Hydraulic Motors

1- Introduction

As in the Case of Hydraulic Cylinders, 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 called a Hydraulic Motor, can Rotate Continuously at an rpm that is determined by The Motor's Input Flow-Rate.

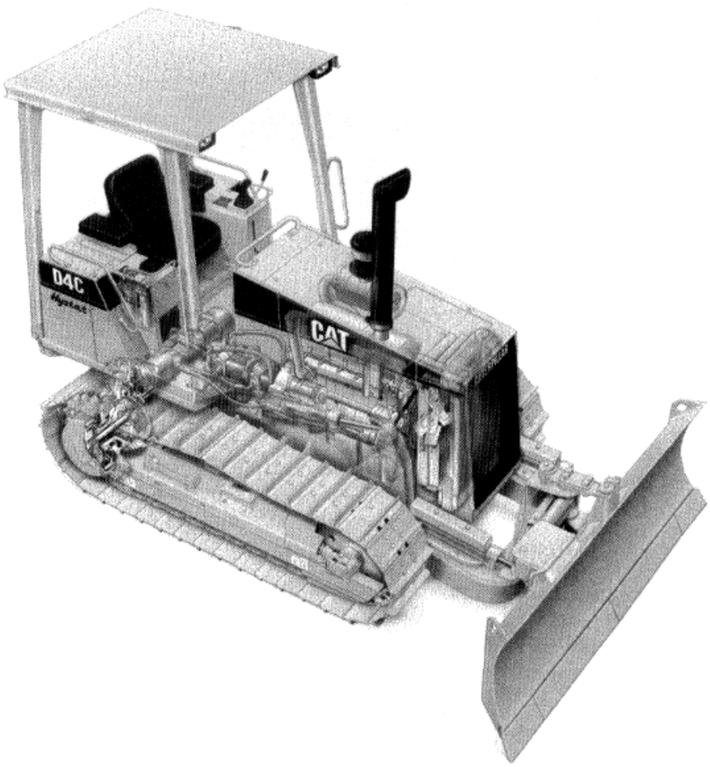
In Reality, Hydraulic Motors are Pumps that have been redesigned to withstand the Different Forces that are involved in Motor Applications. Hydraulic Motors are of the: Gear, Vane, or Piston Configuration.

Hydrostatic Transmissions are Hydraulic Systems specifically designed to have a Pump Drive a Hydraulic Motor. A Hydrostatic Transmission Transforms Mechanical Power into Fluid Power and then Reconverts the Fluid Power Back into Shaft Power. The Advantages of Hydrostatic Transmissions include:

1. Power Transmission to Remote Areas,
2. Infinitely Variable Speed Control,
3. Self-Overload Protection,
4. Reverse Rotation Capability,
5. Dynamic Braking, and
6. A High Power-to-Weight Ratio

Applications include:

1. Materials Handling Equipment,
2. Farm Tractors,
3. Railway Locomotives,
4. Buses,
5. Prime Mowers, and
6. Machine Tools



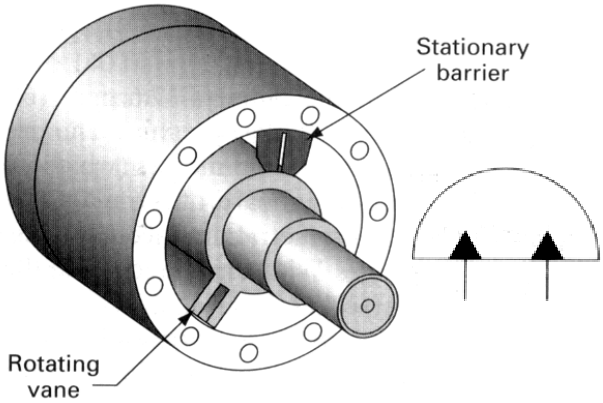
A Cutaway View of a Track-Type Tractor that is driven by Two Hydrostatic Transmissions. Each of the Two Tracks has its own Separate Hydraulic Circuit.

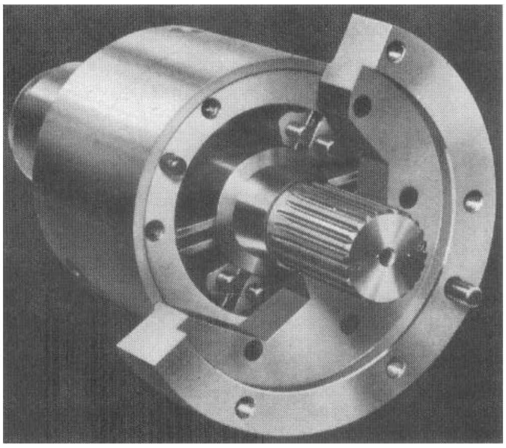
The Two Variable Displacement Piston Pumps are attached Directly to the Diesel Engine Flywheel housing. Each Pump Delivers 17.6 gpm (66.7 Lpm) at the Rated Speed of 2400 rpm and 1000 psi (6900 kPa) Pressure. The Pressure Relief Valve Setting is 2500 psi (17,200 kPa). The Two Piston Motors (which power the drive sprockets for the two tracks) are Mounted inboard of the Main Frame. These Motors can run with Two Different Volumetric Displacements, as Controlled by the Operator, to provide Two Speed Ranges or with a Single Joystick, the Operator can Control Speed, Machine Direction, and Steering. The Front Variable Pitch and Tilt Blade is driven by Hydraulic Cylinders to provide the necessary down Force, Pry-Out Force, and Blade Control for Maximum Production Capabilities. Applications for this Tractor include: Finish Grading, Back-Filling Ditches, Landscaping, Medium Land Clearing, and Heavy Dozing.

2- LIMITED ROTATION HYDRAULIC MOTORS

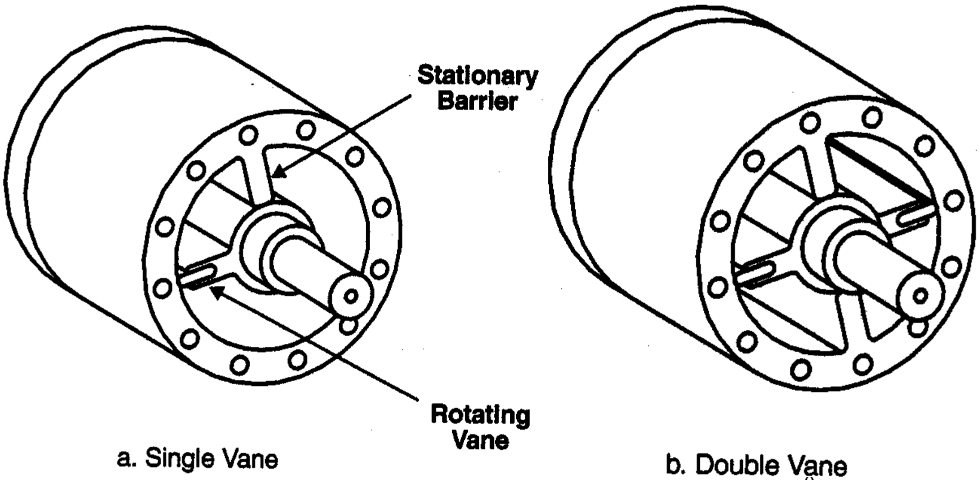
A Limited Rotation Hydraulic (also called Oscillation Motor or Rotary Actuator provides Rotary Output Motion over a Finite angle. Rotary Actuator Produces High Instantaneous Torque in Either Direction and Requires Only a Small Space and Simple Mountings. Rotary Actuators consist of a Chamber(s) Containing 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.

A Direct-Acting Vane-Type Actuator is shown schematically along with its Graphic Symbol. Fluid under Pressure is directed to One Side of the Moving Vane, Causing it to Rotate. This Type provides about 280° of Rotation.





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. Since it 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.



Single Vane Rotary Actuators are usually limited to about 280^0 of Rotation and Double Vane to about 200^0

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 (Ib, N)
A = Surface Area of Vane in contact with Oil (in^2, m^2)
T = Torque Capacity (in • Ib, N • m)

The Force on the Vane = The Pressure X The Vane Surface Area:

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

The Torque = The Vane Force X The Mean Radius of the Vane:

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

On Rearranging we have

$$T = \frac{pL}{2}\,(R_V^2 - R_R^2)$$

A Second Equation for Torque can be Developed by noting the following Relationship for Volumetric Displacement V_D:

$$V_D = \pi\,(R_V^2 - R_R^2)L$$

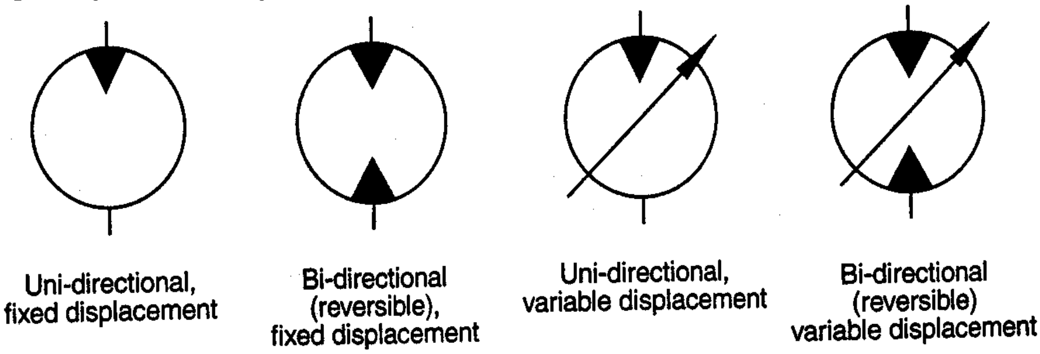
Combining the last two Equations yields

$$T = \frac{pV_D}{2\pi}$$

Observe from Equation that torque capacity can be increased by increasing: The Pressure or Volumetric Displacement or Both.

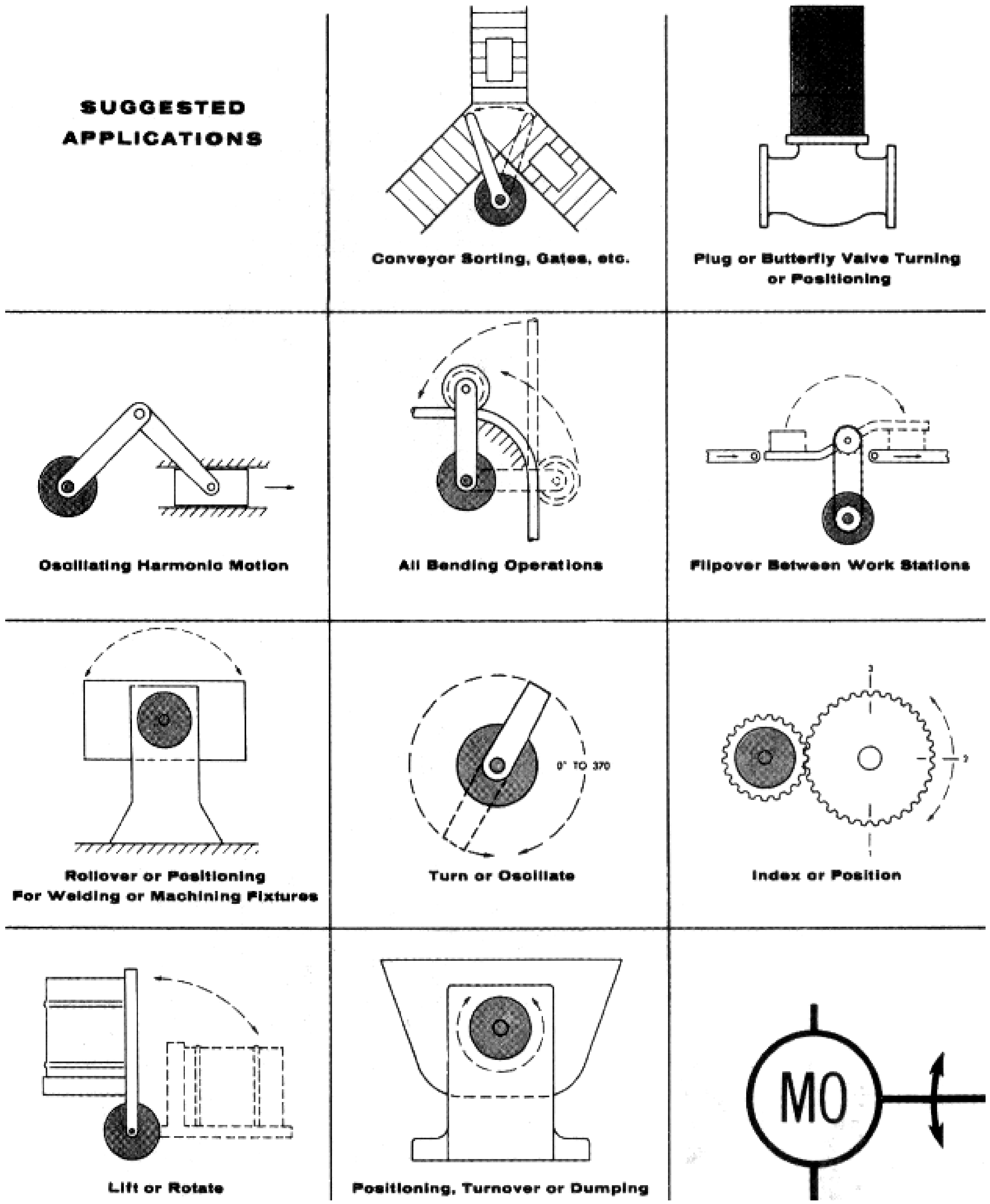
Applications For Rotary Actuators

Graphic Symbols for Hydraulic Motors



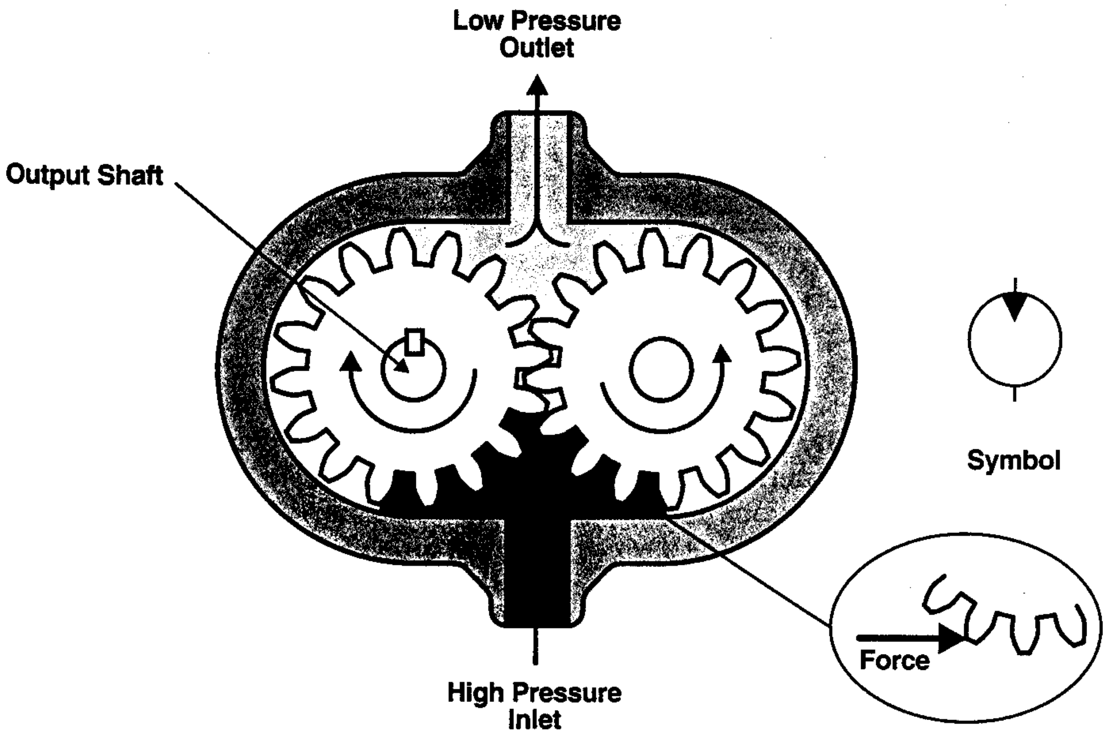
Applications for Rotary Actuators include:

- Conveyor Sorting
- Positioning for Welding
- Air Bending Operations
- Valve Turning,
- Flip over between Work Stations,
- Lifting,
- Rotating
- Dumping



<u>3- GEAR MOTORS</u>

Hydraulic Motors can rotate continuously and as such have the Same Basic Configuration as Pumps. Instead of Pushing on the Fluid as Pumps do, Motors are pushed on by the Fluid. Hydraulic Motors develop Torque and Produce Continuous Rotary Motion. Hydraulic Motor is pressurized from an Outside source; Most Hydraulic Motors have Casing Drains to protect Shaft Seals. There are Three Basic Types of Hydraulic Motors: Gear, Vane, and Piston. A Gear Motor Develops Torque due to Hydraulic Pressure acting on the Surfaces of the Gear Teeth.

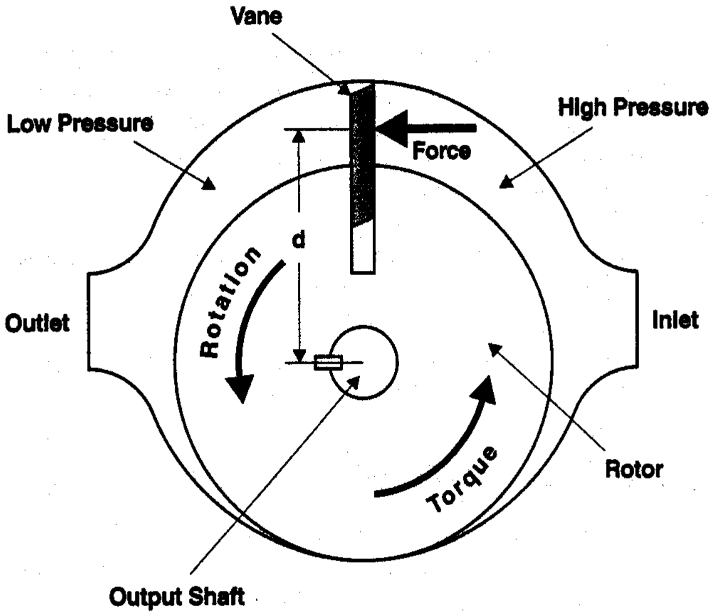


The Direction of Rotation of the Motor can be reversed by reversing the Direction of Flow. As is the Case for Gear Pumps, The Volumetric Displacement of a Gear Motor is Fixed. The Gear Motor shown in Figure 6 is Not Balanced with respect pressure Loads. The High Pressure at the Inlet, Coupled with The Low Pressure at the Outlet, produces a Large Side Load on the Shaft and Bearings. 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 Low Cost.

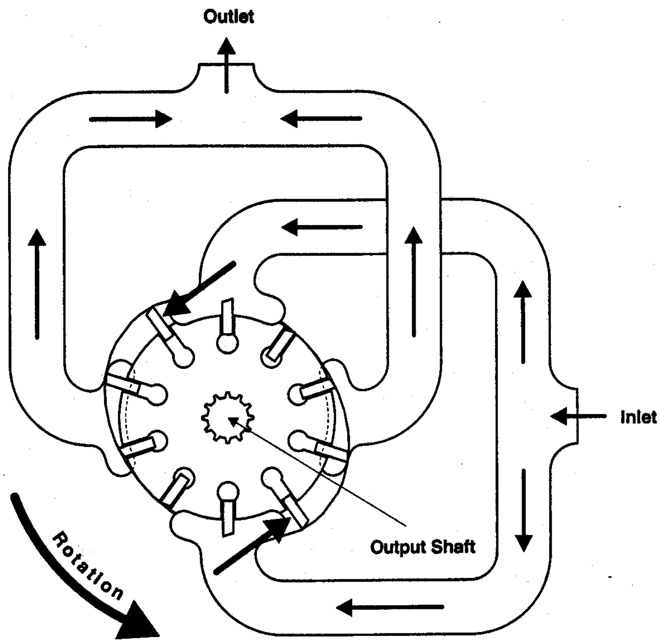
Hydraulic Motors can also be of the Internal Gear Design. This Type can operate at Higher Pressures and Speeds and also has Greater Displacements than the External Gear Motor. As in the Case of Pumps, Screw Type Hydraulic Motors exist using Three Meshing Screws (A Power Rotor and Two Idler Rotors). The 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 in^3.

4- 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) are used to Force the Vanes Radially Outward. No Centrifugal Force exists until the Rotor Starts to Revolve. The Vanes must have some



means other than Centrifugal Force to hold them against the Cam Ring. Some Designs use springs; 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.

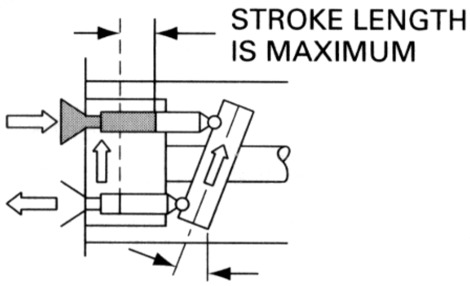


Vane Motors are universally of the Balanced Design. In this Design, Pressure Buildup at Either Port is Directed to two interconnected Cavities Located 180° apart. The Side Loads that are created are therefore Canceled Out. Since Vane Motors are Hydraulically Balanced, They are Fixed Displacement Units. 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.

5- PISTON MOTORS In-Line Piston Motor Swash Plate Design

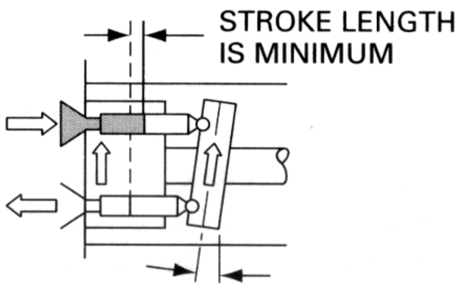
Piston Motors can be Either Fixed Or Variable Displacement Units. They generate Torque by Pressure Acting on the Ends of Pistons Reciprocating inside a Cylinder Block. The In-Line Design in which The Motor Drive Shaft and Cylinder Block are centered on the Same Axis. Pressure acting on the Ends of the Pistons generates a Force against an Angled Swash Plate. This causes the Cylinder Block to Rotate with a Torque that is Proportional to the Area of the Pistons. The Torque is also a Function of the Swash Plate Angle.

The Swash Plate Angle Determines the Volumetric Displacement. In Variable Displacement Units, the Swash Plate is mounted in a Swinging Yoke. The Angle of the Swash Plate can be altered by Various Means, such as A Lever, Hand-Wheel, or Servo Control. If the Swash Plate Angle is increased, The Torque Capacity is increased, but the Drive Shaft speed is decreased. Mechanical Stops are usually In-corporated so that The Torque and Speed Capacities Stay within Prescribed Limits.



(MAXIMUM DISPLACEMENT)

MAXIMUM SWASH PLATE ANGLE AND MAXIMUM TORQUE CAPABILITY

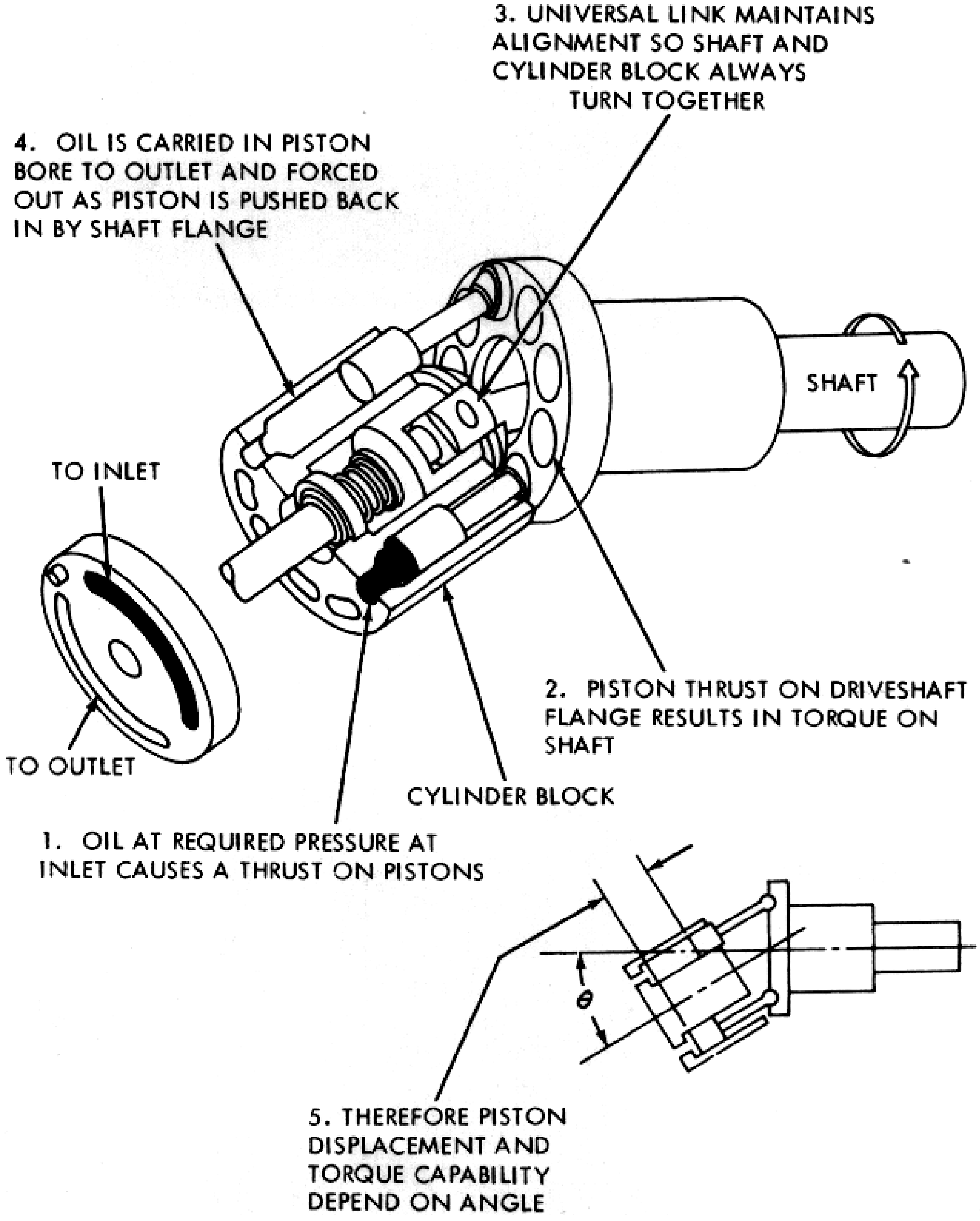


(MINIMUM DISPLACEMENT)

MINIMUM SWASH PLATE ANGLE AND MINIMUM TORQUE CAPABILITY

Axial Piston Motor
Bent-Axis Design

A Bent-Axis Piston Motor develops Torque due to Pressure Acting on Reciprocating Pistons. This Design has the Cylinder Block and Drive Shaft Mounted at an Angle to Each Other so that the Force is exerted on the Drive Shaft Flange.



Speed and Torque Depend on the Angle Between the Cylinder Block and Drive Shaft. The Larger the Angle, the Greater the Displacement and Torque but the Smaller the Speed will be. This Angle Varies from a Minimum of 7½° to a Maximum of 30°. Piston Motors are <u>the Most Efficient</u> of the Three Basic Types and are Capable of Operating at The <u>Highest Speeds and Pressures</u>. 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.

6- 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:

$$T_T(\text{in} \cdot \text{lb}) = \frac{V_D(\text{in}^3/\text{rev}) \times p\,(\text{psi})}{2\pi}$$

$$T_T(\text{N} \cdot \text{m}) = \frac{V_D(\text{m}^3/\text{rev}) \times p\,(\text{Pa})}{2\pi}$$

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:

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

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

$$\text{Theoretical Power (W)} = T_T(\text{N} \cdot \text{m}) \times N\,(\text{rad/s})$$

$$= \frac{V_D(\text{m}^3/\text{rev}) \times p\,(\text{Pa}) \times N\,(\text{rad/s})}{2\pi}$$

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.

$$Q_T\,(\text{gpm}) = \frac{V_D\,(\text{in}^3/\text{rev}) \times N\,(\text{rpm})}{231}$$

$$Q_T(\text{m}^3/\text{s}) = V_D\ (\text{m}^3/\text{rev}) \times N\,(\text{rev/s})$$

7- HYDRAULIC MOTOR PERFORMANCE

The Performance of Any Hydraulic Motor Depends on The Precision of its Manufacture as well as The Maintenance of Close Tolerances under Design Operating Conditions. As in the case for Pumps, Internal Leakage (Slippage) between The Inlet and Outlet reduces the Volumetric Efficiency of a Hydraulic Motor. Similarly, Friction between Mating Parts and due to Fluid Turbulence Reduces the Mechanical Efficiency of a Hydraulic Motor. Gear Motors have an Overall Efficiency of 70 to 75% as compared to 75 to 85% for Vane Motors and 85 to 95% for Piston Motors. Some Systems require that a Hydraulic Motor Start under Load. Such Systems Should Include a Stall-Torque Factor When making Design Calculations. For Example, Only about 80% of the Maximum Torque can be Expected If the Motor is required to start either under Load or Operate at Speeds below 500 rpm.

Motor Efficiencies

Hydraulic Motor Performance is evaluated on the same three Efficiencies (Volumetric, Mechanical, and Overall) used for Hydraulic Pumps.

1- Volumetric Efficiency (η_v)

The Volumetric Efficiency of a Hydraulic Motor is the Inverse of that for a Pump

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

Determination of Volumetric Efficiency requires the Calculation of the Theoretical Flow-Rate.

2- Mechanical Efficiency (η_m)

The Mechanical Efficiency of a Hydraulic Motor is The Inverse of that for a Pump

$$\eta_m = \frac{\text{actual torque delivered by motor}}{\text{torque motor should theoretically deliver}} = \frac{T_A}{T_T}$$

As

$$T_T(\text{in} \cdot \text{lb}) = \frac{V_D\,(\text{in}^3) \times p\,(\text{psi})}{2\pi}$$

$$T_T(\text{N} \cdot \text{m}) = \frac{V_D\,(\text{m}^3/\text{rev}) \times p\,(\text{Pa})}{2\pi}$$

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

$$T_A\,(\text{N} \cdot \text{m}) = \frac{\text{actual wattage delivered by motor}}{N\,(\text{rad/s})}$$

3- Overall Efficiency (η_o)

As in the Case for Pumps, Overall Efficiency of a Hydraulic Motor = Volumetric X Mechanical Efficiencies

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

In English Units

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

In Metric Units

$$\eta_o = \frac{T_A\ (\text{N}\cdot\text{m}) \times N\ (\text{rad/s})}{p\ (\text{Pa}) \times Q_A\ (\text{m}^3/\text{s})}$$

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.

Next figure represents Typical Performance Curves Obtained for A 6-in^3 Variable Displacement Motor Operating at Full Displacement. The Upper Graph gives Curves of Overall and Volumetric Efficiencies as a function of Motor Speed (rpm) for Pressure Levels of 3000 and 5000 psi. The Lower Graph gives Curves of Motor Input Flow (gpm) and Motor Output Torque (in • Ib) as a function of Motor Speed (rpm) for the Same Two Pressure Levels.