and pressures of 5000 psi can be obtained with piston motors.
- Large piston motors are capable of delivering flows up to 450 gpm.



PISTON MOTORS





PISTON MOTORS

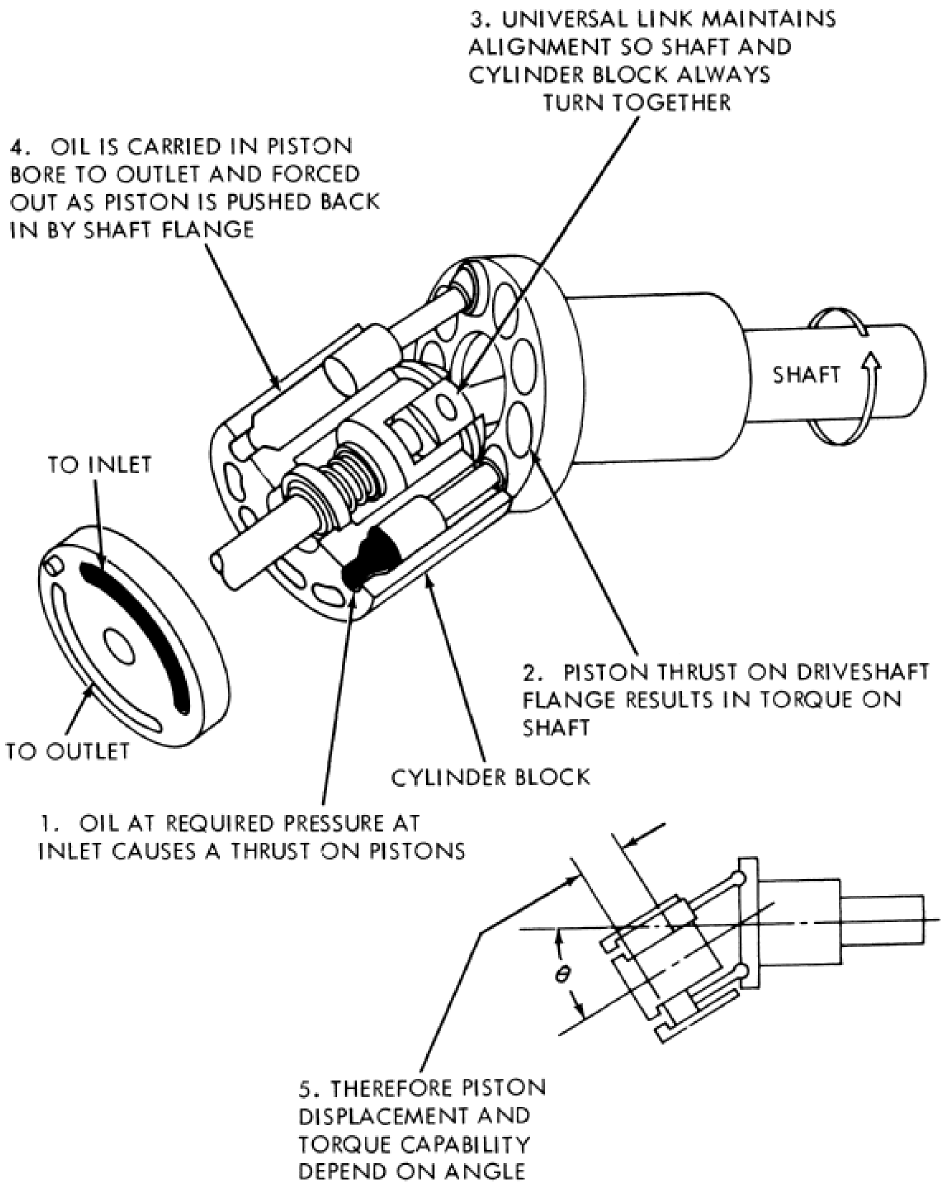


Figure 7-14. Bent-axis piston motor. *(Courtesy of Sperry Vickers, Sperry Rand Corp., Troy, Michigan.)*

Figure 7-15. Fixed displacement bent-axis piston motor. *(Courtesy of Sperry Vickers, Sperry Rand Corp., Troy, Michigan.)*

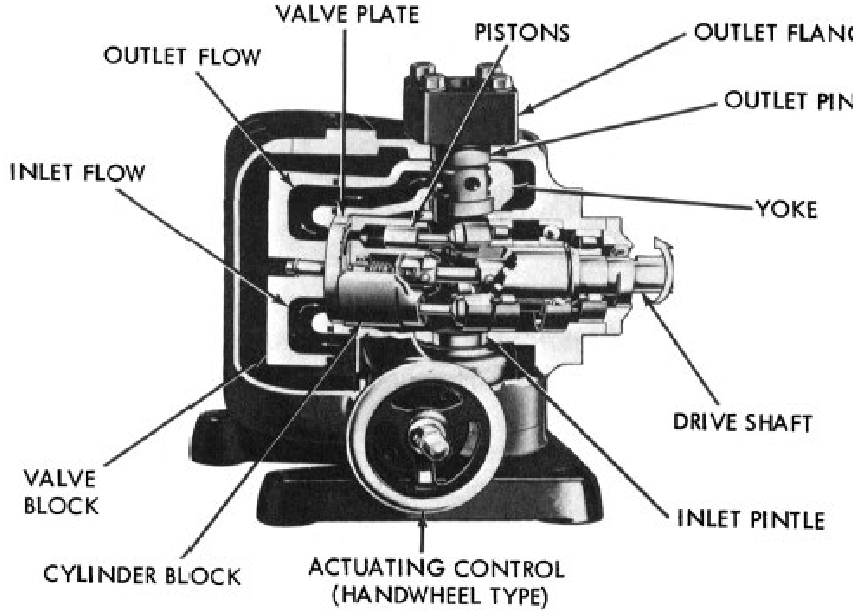


Figure 7-16. Variable displacement bent-axis piston motor with handwheel control. *(Courtesy of Sperry Vickers, Sperry Rand Corp., Troy, Michigan.)*

HYDRAULIC MOTOR THEORETICAL TORQUE, POWER, AND FLOW RATE

- Due to frictional losses, a hydraulic motor delivers less torque than it should theoretically.
- The theoretical torque (which is the torque that a frictionless hydraulic motor would deliver) can be determined by the following equation developed for limited rotation hydraulic actuators.

$$T_T(\text{in}\cdot\text{lb}) = \frac{V_D(\text{in}^3/\text{rev}) \times p(\text{psi})}{2\pi} \quad \textbf{(7-4)}$$

Using metric units, we have

$$T_T(\text{N}\cdot\text{m}) = \frac{V_D(\text{m}^3/\text{rev}) \times p(\text{Pa})}{2\pi} \quad \textbf{(7-4M)}$$

Thus, the theoretical torque is proportional not only to the pressure but also to the volumetric displacement.

The theoretical horsepower (which is the horsepower a frictionless hydraulic motor would develop) can also be mathematically expressed:

$$\text{HP}_T = \frac{T_T(\text{in}\cdot\text{lb}) \times N(\text{rpm})}{63{,}000}$$

$$= \frac{V_D(\text{in}^3/\text{rev}) \times p(\text{psi}) \times N(\text{rpm})}{395{,}000} \quad \textbf{(7-5)}$$

In metric units,

$$\text{theoretical power (W)} = T_T(\text{N}\cdot\text{m}) \times N(\text{rad/s})$$

$$= \frac{V_D(\text{m}^3/\text{rev}) \times p(\text{Pa}) \times N(\text{rad/s})}{2\pi} \quad \textbf{(7-5M)}$$

Also, due to leakage, a hydraulic motor consumes more flow rate than it should theoretically. The theoretical flow rate is the flow rate a hydraulic motor would consume if there were no leakage. As is the case for pumps, the following equation gives the relationship among speed, volumetric displacement, and theoretical flow rate.

$$Q_T(\text{gpm}) = \frac{V_D(\text{in}^3/\text{rev}) \times N(\text{rpm})}{231} \quad \textbf{(7-6)}$$

or

$$Q_T(\text{m}^3/\text{s}) = V_D(\text{m}^3/\text{rev}) \times N(\text{rev/s}) \quad \textbf{(7-6M)}$$

HYDRAULIC MOTOR THEORETICAL TORQUE, POWER, AND FLOW RATE

- Due to frictional losses, a hydraulic motor delivers less torque than it should theoretically.
- The theoretical torque (which is the torque that a frictionless hydraulic motor would deliver) can be determined by the following equation developed for limited rotation hydraulic actuators.

EXAMPLE 7-2

A hydraulic motor has a 5-in^3 volumetric displacement. If it has a pressure rating of 1000 psi and it receives oil from a 10-gpm theoretical flow-rate pump, find the motor

a. Speed
b. Theoretical torque
c. Theoretical horsepower

Solution

a. From Eq. (7-6) we solve for motor speed:

$$N = \frac{231Q_T}{V_D} = \frac{(231)(10)}{5} = 462 \text{ rpm}$$

b. Theoretical torque is found using Eq. (7-4):

$$T_T = \frac{V_D p}{2\pi} = \frac{(5)(1000)}{2\pi} = 795 \text{ in} \cdot \text{lb}$$

c. Theoretical horsepower is obtained from Eq. (7-5):

$$HP_T = \frac{T_T N}{63{,}000} = \frac{(795)(462)}{63{,}000} = 5.83 \text{ HP}$$

HYDRAULIC MOTOR PERFORMANCE

1. **Volumetric efficiency (η_v).** The volumetric efficiency of a hydraulic motor is the inverse of that for a pump. This is because a pump does not produce as much flow as it should theoretically, whereas a motor uses more flow than it should theoretically due to leakage. Thus, we have

$$\eta_v = \frac{\text{theoretical flow-rate motor should consume}}{\text{actual flow-rate consumed by motor}} = \frac{Q_T}{Q_A} \quad \textbf{(7-7)}$$

2. **Mechanical efficiency (η_m).** The mechanical efficiency of a hydraulic motor is the inverse of that for a pump. This is because due to friction, a pump requires a greater torque than it should theoretically whereas a motor produces less torque than it should theoretically. Thus, we have

$$\eta_m = \frac{\text{actual torque delivered by motor}}{\text{torque motor should theoretically deliver}} = \frac{T_A}{T_T} \quad \textbf{(7-8)}$$

Equations (7-9) and (7-10) allow for the calculation of T_T and T_A, respectively:

$$T_T(\text{in} \cdot \text{lb}) = \frac{V_D(\text{in}^3) \times p(\text{psi})}{2\pi} \quad \textbf{(7-9)}$$

or

$$T_T(\text{N} \cdot \text{m}) = \frac{V_D(\text{m}^3/\text{rev}) \times p(\text{Pa})}{2\pi} \quad \textbf{(7-9M)}$$

$$T_A(\text{in} \cdot \text{lb}) = \frac{\text{actual HP delivered by motor} \times 63{,}000}{N(\text{rpm})} \quad \textbf{(7-10)}$$

or

$$T_A(\text{N} \cdot \text{m}) = \frac{\text{actual wattage delivered by motor}}{N(\text{rad/s})} \quad \textbf{(7-10M)}$$

3. **Overall efficiency (η_o).** As in the case for pumps, the overall efficiency of a hydraulic motor equals the product of the volumetric and mechanical efficiencies.

$$\eta_o = \eta_v \eta_m \quad \textbf{(7-11)}$$

$$= \frac{\text{actual power delivered by motor}}{\text{actual power delivered to motor}}$$

In English units, we have

$$\eta_o = \frac{\dfrac{T_A(\text{in} \cdot \text{lb}) \times N(\text{rpm})}{63{,}000}}{\dfrac{p(\text{psi}) \times Q_A(\text{gpm})}{1714}} \quad \textbf{(7-12)}$$

In metric units, we have

$$\eta_o = \frac{T_A(\text{N} \cdot \text{m}) \times N(\text{rad/s})}{p(\text{Pa}) \times Q_A(\text{m}^3/\text{s})} \quad \textbf{(7-12M)}$$

Note that the actual power delivered to a motor by the fluid is called *hydraulic power* and the actual power delivered to a load by a motor via a rotating shaft is called *brake power*.

HYDRAULIC MOTOR PERFORMANCE

EXAMPLE 7-3

A hydraulic motor has a displacement of 10 in³ and operates with a pressure of 1000 psi and a speed of 2000 rpm. If the actual flow rate consumed by the motor is 95 gpm and the actual torque delivered by the motor is 1500 in · lb, find

a. η_v

b. η_m

c. η_o

d. The actual horsepower delivered by the motor

Solution

a. To find η_v, we first calculate the theoretical flow rate:

$$Q_T = \frac{V_D N}{231} = \frac{(10)(2000)}{231} = 86.6 \text{ gpm}$$

$$\eta_v = \frac{Q_T}{Q_A} = \frac{86.6}{95} = 0.911 = 91.1\%$$

b. To find η_m, we need to calculate the theoretical torque:

$$T_T = \frac{V_D p}{2\pi} = \frac{(10)(1000)}{2\pi} = 1592 \text{ in} \cdot \text{lb}$$

$$\eta_m = \frac{T_A}{T_T} = \frac{1500}{1592} = 0.942 = 94.2\%$$

c. $$\eta_o = \eta_v \eta_m = 0.911 \times 0.942 = 0.858 = 85.8\%$$

d. $$HP_A = \frac{T_A N}{63{,}000} = \frac{(1500)(2000)}{63{,}000} = 47.6 \text{ hp}$$

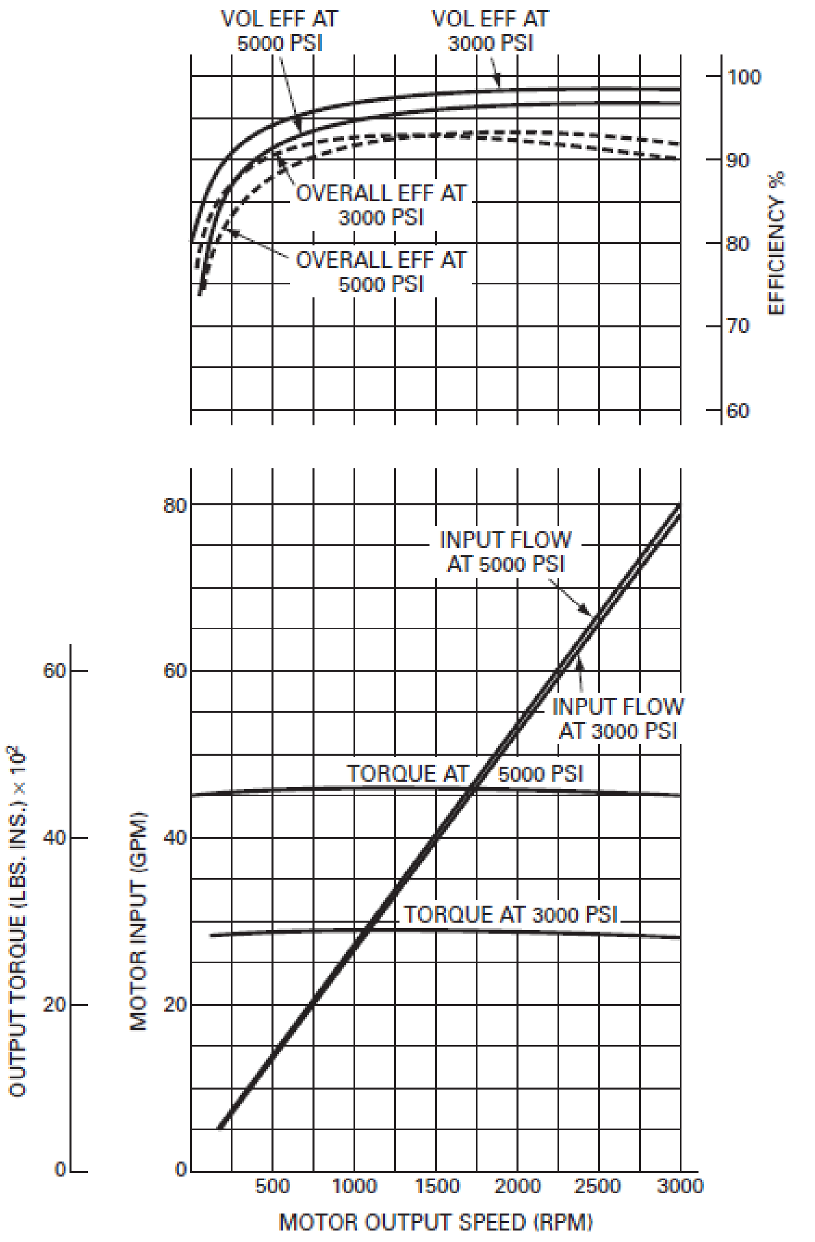
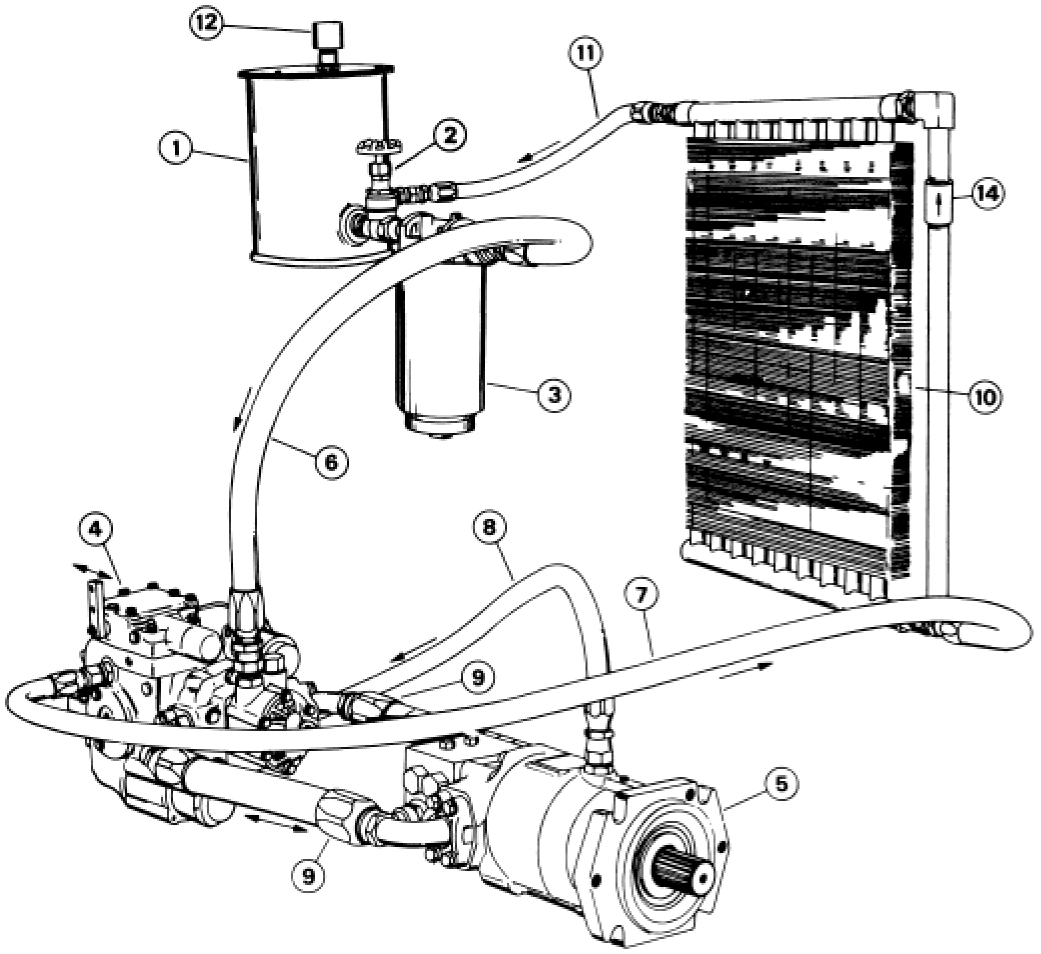


Figure 7-17. Performance curves for 6-in³ variable displacement motor. *(Courtesy of Abex Corp., Denison Division, Columbus, Ohio.)*

HYDROSTATIC TRANSMISSIONS

A system consisting of a hydraulic pump, a hydraulic motor, and appropriate valves and pipes can be used to provide adjustable-speed drives for many practical applications. Such a system is called a *hydrostatic transmission*. There must, of course, be a prime mover such as an electric motor or gasoline engine. Applications in existence include tractors, rollers, front-end loaders, hoes, and lift trucks. Some of the advantages of hydrostatic transmissions are the following:

1. Infinitely variable speed and torque in either direction and over the full speed and torque ranges
2. Extremely high power-to-weight ratio
3. Ability to be stalled without damage
4. Low inertia of rotating members, permitting fast starting and stopping with smoothness and precision
5. Flexibility and simplicity of design



1. Reservoir
2. Shut-off Valve
3. Filter
4. Variable Displacement Pump
5. Fixed Displacement Motor
6. Inlet Line
7. Pump Case Drain Line
8. Motor Case Drain Line
9. High Pressure Lines
10. Heat Exchanger
11. Reservoir Return Line
12. Reservoir Fill Cap or Breather
14. Heat Exchanger By-pass Valve

Figure 7-18. Hydrostatic transmission system. *(Courtesy of Sundstrand Hydro-Transmission Division, Sundstrand Corp., Ames, Iowa.)*

HYDROSTATIC TRANSMISSIONS

EXAMPLE 7-4

A hydrostatic transmission, operating at 1000-psi pressure, has the following characteristics:

Pump	*Motor*
$V_D = 5 \text{ in}^3$	$V_D = ?$
$\eta_v = 82\%$	$\eta_v = 92\%$
$\eta_m = 88\%$	$\eta_m = 90\%$
$N = 500$ rpm	$N = 400$ rpm

Find the

a. Displacement of the motor

b. Motor output torque

Solution

a.

$$\text{pump theoretical flow rate} = \frac{\text{displacement of pump} \times \text{pump speed}}{231}$$

$$= \frac{(5)(500)}{231} = 10.8 \text{ gpm}$$

$$\text{pump actual flow rate} = \text{pump theoretical flow rate} \times \text{pump volumetric efficiency}$$

$$= (10.8)(0.82) = 8.86 \text{ gpm}$$

Since the motor actual flow rate equals the pump actual flow rate we have

$$\text{motor theoretical flow rate} = \text{pump actual flow rate} \times \text{motor volumetric efficiency}$$

$$= (8.86)(0.92) = 8.15 \text{ gpm}$$

$$\text{motor displacement} = \frac{\text{motor theoretical flow rate} \times 231}{\text{motor speed}}$$

$$= \frac{(8.15)(231)}{400} = 4.71 \text{ in}^3$$

b. hydraulic HP delivered to motor =

$$\frac{\text{system pressure} \times \text{actual flow rate to motor}}{1714}$$

$$= \frac{(1000)(8.86)}{1714} = 5.17 \text{ hp}$$

$$\text{brake HP delivered by motor} = 5.17 \times 0.92 \times 0.90 = 4.28$$

$$\text{torque delivered by motor} = \frac{\text{HP delivered by motor} \times 63{,}000}{\text{motor speed}}$$

$$= \frac{4.28 \times 63{,}000}{400} = 674 \text{ in} \cdot \text{lb}$$

HYDRAULIC MOTOR PERFORMANCE IN METRIC UNITS

EXAMPLE 7-5

A hydraulic motor has a 82-cm³ (0.082-L) volumetric displacement. If it has a pressure rating of 70 bars and it receives oil from a 0.0006-m³/s (0.60-Lps or 36.0-Lpm) theoretical flow-rate pump, find the motor

a. Speed
b. Theoretical torque
c. Theoretical power

Solution

a. From Eq. (7-6M) we solve for the motor speed:

$$N = \frac{Q_T}{V_D} = \frac{0.0006 \text{ m}^3/\text{s}}{0.000082 \text{ m}^3/\text{rev}} = 7.32 \text{ rev/s} = 439 \text{ rpm}$$

b. Theoretical torque is found using Eq. (7-4M):

$$T_T = \frac{V_D p}{2\pi} = \frac{(0.000082 \text{ m}^3)(70 \times 10^5 \text{ N/m}^2)}{2\pi} = 91.4 \text{ N} \cdot \text{m}$$

c. Theoretical power is obtained as follows:

$$\text{theoretical power} = T_T N = (91.4 \text{ N} \cdot \text{m})(7.32 \times 2\pi \text{ rad/s})$$
$$= 4200 \text{ W} = 4.20 \text{ kW}$$

HYDRAULIC MOTOR PERFORMANCE IN METRIC UNITS

EXAMPLE 7-6

A hydraulic motor has a displacement of 164 cm³ and operates with a pressure of 70 bars and a speed of 2000 rpm. If the actual flow rate consumed by the motor is 0.006 m³/s and the actual torque delivered by the motor is 170 N · m, find

a. η_v
b. η_m
c. η_o
d. The actual kW delivered by the motor

Solution

a. To find the volumetric efficiency, we first calculate the theoretical flow rate:

$$Q_T = V_D N = (0.000164 \text{ m}^3/\text{rev})\left(\frac{2000}{60} \text{ rev/s}\right) = 0.00547 \text{ m}^3/\text{s}$$

$$\eta_v = \frac{Q_T}{Q_A} = \frac{0.00547}{0.006} = 0.912 = 91.2\%$$

b. To find η_m, we need to calculate the theoretical torque:

$$T_T = \frac{V_D p}{2\pi} = \frac{(0.000164)(70 \times 10^5)}{2\pi} = 182.8 \text{ N} \cdot \text{m}$$

$$\eta_m = \frac{T_A}{T_T} = \frac{170}{182.8} = 0.930 = 93.0\%$$

c. $\eta_o = \eta_v \eta_m = 0.912 \times 0.930 = 0.848 = 84.8\%$

d. actual power $= T_A N = (170)\left(2000 \times \frac{2\pi}{60}\right) = 35{,}600 \text{ W} = 35.6 \text{ kW}$

HYDRAULIC MOTOR PERFORMANCE IN METRIC UNITS

EXAMPLE 7-7

A hydrostatic transmission, operating at 70 bars pressure, has the following characteristics:

Pump	*Motor*
$V_D = 82\ \text{cm}^3$	$V_D = ?$
$\eta_v = 82\%$	$\eta_v = 92\%$
$\eta_m = 88\%$	$\eta_m = 90\%$
$N = 500$ rpm	$N = 400$ rpm

Find the

a. Displacement of the motor

b. Motor output torque

Solution

a. pump theoretical flow rate = displacement of pump × pump speed

$$= (0.000082)\left(\frac{500}{60}\right) = 0.000683\ \text{m}^3/\text{s}$$

pump actual flow rate = pump theoretical flow rate × pump volumetric efficiency

$$= (0.000683)(0.82) = 0.000560\ \text{m}^3/\text{s}$$

Since the motor actual flow rate equals the pump actual flow rate, we have

motor theoretical flow rate = pump actual flow rate × motor volumetric efficiency

$$= (0.000560)(0.92) = 0.000515\ \text{m}^3/\text{s}$$

$$\text{Motor displacement} = \frac{\text{motor theoretical flow rate}}{\text{motor speed}}$$

$$= \frac{0.000515}{400/60} = 0.0000773\ \text{m}^3 = 77.3\ \text{cm}^3$$

b. hydraulic power delivered to motor = system pressure × actual flow rate to motor

$$= (70 \times 10^5)(0.000560) = 3920\ \text{W}$$

$$\text{brake power delivered by motor} = (3920)(0.92)(0.90) = 3246\ \text{W}$$

$$\text{torque delivered by motor} = \frac{\text{power delivered by motor}}{\text{motor speed}}$$

$$= \frac{3246}{400 \times 2\pi/60} = 77.5\ \text{N} \cdot \text{m}$$

end