AEROSPACE RECOMMENDED PRACTICE

ARP4940

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Application Guide for Aerospace Hydraulic Motors

RATIONALE

There is a need for a document to provide guidance to aerospace engineers for understanding and characterizing hydraulic motors for a variety of high speed/high performance aerospace applications. This document provides information that supplements and can be used with accepted industry specifications.

TABLE OF CONTENTS

1. SCOPE

This SAE Aerospace Recommended Practice (ARP) is an application guide for fixed and variable displacement hydraulic motors. It provides details of the characteristics of fixed and variable displacement hydraulic motors, architectures, circuit designs, controls, and typical applications. The applications include airborne and defense vehicles with emphasis on high performance applications.

1.1 Purpose

The purpose of this document is to apprise the system designer of the available options in the control and application of hydraulic motors and it provides guidance in how to integrate them in a control system.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

AS595 Aerospace - Civil Type Variable Delivery, Pressure Compensated, Hydraulic Pump

ARP1280 Aerospace - Application Guide for Hydraulic Power Transfer Units

ARP1383 Aerospace - Impulse Testing of Hydraulic Components

AIR1899 Aerospace Military Aircraft Hydraulic System Characteristics

ARP4386 Terminology and Definitions for Aerospace Fluid Power, Actuation and Control Technologies

AIR5005 Aerospace - Commercial Aircraft Hydraulic Systems

AS7997 Motors, Aircraft Hydraulic, Constant Displacement - General Specification For

AS19692 Pumps, Hydraulic, Variable Flow, General Specification For

2.2 Definitions

Refer to ARP4386 for terms that are generally used in this document.

High speed applications, in the context of hydraulic motors as discussed in this document, are those where speeds are approaching or exceeding the typical rated speeds for pumps of similar displacements as defined in AS595 and AS19692.

High performance applications, in the context of hydraulic motors as discussed in this document, are those where rapid changes of speed occur in a cyclic manner during the life of the motor.

Windage is defined as the mechanical torque required to overcome the resistance of the rotating group of a hydraulic pump or motor due to the hydraulic fluid surrounding the rotating group. The torque is a function of rotational speed.

3. MOTOR DESIGNS

Refer to Appendix A for design parameters and specification guidelines for hydraulic motors.

3.1 Fixed Displacement Motors

3.1.1 Design

Fixed displacement motors designs include diverse technologies such as piston, vane and gear types. For high pressure applications, piston motors are generally used. The common piston motor designs are axial piston inline and bent axis types.

Inline designs are simpler, lighter and typically are lower cost. The bent axis designs have lower mechanical and volumetric losses, and have better break-out and low speed characteristics

3.1.2 Performance Characteristics

The displacement of a fixed displacement motor is selected to provide the necessary torque required by the application, by considering that the theoretical torque is the product of displacement and differential (inlet - outlet) pressure. Once the displacement is selected, the theoretical flow required to operate the motor at the required speed is the product of displacement and speed.

Output speed is a function of input flow less volumetric losses, which are typically pressure dependent. The losses include internal leakage around the pistons and under the cylinder block/barrel and piston shoes or other piston linkages. Since the losses are pressure, not speed dependent, the volumetric efficiency increases with speed.

Output torque losses result from friction and windage, and are speed and pressure dependent. At higher speeds, windage is a dominant factor. At break-out, torque efficiency is usually lower than at moderate speeds, then decrease at higher speeds.

3.2 Variable Displacement Motors

3.2.1 Design

Refer to Figure 1.

Variable displacement motors are controlled by a swash plate, whose angle is controlled to vary the displacement of the motor. Displacement is generally a function of the tangent of the swash plate angle.

They lend themselves most readily to variable displacement adaptation for both uni-directional and bi-directional application. For uni-directional applications, such as a generator drive, the swash angle varies from zero to maximum in one direction only. For bi-directional applications the displacement varies from positive to negative passing through the zero displacement position. These implementations are called “overcenter”, because the swash angle crosses the center on zero-displacement point. It is important to note that in overcenter motors, the Inlet (high pressure) and Return (low pressure) ports always remain unchanged regardless of direction of rotation - the direction is determined by the swash plate position on either side of center.

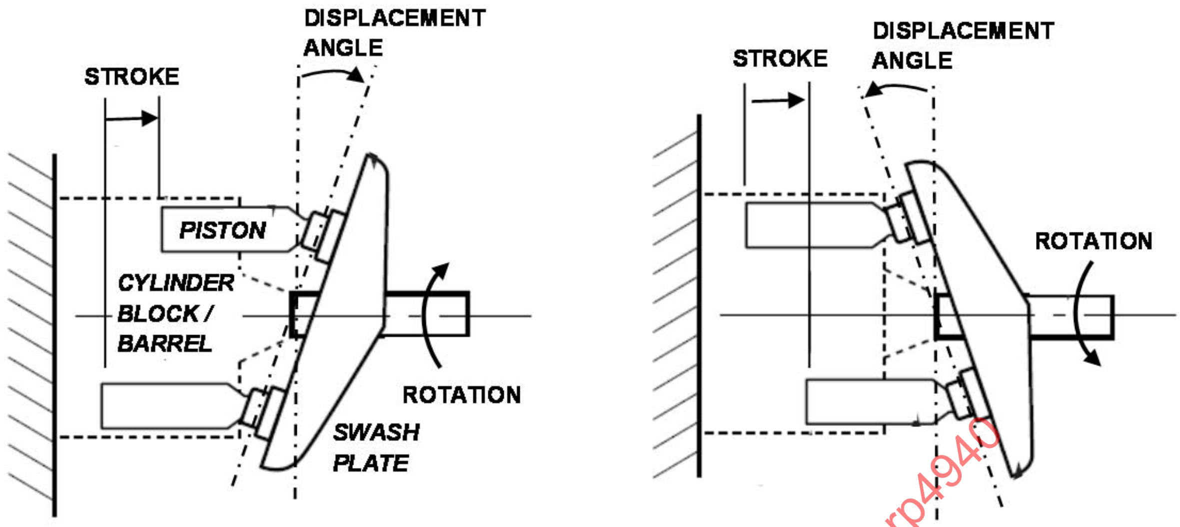


FIGURE 1 - OVER-CENTER VARIABLE DISPLACEMENT MOTOR

3.2.2 Performance Characteristics

3.2.2.1 Torque Output - Continuous rotation

Refer to Figure 2 for a typical example.

When the motor is running, the torque output is directly proportional to displacement with an offset to balance losses. This offset increases with speed. The torque characteristic is continuous through null as long as the direction of rotation does not change.

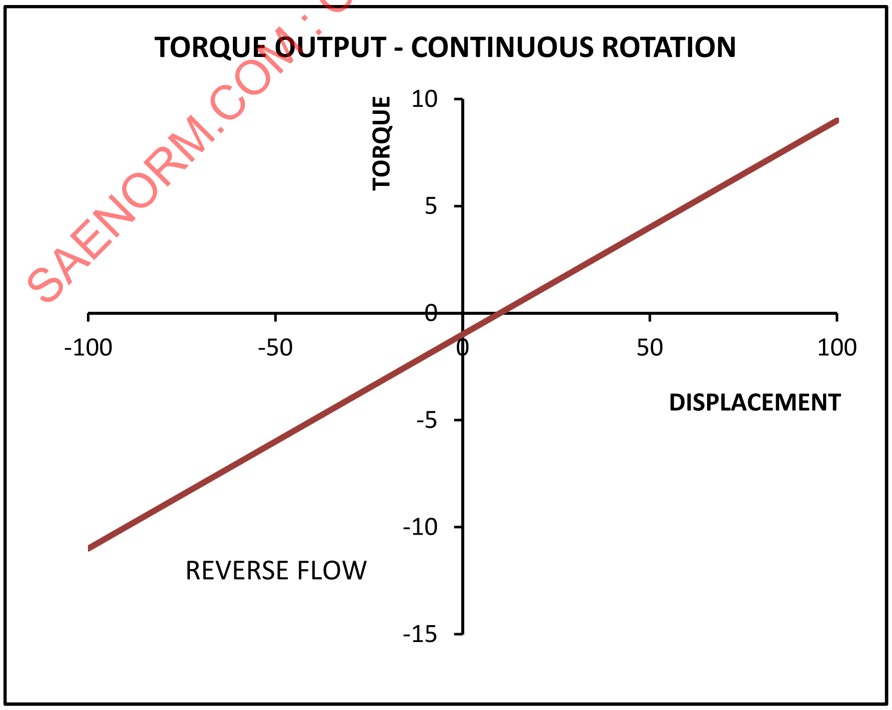


FIGURE 2 - TORQUE (EXAMPLE) OUTPUT VERSUS DISPLACEMENT, CONTINUOUS ROTATION

3.2.2.2 Torque Output - Starting

Refer to Figure 3 for a typical example.

When starting the motor, there is a discontinuity as the motor requires approximately 30% displacement to start even against low loads. This should be considered in the control system design.

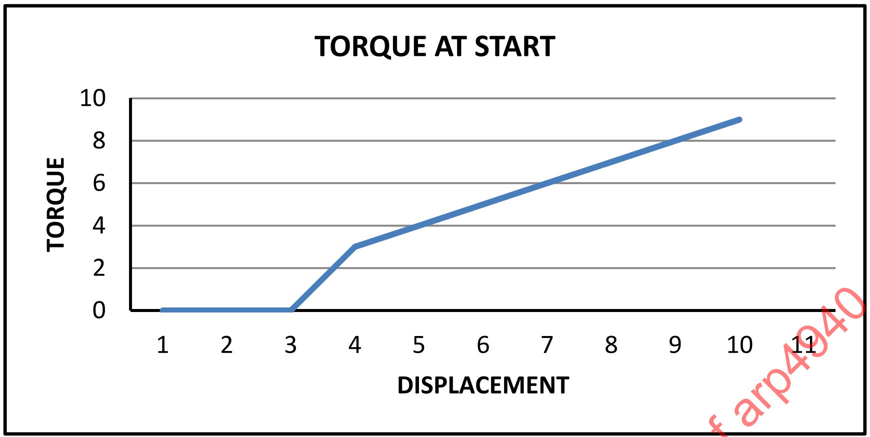


FIGURE 3 - TORQUE OUTPUT VERSUS DISPLACEMENT, STARTING (EXAMPLE)

3.2.2.3 Reverse Flow

When rotating in one direction and braking is required, displacement in the opposite direction is commanded. This will reverse the flow direction. This means the unit will operate as a pump drawing flow from the low pressure port and discharging it into the high pressure port, creating the braking torque. The hydraulic system should be designed to accommodate this, i.e., the main system should allow this or provisions around the motor should allow it. If the braking energy is small this can be done with cross port relief valves. In the case of a hoist, which could have longer periods of operation with negative loads, this may not be possible.

4. OPERATIONAL CHARACTERISTICS

4.1 System Architecture

Refer to Figures 4 (i) and 4(ii).

Hydraulic motors and the loads that they drive can be integrated in either open loop or closed loop architectures. This refers to the method the motors are connected to the hydraulic sources, not the scheme that is used to control the motors and their loads.

In conventional “open loop” or “central” hydraulic systems, as shown in Figure 4 (i), one or more pumps pressurize a common hydraulic trunk line, to which multiple consumers are connected. In this manner, consumers can be linear actuators and/or motor driven actuators, with each consumer extracting power from the central system independently, but not to exceed the total power available. Such a system architecture is used for powering flight controls, landing gear, brakes and utility systems such as winches, hoists, doors, and special mission related equipment.

An alternate architecture is the “closed loop” system, as shown in Figure 4 (ii), where a pump is directly connected to, and dedicated to a single consumer, and the pump and consumer are controlled simultaneously to achieve the desired torque and speed output. These systems are rare on aircraft applications, but may be found on afterburner exhaust nozzle controls, propeller pitch controls and remotely located doors and winches.

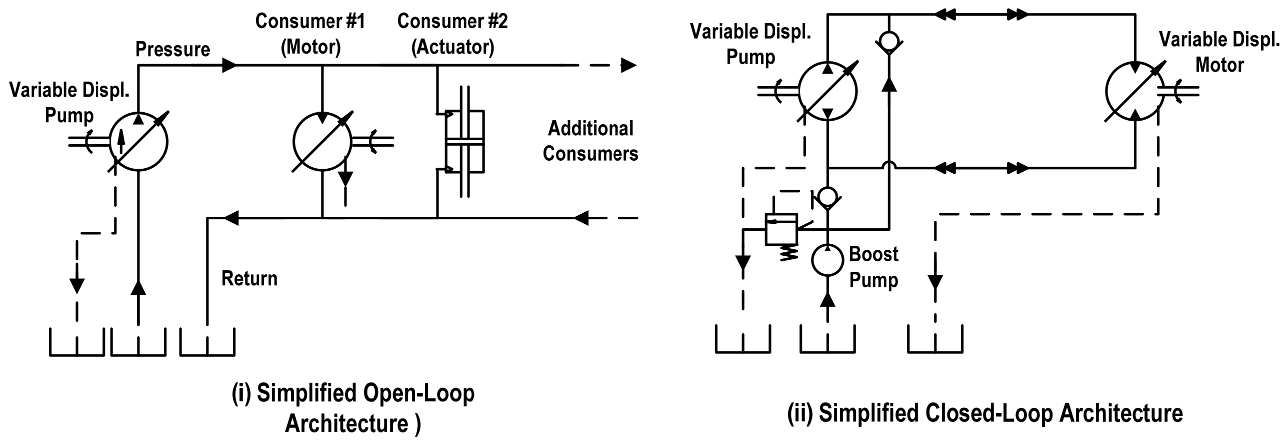


FIGURE 4 - EXAMPLES OF CLOSED AND OPEN LOOP HYDRAULIC SYSTEM ARCHITECTURES

4.2 System Integration Considerations

The integration of the motor into the actuation and hydraulic systems should take into account the nature of the load, the type of control desired, and the characteristics of the hydraulic system which provides power to the actuator. In particular, the following system parameters should be considered:

4.2.1 Load Inertia

The total load inertia, including that of the motor itself, and acceleration rates have a significant influence on system design.

4.2.2 Starting Conditions

The following are the important considerations during the start phase of motor operation:

- The rate of opening of the supply control valve
- The load inertia and drive train stiffness

If the control valve opens rapidly and the load inertia is high in relation to the drivetrain stiffness it is possible that an oscillation of the drivetrain will ensue. The analysis of this potential problem would normally be the responsibility of the system designer but the motor supplier should be aware of the problem as it could cause load reversals inside the motor which could be damaging to the motor.

Another effect which could be damaging is cavitation in the inlet line as a result of the preceding shut down. If the inlet line is essentially empty at the time of start valve opening the resulting rush of fluid to fill the void could cause a 'water hammer' effect potentially causing damage to the motor or drivetrain.

4.2.3 Stopping Conditions

Stopping a motor requires careful consideration. Due to the inertia of the motor (and load), closing a valve while the motor is running may impose high pressure requiring installation of cross port relief valves or special anti-cavitation valves. This is to prevent water hammer effects occurring due to a rapid stop, which could cause a pressure spike in either the supply line, the motor outlet port or both.

When the motor decelerates over a relief valve, a bypass is required to provide inlet to the motor from a low pressure source. If a high inertia load is controlled, recirculating the fluid in a relief/inlet loop will cause local heating of the fluid, with the possibility of damage to the motor and fluid; in this case, a replenishing system is required to provide fresh oil to the motor inlet during deceleration.

If the motor is brought to a stop by restricting the inlet and outlet flow, cavitation could be caused at the inlet port which will reduce or eliminate the braking effect.

If the inlet flow is not significantly restricted, the restriction of the discharge flow could cause overpressure.

The necessity of such measures depends on load inertia and drive train stiffness. This should be determined by dynamic analysis.

4.2.3.1 Hydraulic and Mechanical Braking

There is a possibility that mechanical braking from an emergency stop or at the end of a normal operating cycle imposes the highest load on the motor drive shaft. The brake may stop the rotation at a speed that is fast enough that the inertia of the motor creates a torque significantly in excess of the normal motor torque. In these situations, the hydraulic and mechanical braking should be considered together to minimize shaft loads, and the expected loads should be specified.

4.3 Motor Efficiency

4.3.1 Mechanical Efficiency

It can be misleading to try to use a single motor efficiency in calculations as this changes with speed and differential pressure and in the case of variable displacement motors with the actual displacement condition being analyzed. It is better to use torque loss of the motor in relation to speed and subtract this value from the theoretical torque at the actual differential pressure, speed and displacement condition under consideration.

The torque loss depends on the rotating group size (maximum displacement) and includes the losses from internal pressure losses due to flow and drag torque, such as viscous and windage losses and tare friction. It is approximately proportional to speed as shown in Figure 5. Pressure has a second order influence on the drag torque. For axial piston inline motors the drag torque increases significantly at low speed.

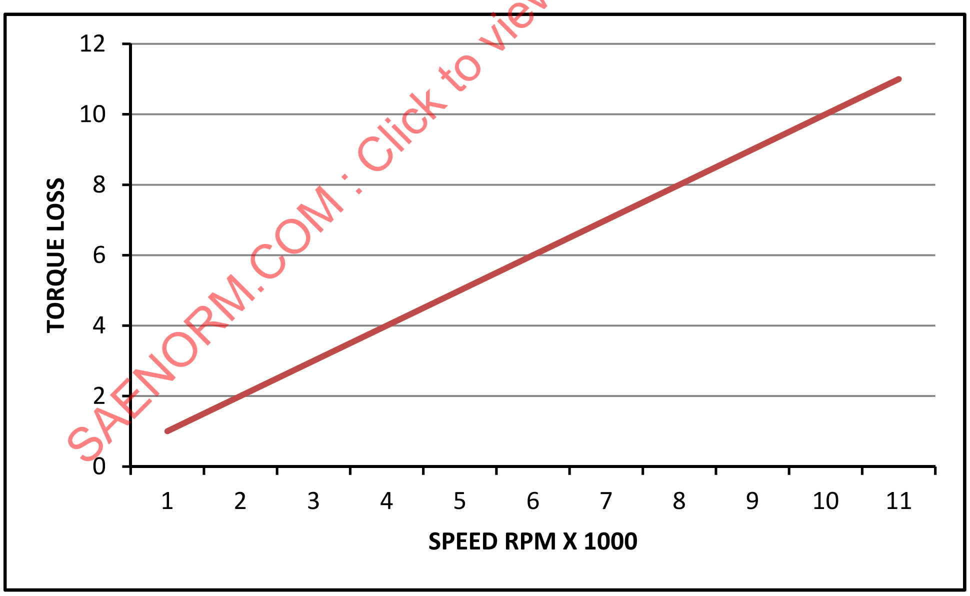


FIGURE 5 - TORQUE LOSS VERSUS SPEED - TYPICAL

4.3.1.1 Breakout Torque

The breakout torque characteristics of different motor types vary considerably. Bent axis type motors have high break-out torque efficiency, typically over 90% Axial piston inline type motors have breakout torque efficiencies varying between 65% and 75% depending on the internal geometry of the particular design.

4.3.1.2 Stall Torque

Stall torque will vary with angular position of the shaft.

4.3.1.2.1 Measurement of Stall Torque

Care should be taken with the measurement of the starting torque produced by a hydraulic motor. One of the best ways is to operate it smoothly at very low speed, typically 0.1 to 1% of rated speed. Measure and make a continuous record of the torque produced. The stall torque is the lowest level in the torque ripple curve.

The pressure supply should be stable to prevent pressure ripple producing any dither effect resulting in optimistic values.

4.3.2 Volumetric Efficiency

Volumetric efficiency will generally be over 95% at rated speed, and decrease at lower operating speed or if the actual displacement is very low compared to the maximum displacement of the unit. In most applications it is sufficient to specify flow consumption rather than volumetric efficiency, and assume flow loss is more of a function of pressure than flow or speed.

4.4 Overspeed

The hydraulic system powering and controlling the motor should include provisions to prevent overspeeding of the motor and the actuation system. Ideally this should be outside the primary control system and should always consider any potential aiding load and failures within the control system.

For aiding loads, shutting off the supply flow may not always be effective as the motor could cavitate eliminating any braking effect.

Another phenomenon often experienced by piston motors is lifting of the cylinder block or barrel due to high acceleration, rapid reversal in rotation, and excessive speed. In these cases, high pressure fluid from the inlet can fill the motor case with system pressure. The motor designer should be apprised of the possibility of conditions being anticipated during the operation of the motor so that safeguards can be implemented.

To guard against the case bursting, the cases of motors are now generally required to resist system pressure without rupture. To guard against block or barrel lift, motor designers have effective solutions.

4.5 Pumping Mode

Some motor applications may include a pumping mode (overrunning load) operation. The motor control system should be designed to minimize overspeed and over/under pressure loading of the motor. If such an operation is expected, the conditions for this operation should be defined in the specification. During situations where loads should be retarded or where decelerations should take place, the motor will continue in a pumping mode operation.

The system and the motor should be designed to perform this function under worst case conditions without failure or significant performance deterioration. Specifically, the pressures and flows generated at the pumping mode outlet side should be managed. Also the system should be designed to eliminate potential pumping mode inlet side cavitation or be capable of operating for the anticipated time in this mode without significant deterioration. Severe cavitation at the inlet may prevent pressurization of the outlet, thereby reducing the braking effect of the motor.

Special considerations of heat generation should be evaluated in the braking mode where:

- The motor is working as a pump
- The fluid is not returned to the supply, but is required to pass over a relief valve and then returned to the inlet of the motor.

The volumes are usually small, and the motor may be called upon to absorb a substantial amount of energy from the load into a small fluid volume. This may elevate the temperature of the fluid to beyond the specification limits.

4.6 Types of Controls

4.6.1 Capabilities Definition

Hydraulic motors can be controlled in a variety of ways, depending upon the design of the motor, whether it is fixed or variable displacement, as well as the characteristics of the application in which it is installed. In general, control is accomplished in one of two ways - torque or speed control.

In the case of fixed displacement motors, controlling the main system flow to the motor by means of external valving is the basis of speed control. This type of control also includes applying and removing pressure to the motor, which is the most fundamental control - stop or run. Typical implementations include controlling flow either to or from the motor by hydromechanical control valves or electrohydraulic valves.

In the case of variable displacement motors, torque control is achieved by controlling motor displacement, which, with pressure, controls motor output torque. Implementation of this control scheme also includes the use of hydromechanical control or electrohydraulic valves, but in this case the valves are used to control motor displacement rather than the main flow through the motor. Even though the fundamental control is torque, speed control can be also achieved using appropriate speed feedback, but it should be noted that given the system pressure at the motor inlet port controlling displacement is directly manifested in output torque.

4.6.2 Fixed Displacement

Fixed displacement motors do not have internal controls as there is nothing inherent in their design that allows for any regulation of its operating parameters. Thus fixed displacement motors are controlled by external valving and circuit architecture.

4.6.2.1 On/off Control

Refer to Figure 6.

On-off control is the most basic control of fixed displacement motors. The simplest implementation of such a control is in the case of a motor that only needs to operate in one direction. In this case, a 2-way valve that directs or blocks flow to the motor is sufficient. The valve can be located at either the inlet or outlet port of the motor; however, if located at the outlet port, the motor remains pressurized at both ports simultaneously, and should be designed accordingly.

The motor case drain port can be connected internally to the motor return (or exhaust) port, provided that the return pressure in that part of the circuit is compatible with the motor structural integrity and performance objectives.

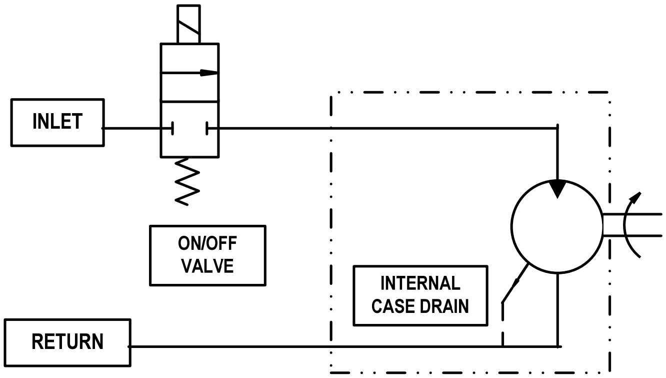


FIGURE 6 - BASIC ON-OFF CONTROL FOR UNIDIRECTIONAL FIXED DISPLACEMENT MOTOR

The On/Off valve also serves to isolate the motor/actuator from the hydraulic system when not in use, or in case a malfunction of the subsystem occurs.

4.6.2.2 Flow Control

The basic control as shown in Figure 6 can typically consume all of the flow available from the pumps unless some flow control device is provided to limit the flow the motor can extract from the system, and also prevent overspeeding the motor. Since motor flow demand is the product of displacement and speed, flow and speed are closely correlated. Therefore, limiting motor flow also limits motor speed.

Flow controls may be located upstream or downstream of the motor, that is at the inlet or outlet ports, or at both ports.

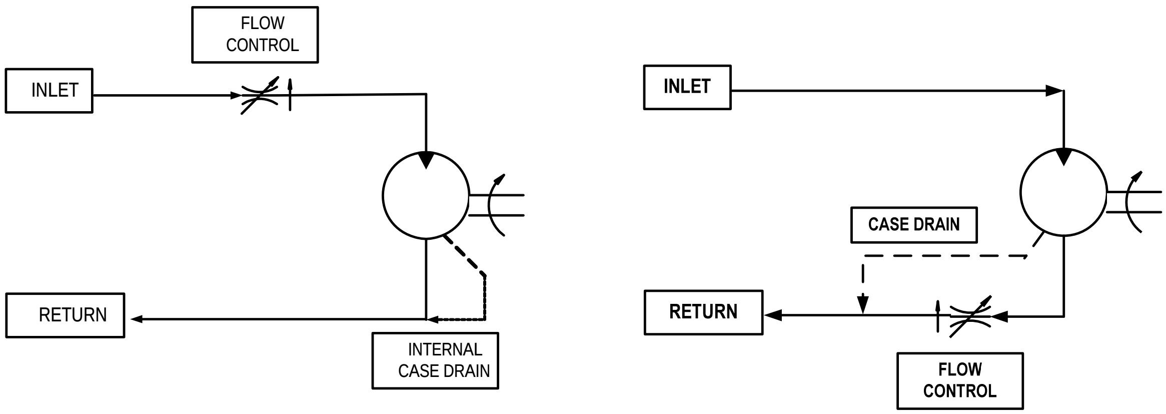
When flow controls are upstream, the flow to the inlet of the motor is regulated, but an over-running load can overspeed the motor, making the motor act like a pump, thereby negating the effect of the inlet flow control and possibly creating cavitation at the inlet. In cases where over-running loads are present, additional controls are required at the motor outlet. These may be counterbalance valves, which regulate outlet flow in response to inlet pressure, or servo valves that simultaneously regulate both inlet and outlet flow.

When the flow control is downstream, the effect of over-running is overcome, but in this implementation, there is always high pressure at both the inlet and exhaust ports of the motor, so the motor needs to be designed to accommodate that condition.

When downstream flow controls are used, the case drain of the motor should be connected to the system return line downstream of all control valves.

In the case of bidirectional motors, flow controls may be installed at both ports, and bypassed by check valves so they control only the flow in the selected direction.

Figure 7 illustrates some flow control concepts - (i) and (ii) depict inlet and return line flow controls, while (iii) depicts dual flow controls where the flows in each direction can be set independently, while the case drain finds the return side by means of the case drain check valves (sometimes called “foot valves”), which, when provided, are usually built into the motor port/valve plate.



(i) Uni-directional, Inlet flow control

(ii) Uni-directional, Return flow control

(iii) Bi-directional, Dual Inlet flow control

FIGURE 7 - FLOW CONTROL CONCEPTS FOR FIXED DISPLACEMENT MOTORS

Another necessary addition is an anti-cavitation check valve that provides a source of fluid to circulate through the motor after the on/off valve is closed, while the motor is decelerating. Figure 8 illustrates the addition of this feature for a uni-directional motor.

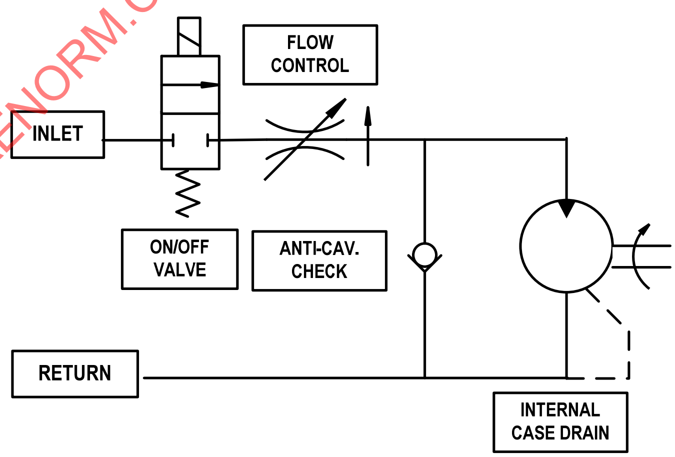


FIGURE 8 - BASIC ON-OFF CONTROL WITH FLOW CONTROL AND ANTI-CAVITATION CHECK

In addition to the flow control limiting the flow extraction from the hydraulic system, another flow control sometimes installed in series with the flow control is a flow fuse, which is set to a higher flow actuation value than the flow control valve. The purpose of the fuse is to shut the flow to the motor in case the flow control valve fails to limit flow to the required value, in order to protect the rest of the hydraulic system from excessive flow demand. Once the flow fuse has actuated, it will remain closed until pressure is completely removed from the system, but will be open the next time the system is pressurized.

4.6.2.3 Directional Control

In the case of a bidirectional motor, generally a 4-way, 3-position valve is used to control not only stopping and running the motor, but also the direction or rotation. This is achieved by having the two opposite valve positions directing flow to the two opposite motor ports, while the center position of the valve blocks pressure to the motor ports, thereby causing the motor to remain stopped.

For bidirectional motors, it is important to ensure that the case is always connected to the motor return, regardless of which port is the pressure source. This can be achieved by foot valves as described in 4.6.2.2.

Another consideration is the protection against overpressure, especially when the directional control is suddenly shut off and the motor is decelerating. In this case, a pair of cross-port relief valves are usually provided to allow controlled deceleration pressure in either direction of rotation.

Figure 9 illustrates a typical bidirectional control that includes all the elements discussed above. In this example, there is a single flow control upstream of the directional valve, so that the maximum flow limit is the same in both directions of rotation. However, the scheme depicted in Figure 6 (iii) can be used instead if the flow limit in the two directions of rotation needs to be different.

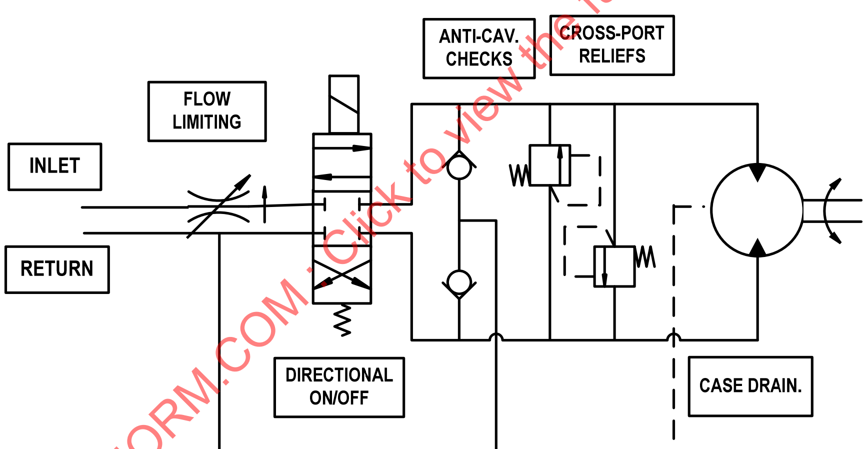


FIGURE 9 - TYPICAL FIXED DISPLACEMENT BI-DIRECTIONAL CONTROL

4.6.2.4 Speed Controls

4.6.2.4.1 Hydromechanical Control

The flow control schemes described above are suitable for limiting flow extraction from the circuit, but do not provide accurate control of motor speed because they control the high pressure inlet, some of which is lost inside the motor and thus does not contribute to speed. For more accurate speed control, a “hydrostat” device is used that monitors outlet flow from the motor, which is a more accurate measure of motor speed. This is accomplished by detecting a small pressure drop across an orifice in the return line and using that differential pressure to control an inlet flow control valve, or “hydrostat”. This is depicted in Figure 10.

NOTE: Controlling a fixed displacement motor in this manner may cause significant heat generation, in the case where a small torque is required to drive the load (compared to the maximum design torque), causing significant pressure to be throttled across the hydrostat and converted to heat.

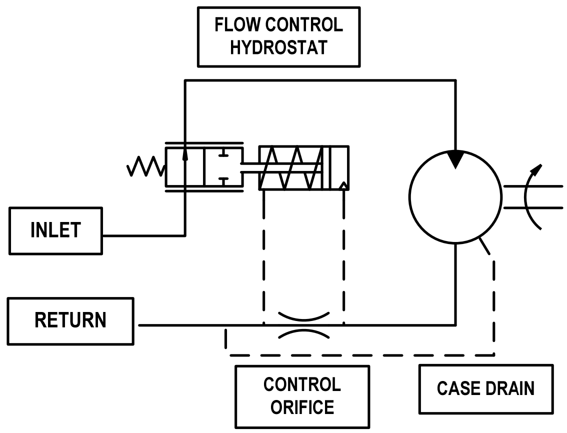


FIGURE 10 - SPEED CONTROL USING HYDROSTAT

4.6.2.4.2 Electrohydraulic Control

The directional valve in Figure 9 may be replaced by an electrohydraulic servovalve (EHSV), which will provide precise speed control in either direction of rotation if the feedback signal is derived from speed. This is shown in Figure 11. Note that the heat generation comment in 4.6.2.4.1 also applies for the flow across the EHSV.

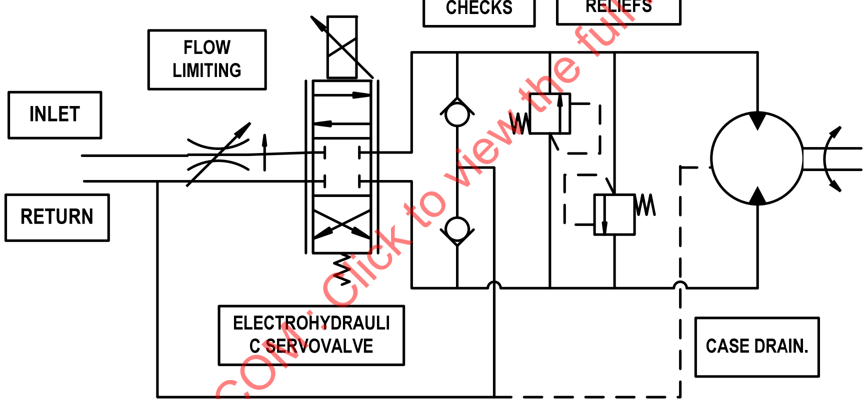


FIGURE 11 - FIXED DISPLACEMENT ELECTROHYDRAULIC SERVOMOTOR

4.6.3 Variable displacement control

4.6.3.1 Torque/Speed Control Overview

The torque output of a motor is primarily a function of the product of differential supply pressure and displacement. Normally, torque is established by the load, so the motor displacement will be adjusted by some control means discussed below to provide the torque required to achieve the desired motor speed.

Since the motor flow demand is the product of displacement and speed, the flow rate is a consequence of the torque and speed demand, and is directly dependent on displacement. It is assumed that the motor/actuator system is designed such that the total flow demanded does not exceed the flow capacity of the hydraulic system, so the inlet pressure will remain near-constant as controlled by the system pump. Therefore, torque, speed and flow are intimately related in variable displacement motor control. In such control systems it is therefore necessary to sense both displacement and speed.

4.6.3.2 Dual-displacement Control

This is the simplest control scheme for variable motors; essentially it results in two fixed displacement configurations:

- One for maximum torque (displacement) and moderate speed
- The second, at reduced displacement, for lower torque and higher speed

The displacement control is controlled by high pressure applied to the displacement control actuator that can be triggered by a pilot signal from a solenoid valve, or from another suitable source.

This scheme is analogous to a two-speed transmission, and is often used the same way - the high displacement mode for starting and accelerating, and the low displacement mode for high speed running.

An ON/OFF valve is generally used to start and stop the motor, with a flow limiting control means to limit the maximum flow extraction from the system.

The basic control of a dual-displacement variable motor is shown in Figure 12.

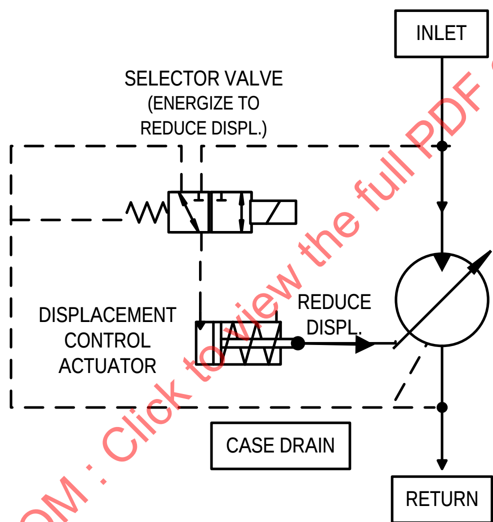


FIGURE 12 - DUAL-DISPLACEMENT MOTOR CONTROL

4.6.3.3 Hydro-mechanical Control

The simplest control of a continuously variable displacement motor is a hydro-mechanical pressure compensator, analogous to the controls commonly found on variable displacement pumps, except that the compensator logic is reversed.

The sequence of how the hydro-mechanical system works is as follows:

a. When the motor is first engaged, for example by opening the on/off valve, it is at maximum displacement and begins to accelerate the load.

b. As the load speed increases, the pressure required to maintain rotation increases (assuming it is a resistive load) and reaches the flow control valve pre-set, that is, the flow limit assigned to this motor.

c. At that point, the inlet pressure to the motor drops, and the displacement begins to decrease, reducing output torque and therefore acceleration.

d. The speed continues to increase, but at a lower rate, with output torque always balancing the inlet pressure.

e. Speed continues to increase as displacement decreases until either the minimum displacement stop is reached, or the motor speed reaches the point where the torque required to maintain rotation just equals the motor output torque at that pressure and displacement.

The resulting flow - speed curve follows the constant flow curve, which is a near-constant power curve assuming inlet pressure remains near-constant.

This scheme is shown in Figure 13.

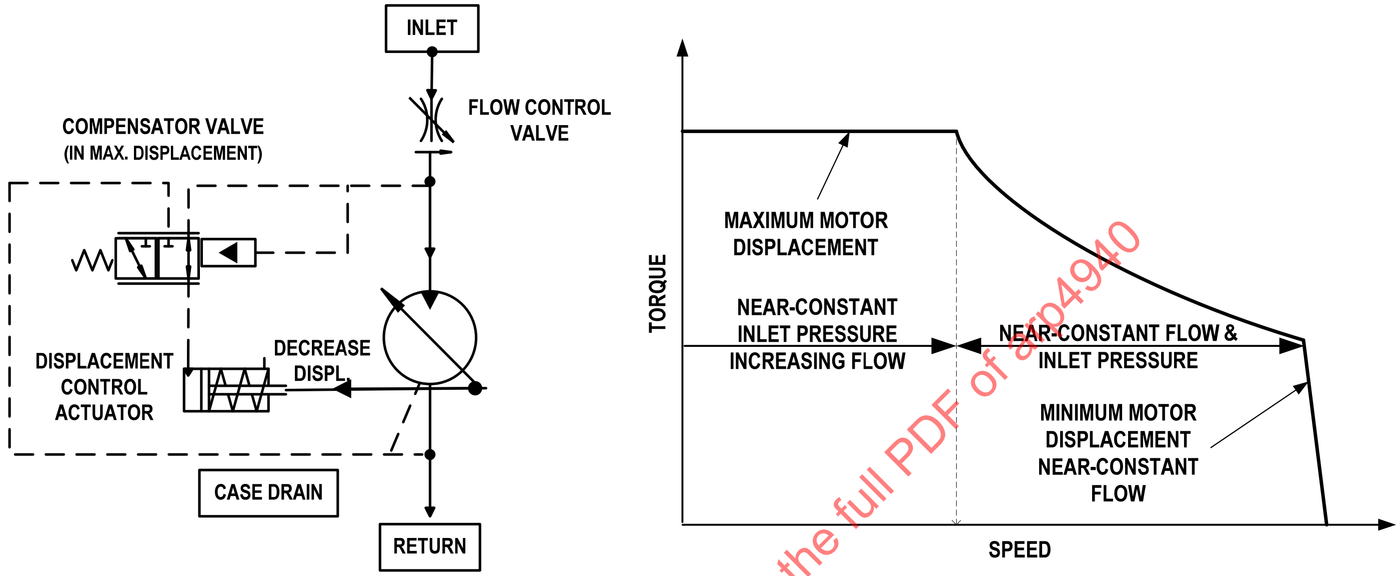


FIGURE 13 - PRESSURE COMPENSATED VARIABLE MOTOR CONTROL (EXAMPLE)

4.6.3.4 Electronic Control

Electronic displacement control is accomplished by using an electrohydraulic servovalve (EHSV) to control the displacement. Such motors can be “overcenter”, that is, the swash plate can swing to either side of the center, or zero-displacement point, which then determines the motor’s direction of rotation.

The swash plates of overcenter motors are controlled by a pair of actuators, each applying force to opposite direction of the swash plate. The differential force determines the position of the swash plate, from full clockwise to full counterclockwise.

The sequence of how the electronic control system works is as follows:

a. The EHSV controls the pair of displacement control actuators based on signals from an electronic controller.

b. The controller generally issues a command velocity (speed and direction) for the motor, and with speed feedback, adjusts the swash angle to provide just the right torque to achieve the commanded speed.

c. Swash plate angle is also used as feedback to achieve stable control.

d. The electronic controller can then be also used to limit maximum flow, speed and acceleration, as required by the nature of the load.

This scheme is illustrated in Figure 14.

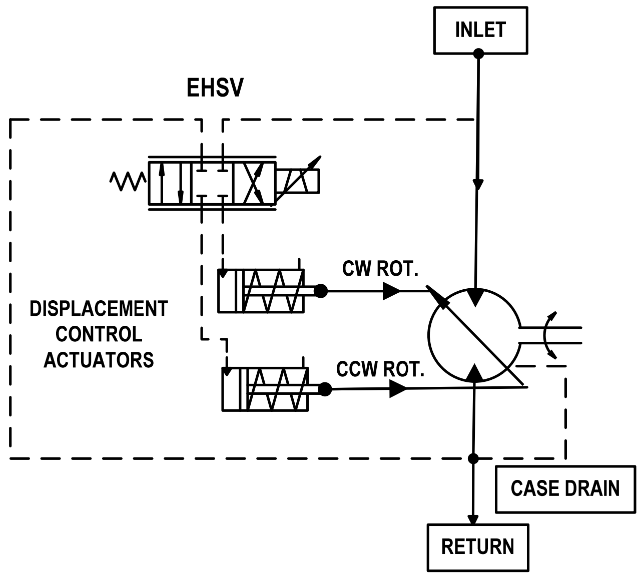


FIGURE 14 - VARIABLE DISPLACEMENT ELECTROHYDRAULIC SERVO CONTROL

5. MOTOR APPLICATIONS

Fixed displacement motors are used in applications where simplicity is desired, and efficiency (i.e., heat generation caused by valving losses or flow demand exceeding supply capacity) are not factors. These include mainly intermittent applications.

Variable displacement motors can be used in most of the application where fixed displacement motors are used in which efficiency is of paramount importance. In these applications, heat generation may be important, or its operation may span high torque low speed to high speed low torque range.

Hydraulic motor applications are listed, with their leading particulars, in AIR1899 and AIR5005 for military and commercial aircraft types.

5.1 Secondary Flight Control Drives

Flap, slat, horizontal stabilizer drives and other secondary flight control drives are characterized by low inertia loads that can be resistive or over-running. The motor should be able start under any loading condition imposed by the aerodynamic loads on the aircraft control surface and maintain speed until it is stopped.

These systems have traditionally used fixed displacement motors, but there are some recent examples utilizing variable displacement motors. Variable displacement motors are almost always electrohydraulic servovalve controlled.

5.2 Hoist and Winch Drives

These systems are characterized by high and low inertia loads that should be raised (resistive) or lowered (over-running). The motor should be able to start with high static load imposed by the cable tension, and also maintain precise control at low speed.

While some older applications are using fixed displacement motors, this is an ideal application for variable displacement, as prolonged lowering heavy loads (as in undersea applications) can generate excessive heat if a fixed displacement motor is used.