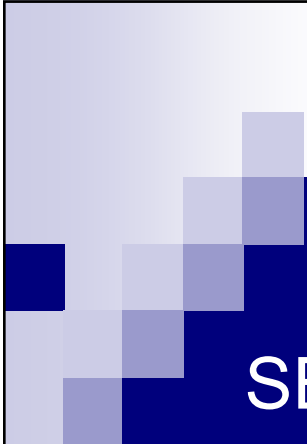




Chapter 11

SERVO VALVES

Fluid Power Circuits and
Controls, John S.Cundiff,
2001

- 
- Servo valves were developed to facilitate the adjustment of fluid flow based on the changes in the load motion.

Typical Open-Loop System

- Goal is to maintain constant speed as the magnitude of the load changes.

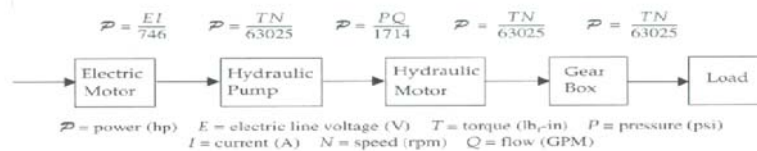


FIGURE 11.1
Typical open-loop system.

■ As load increases

- Torque on hydraulic motor increases, pressure then increases and leakage in the motor increases.
- Pressure increase is immediately “seen” at the pump and where leakage increases and flow decreases for each revolution.
- Increased pressure causes pump input torque to increase, which causes the electric motor to slow down reducing the pump output even more, and thus reduces motor speed even more.

- **Closed loop system**
 - Speed feedback signal causes the pump displacement to increase until motor speed equals desired speed.
 - Within operating range, a load increase does not reduce motor speed.

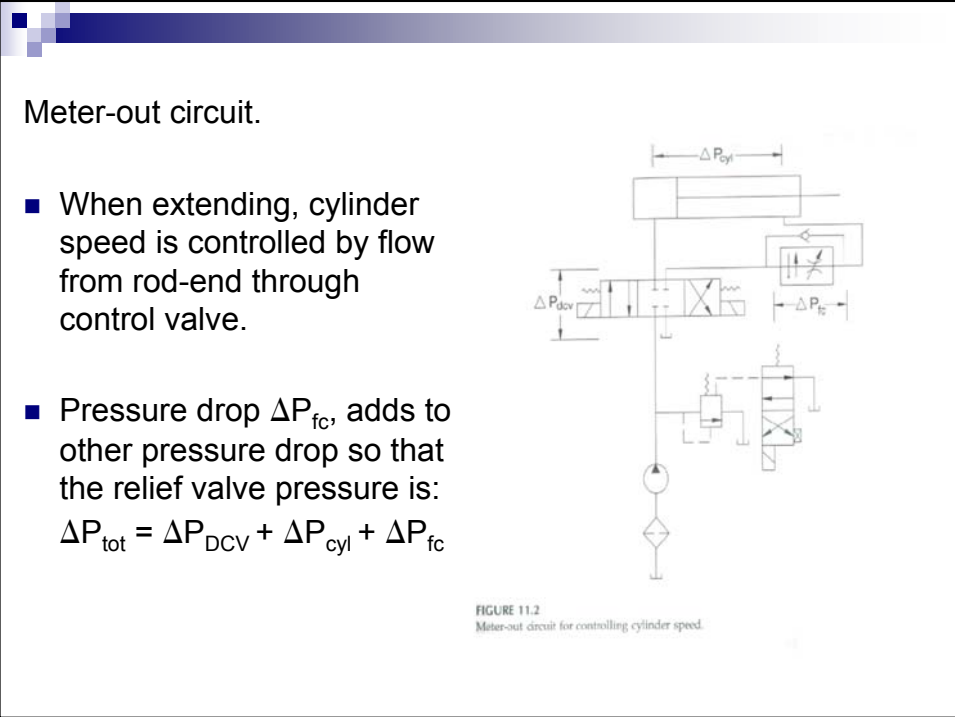
- **Closed loop system**
 - Speed feedback signal causes the pump displacement to increase until motor speed equals desired speed.
 - Within operating range, a load increase does not reduce motor speed.

- Meter-out circuit.
- When extending, cylinder speed is controlled by flow from rod-end through control valve.
- Pressure drop ΔP_{fc} adds to other pressure drop so that the relief valve pressure is:

$$\Delta P_{tot} = \Delta P_{DCV} + \Delta P_{cyl} + \Delta P_{fc}$$

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- Pressure compensation in the flow control valve maintains a constant ΔP_{fc} , by adjusting the size of the orifice as flow changes.
- The flow control valve is also temperature compensated, adjusting the orifice based on fluid temperature.
- As load pressure goes up, pump flow decreases due to increased internal leakage.

- Leakage between pressure line and the return line in DCV increases. Pump and valve leakage reduces cylinder speed.
- The DCV and flow control valve can be replaced with a servo valve while keeping the rest of circuit the same except for an added pressure line filter.

- Total pressure at the relief valve for a given load with filter is

$$\Delta P_{\text{tot1}} = \Delta P_{\text{sv1}} + \Delta P_{\text{cyl1}} + \Delta P_{\text{f}}$$

- Assume the corresponding flow across the relief valve is Q_{r1} . If cylinder load increases, pressure drop across cylinder becomes ΔP_{cyl2} .

- Total pressure at relief valve becomes

$$\Delta P_{\text{tot2}} = \Delta P_{\text{sv1}} + \Delta P_{\text{cyl2}} + \Delta P_{\text{f}}$$

- Flow across relief valve increases to Q_{r2} . Thus motor slows down.
- If pressure drop across servo valve changed to

$$\Delta P_{\text{tot2}} = \Delta P_{\text{sv2}} + \Delta P_{\text{cyl2}} + \Delta P_{\text{f}} = \Delta P_{\text{tot1}}$$

- Flow across relief valve returns to Q_{r1} , and the speed of cylinder is back to its original value.
- In many applications, a servo valve is just a means of programming an orifice in the circuit.

Programmable Orifice

- Servo valve with line-to-line lap condition.
- Similar to 4-way DCV, the valve has four ports: pressure return, Port A, and Port B.
- When spool is shifted, two orifices are created.

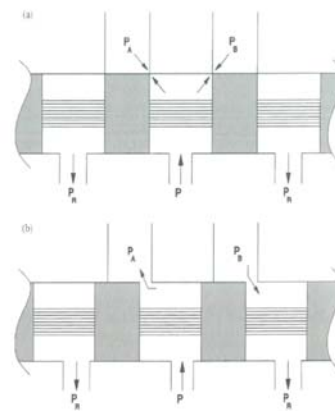


FIGURE 11.5
(a) Four-way servo valve with line-to-line lap condition and (b) shifted four-way servo valve showing pressure drops through the valve.

- Flow through the valve to the cylinder is given by the orifice equation,

$$Q = C_d A_o \sqrt{2g/\gamma} \sqrt{P_s - P_A}$$

Where Q = flow (in³/s)

C_d = orifice coefficient

A_o = orifice area(in²)

γ = fluid density (lb_f/in³)

P_s = supply pressure (psi)

P_A = Port A pressure (psi)

g = gravitational constant

- Flow from the cylinder back through the valve is given by

$$Q = C_d A_o \sqrt{2g/\gamma} \sqrt{P_B - P_R}$$

- Load pressure is defined to be

$$P_L = P_A - P_B$$

- This follows that

$$P_A = P_L + P_B$$

- Substituting in previous equation,

$$Q = C_d A_o \sqrt{2g/\gamma} \sqrt{P_s - (P_L + P_B)}$$

- We assume symmetry meaning the orifice on both sides have same properties.

Equating the two equations, we get

$$\sqrt{P_s - (P_L + P_B)} = \sqrt{P_B - P_R}$$

- Squaring and subtracting both sides,

$$P_s - P_L - P_R = 2 (P_B - P_R)$$

- Substituting back, we get,

$$Q = C_d A_o \sqrt{g/\gamma} \sqrt{P_s - P_L - P_R}$$

- Often, the equation is written

$$Q = k \sqrt{P_S - P_L - P_R}$$

Where $k = C_d A_o \sqrt{g / \gamma}$

- If conductor from the servo valve back to the reservoir is properly sized, $P_R \ll P_S$, then

$$Q = k \sqrt{P_S - P_L}$$

- Servo valves are typically rated by the manufacturer at 1000 psi pressure drop.
- Rated current is applied so valve is fully open.
- Pump speed is increased to achieve a 1000 psi ΔP across the servo valve.
- Measured flow is used to specify the valve size.

Typical performance curves reported in a servo valve technical specification sheet.

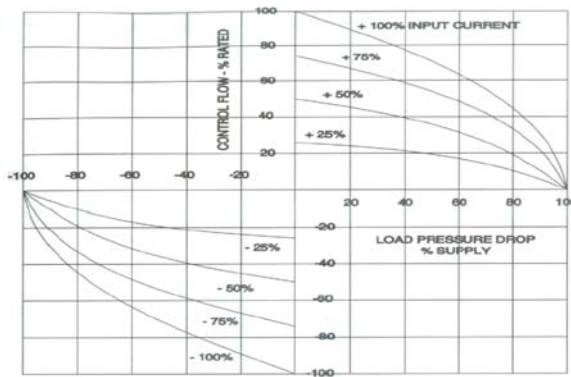


FIGURE 11.6
Typical flow vs. pressure curves for a servo valve.

- Four curves are shown – one for each of the 100%, 75%, 50% and 25% open positions.
- Each of these curves is a plot of the previous equation with different k corresponding to given open position. Considering 100% curve, when load pressure is 100% of supply pressure, $P_L = P_s$, flow through the valve is zero.
- Control flow = 100% (Rated Flow), when $P_L = 0$.



Control of Pump Displacement

- A variable displacement pump is more expensive, but has numerous features which are advantageous for the design of fluid power circuit.
- Servo valve can be used to change pump displacement and thus change the actuator speed.
- An open loop system becomes closed loop, by mounting a transducer on the output shaft of gearbox.

- 
- Transducer output voltage corresponds to a given shaft speed, and is compared to a setpoint voltage which corresponds to the desired speed.
 - Difference between the two voltages is used to increase (or decrease) pump displacement.
 - Pump output is continuously adjusted to maintain constant load speed as the load changes within some range.

- Four basic servo systems.

- Servo Actuators
 - Valve motor
 - Valve cylinder
- Servo Pump systems
 - Servo pump motor
 - Servo pump motor split

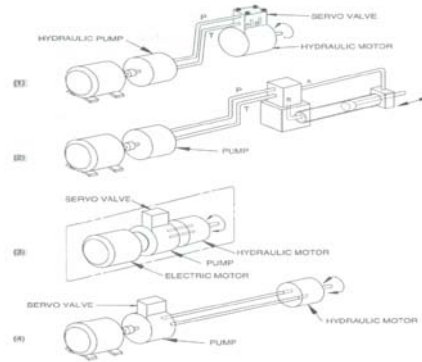


FIGURE 11.7 Four basic servo systems: (1) valve-motor, (2) valve-cylinder, (3) servo pump-motor, and (4) servo pump-motor split. Reprinted with permission from Electrohydraulic Servo Systems, James E. Johnson, Penton Media, Inc., Cleveland, Ohio.

- It is recommended to mount the valve directly on the actuator
- Most accurate system is the servo pump-motor
- This configuration avoids a column of compressed fluid in the lines
- Result : It gives higher natural frequency for system.



SERVO VALVE CONSTRUCTION

- A servo valve is a precisely machined spool-type directional control valve with some type of actuator to control the spool position.
- A torque motor can be used with a hydraulic cylinder to move the spool, rather than a solenoid mounted at the end of the spool.



SERVO VALVE CONSTRUCTION

- Three types of servo-valves.
 - **Single-stage** : Torque motor supplies enough torque to shift the spool against the pressure.
 - **Two-stage**: Torque motor shifts the pilot spool (first stage), which directs flow to shift the second stage. The second stage supplies flow to the actuator.
 - **Three-stage**: Pilot stage shifts second stage, which shifts the third stage. Three-stage valves are used for application with high flow and high pressure.

SERVO VALVE CONSTRUCTION

Torque Motor

- Torque motor consists of an armature, two coils and two pole pieces.
- Coils are wrapped on the armature, and armature is mounted such that the ends are positioned in the center of the air gap between upper and lower pole pieces.

SERVO VALVE CONSTRUCTION

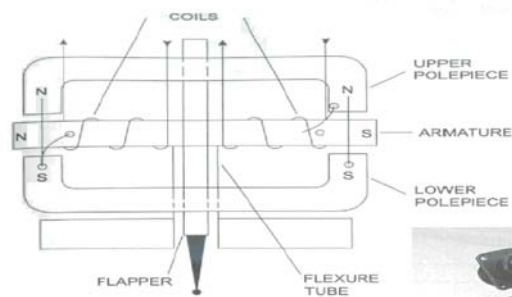


FIGURE 11.8
Construction of a torque motor. Photograph
courtesy of Moog Inc.





SERVO VALVE CONSTRUCTION

- Armature rotates clockwise or counter-clockwise when current is supplied to the coils, depending on polarity.
- The torque motor armature is mounted on a flexible tube which allows it to rotate until the torque produced by magnetic attraction equals the restraining torque in the flexible tube.



SERVO VALVE CONSTRUCTION

- Torque motor can move the pilot spool directly when it rotates. A rod connects the pilot stage spool to armature.
- When armature rotates, it shifts the pilot stage, which ports fluid to the second stage, causing it to shift.
- Feedback linkage ensures second stage spool always has same relative position as pilot stage. If pilot stage spool shifts 25% to right, second stage spool shifts 25% to left.

SERVO VALVE CONSTRUCTION

- Methods for shifting servo valve spool.
- Torque motor can shift the spool directly or indirectly.
- Three indirect methods for shifting the spool.
 - Single flapper nozzle.
 - Double flapper nozzle.
 - Jet pipe.

SERVO VALVE CONSTRUCTION

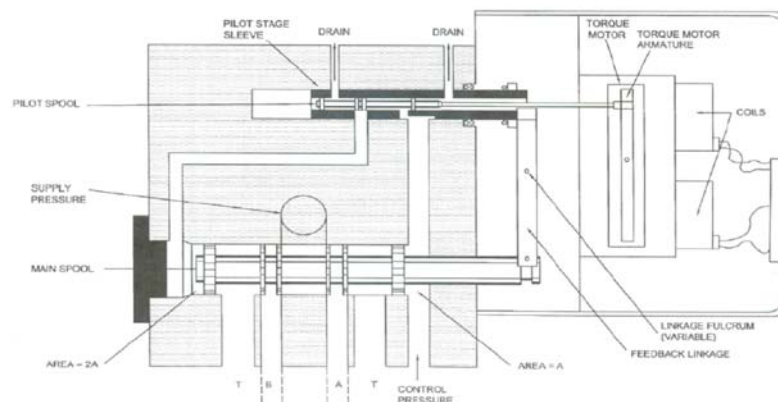


FIGURE 11.9
Two-stage servo valve with spool pilot stage directly linked to torque motor armature. Reprinted with permission from Electrohydraulic Servo Systems, James E. Johnson, Penton Media, Inc., Cleveland, Ohio.

SERVO VALVE CONSTRUCTION

Double flapper nozzle

- Supply pressure is supplied to points P_s , where orifices are formed on each side between the flapper and the opposing nozzles.
- If torque motor rotates the flapper clock-wise. Now orifice on left is smaller than that on right.
- Pressure at A will be greater than the pressure at B. This pressure difference shifts the spool to the right.

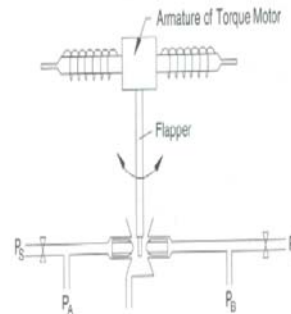


FIGURE 11.10
Diagram of double flapper nozzle as a first stage for a two-stage servo valve (second stage not shown). Reprinted with permission from Electrohydraulic Servo Systems, James E. Johnson, Penton Media, Inc., Cleveland, Ohio.

SERVO VALVE CONSTRUCTION

Jet Pipe

- Design is less sensitive to contamination than the flapper nozzle.
- Nozzle attached to the armature, directs a stream of fluid (pressure P_s) AT TWO RECEIVERS.
- If nozzle is centered, two receivers are hit by similar fluid streams and resultant pressure at end of spool is equal.

SERVO VALVE CONSTRUCTION

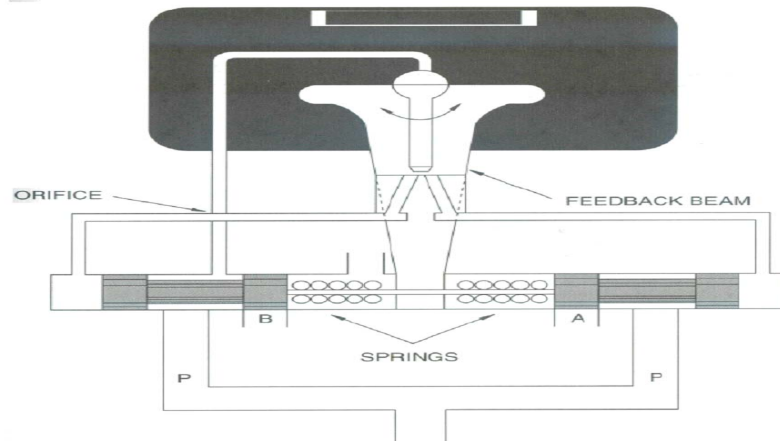


FIGURE 11.12
Diagram of jet pipe used as a first stage for a two-stage servo valve.

SERVO VALVE CONSTRUCTION

- A rotated armature stream of fluid impinges more directly on one nozzle.
- The resulting pressure imbalance shifts the second stage spool.
- Spool shifts until the spring force produces a torque equal to electromagnetic torque.

SERVO VALVE CONSTRUCTION

Valve Construction

■ Port shape (Fig 11.13)

- Servo valve bodies are machined with three common port shapes.
- Refer Fig 11.14 (Effect of port shape on flow).
- A full annulus port gives the highest flow per unit of spool displacement or, correspondingly, per unit of current input to the torque motor.

SERVO VALVE CONSTRUCTION

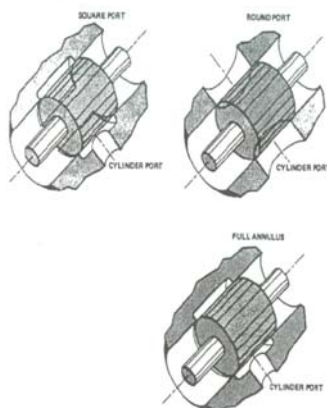


FIGURE 11.13
Common port shapes machined into the body of servo valves.

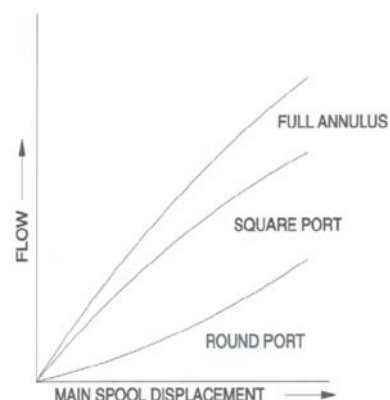


FIGURE 11.14
Flow as a function of spool displacement for common port shapes.

SERVO VALVE CONSTRUCTION

■ Lap Condition (Fig 11.15)

- Lap condition refers to position of the spool lands relative to the openings in the valve body.
- Most common condition is the line-to-line.
- Spool is machined very precisely to obtain line-to-line fit with the opening in the valve body.
- Underlapped valve referred to as open centered valve and overlapped valve as closed center valve.
- Overlapped valve has a deadband so that the spool must move a certain distance before any flow is delivered to the actuator ports.

SERVO VALVE CONSTRUCTION

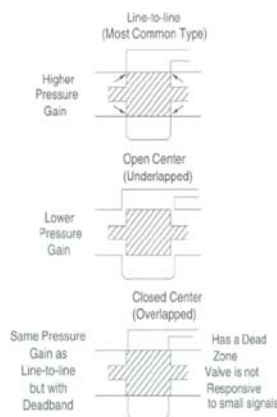


FIGURE 11.15
Three lap conditions for servo valves.

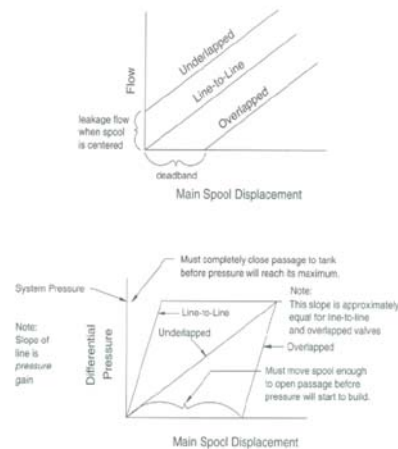


FIGURE 11.16
Flow and pressure as a function of lap condition for the three lap conditions.

VALVE PERFORMANCE

Rated Flow

- Normally specified as the no-load flow, and is measured with no actuator connected between Ports A and B.
- Flow meter is measured between these ports, and will increase as pressure drop across valve ($P_s - P_R$) increases.

VALVE PERFORMANCE

- Typical flow vs. pressure drop curves for a “family” of different size valves.
- A manufacturer usually labels their valves based on a 1000 psi pressure drop.

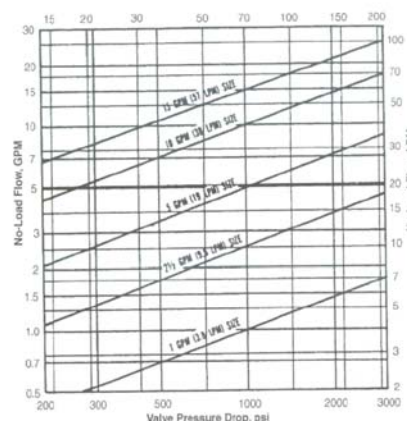


FIGURE 11.18
Change in rated flow with pressure drop across the valve for a family of different size valves.

VALVE PERFORMANCE

■ Pressure Drop

- Load pressure drop is the differential pressure between Ports A and B.

$$P_L = P_A - P_B$$

- Valve pressure drop is the sum of differential pressures across the control orifices of the valve.

$$P_V = P_S - P_L - P_R$$

VALVE PERFORMANCE

Internal Leakage

- Total Flow from the pressure port to return port with Ports A and B blocked is the internal leakage.

VALVE PERFORMANCE

- **Hysteresis** is shown in the figure, which was obtained by increasing current to the valve from 0 to + rated current and then returning through 0 to – rated current and back to 0.
- Typically, hysteresis will be less than 3% of rated current.

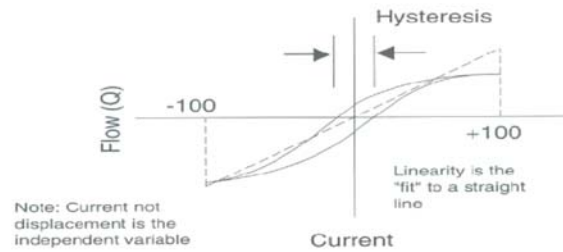


FIGURE 11.19
Flow vs. current input achieved with a constant supply pressure.

VALVE PERFORMANCE

Threshold

- Current that must be applied before a response is detected.
- Good-quality two-stage valves have a threshold less than 0.5% of rated current.

VALVE PERFORMANCE

Gain

- Defined as

$$G = \frac{\text{Output}}{\text{Input}}$$

- Two gains are defined for servo valves:
 - flow gain
 - pressure gain.

VALVE PERFORMANCE

- Flow gain is defined

$$G_{svf} = \text{Flow} / \text{Input Current}$$

- Typical units are in³/s/mA.
- Flow gain is determined by measuring control flow vs. input current and plotting the curve (Fig 11.20)
- Data is collected with no load connected between ports A and B.

VALVE PERFORMANCE

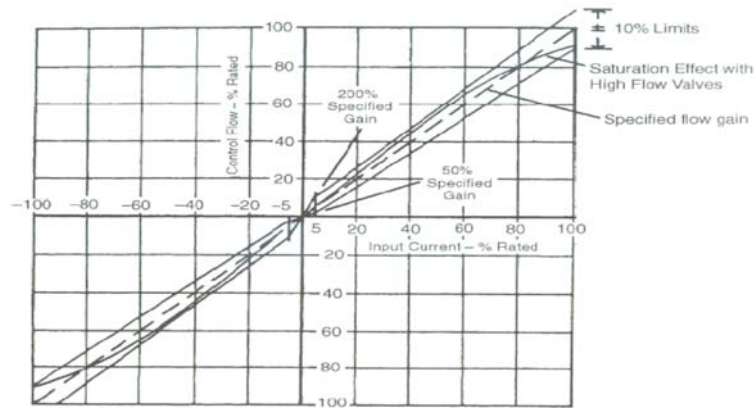


FIGURE 11.20
Data collected to define no-load flow gain.

VALVE PERFORMANCE

- Flow gain is the slope of the curve.
- Actual performance should fall within $\pm 10\%$ of the linear curve.
- Most of the non-linearity occurs in the null region, defined as $\pm 5\%$ of rated current.
- Flow gain in the null region may range from 50% to 200% of expected gain based on the slope of linear line.

VALVE PERFORMANCE

- Special spool cuts are available if performance in the null region is critical.
- Pressure gain is defined as
$$G_{svp} = \text{Pressure} / \text{Input Current}$$
units being psi/mA.
- To measure pressure gain, Ports A and B are blocked.

VALVE PERFORMANCE

- Pressure transducers are mounted in Ports A and B and pressure difference is measured as a function of input current.
- The range of input current to produce a load pressure change from -40% to +40% of supply pressure (P_s) is determined.
- Pressure gain is then
$$G_{svp} = 0.8 P_s / \text{Input Current}$$

VALVE PERFORMANCE

- Pressure gain is a difficult measurement to make.
- A normal range of pressure gain measurements will be 30 to 100% of P_s for an input current equal to 1% of rated current.

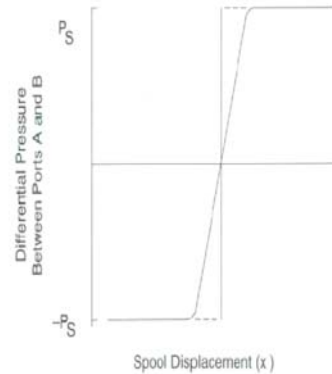


FIGURE 11.21
Typical pressure gain for servo valve.

VALVE PERFORMANCE

Frequency Response

- Relates to the ability of servo system to respond to change in the input voltage.

VALVE PERFORMANCE

- Step input current is applied to the servo valve, and the spool position is plotted versus the time.

- 15 ms open
- 10 ms return

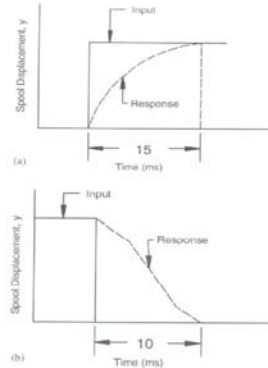


FIGURE 11.23 Time required for the spool of a servo valve to (a) fully open and (b) fully close when a step input current is applied.

VALVE PERFORMANCE

- Total time for one complete cycle is
 $15 \text{ ms} + 10 \text{ ms} = 25 \text{ ms}$
- Frequency is
$$\frac{1 \text{ cycle}}{25 \text{ ms}} \times \frac{1000 \text{ ms}}{\text{s}} = 40 \text{ cycles/s} = 40 \text{ Hz}$$
- If the current is cycled faster than 40 Hz, the valve will not open fully before it begins to close.

VALVE PERFORMANCE

- Ratio of output to input is reported in decibels:

$$\text{dB} = 20 \log_{10} (\text{output/input})$$

- Suppose the output is 50% of the input.

$$\begin{aligned} \text{dB} &= 20 \log_{10} (50/100) = 20 (-0.3) \\ &= -6 \end{aligned}$$

VALVE PERFORMANCE

- Several excitation signals used to determine frequency response

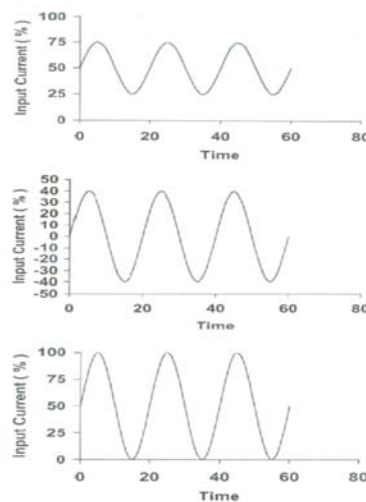


FIGURE 11.24
Excitation signals used to measure frequency response of servo valves.

VALVE PERFORMANCE

- Measured frequency response for three different size valves excited with +/-140% rated current

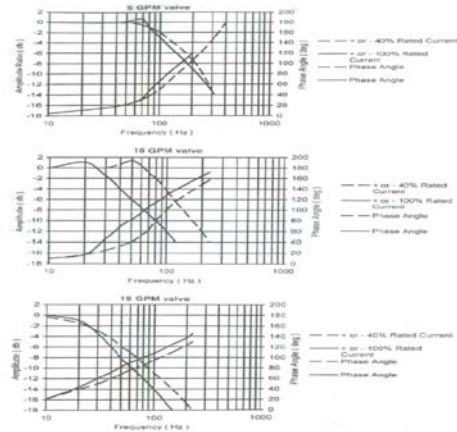


FIGURE 11.25 Frequency response for a "family" of servo valves. Reprinted by permission from Moog, Inc.

VALVE PERFORMANCE

- With +/-100% excitation,
 - a resonant phenomenon develops,
 - output is greater than input for frequencies between 40 and 70 Hz.
 - Both excitation shown as attenuation of o/p at higher frequencies.
 - Valve simply cannot move fast enough to track i/p signal.
 - Larger valves have lower frequency response.

VALVE PERFORMANCE

■ Phase Lag

- Phase lag is number of degrees that output lags behind input. (Fig 11.26)
- Output is 30° behind input, so phase lag is defined to be 30° .
- Phase lag is plotted on frequency response curves.
- Frequency at the phase lag 90° means that the valve is beginning to open when the input signal is just beginning to cycle in opposite direction.

VALVE PERFORMANCE

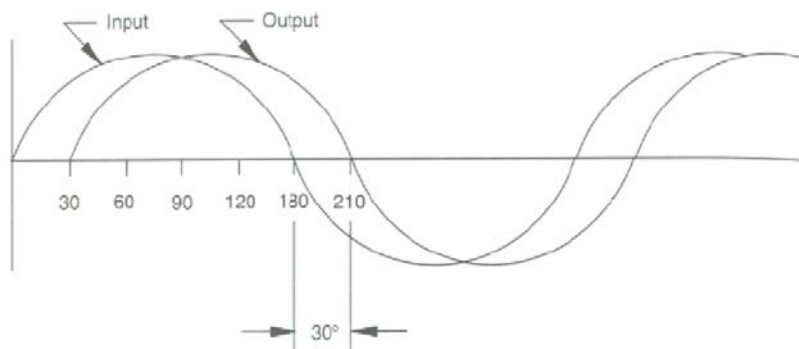


FIGURE 11.26
Output sinewave lags input sinewave by 30° .

Types of Servo Systems

- Servo systems can be used to control position (linear or angular).
- **Hydromechanical Servo System**
- On large machinery, force required to shift transmissions and perform other control functions can be substantial.
- Ease of operation can give an increase in operator productivity.

Types of Servo Systems

- System is hydromechanical servo.
- Mechanical input moves the servo cylinder to new position.
- Input shifts the spool causing the cylinder to move until valve body aligns with the new spool position.
- Valve body and cylinder body are one piece.

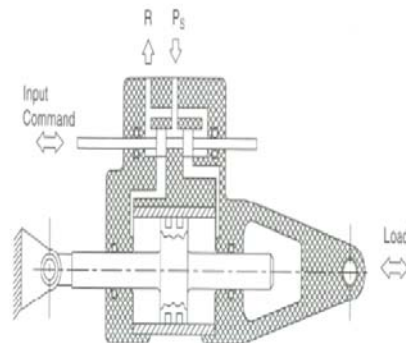


FIGURE 11.27
Hydromechanical servo.

Types of Servo Systems

- **Electrohydraulic Servo Systems**
- Additional flexibility and versatility can be obtained by using an electric input rather than a mechanical input.

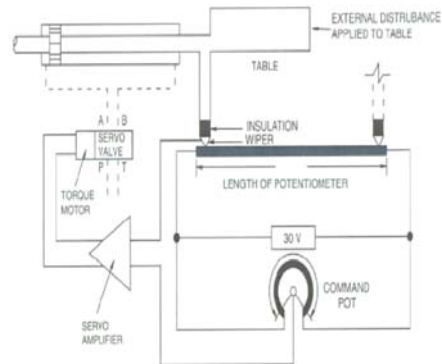


FIGURE 11.29
Electrohydraulic servo positioning system. Reprinted with permission from Electrohydraulic Servo Systems, James E. Johnson, Penton Media, Inc., Cleveland, Ohio.

Types of Servo Systems

- **Pot-Pot Servo**
- Command and feedback signals are obtained from potentiometers.
- Command voltage is obtained by rotating the command potentiometer.
- Command voltage is compared with a voltage obtained from potentiometer mounted adjacent to the work table, known as feedback potentiometer.



Types of Servo Systems

- Difference between the command and feedback voltages is the “error” voltage, and this voltage is the input to an amplifier.
- The amplifier produces a milliamp current proportional to error voltage. This is the input current to the servo valve torque motor.
- Servo valve opens to direct fluid to cylinder which moves the worktable. Table moves the wiper on feedback pot until feedback voltage = command voltage.



Types of Servo Systems

Force, Pressure and Torque Servos

- A force servo uses a force transducer as feedback signal.
- A pressure servo uses a pressure transducer
- Torque servo uses a torque transducer.

Types of Servo Systems

Force Servo

- A force transducer is mounted between cylinder and the load.
- Cylinder increases the force on the load until the transducer output voltage equals command voltage.
- System then hold this force until command signal is changed.

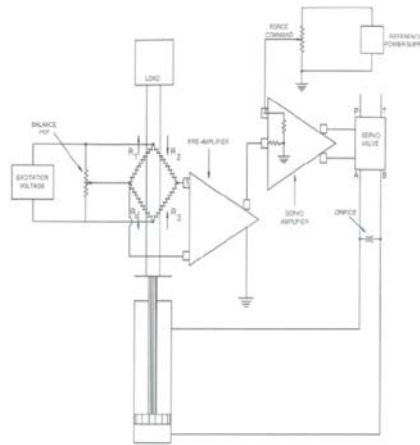


FIGURE 11.30
Force servo. Reprinted with permission from Electrohydraulic Servo Systems, James E. Johnson,
Penton Media, Inc., Cleveland, Ohio.

Types of Servo Systems

Velocity Servos

- Velocity servos are used to control both linear and rotational velocity.
- Typical velocity servo shown in Fig 11.31

Types of Servo Systems

- Difference between velocity servo and positional servo

- Amplifier output is not 0 for 0 voltage
- If it were 0, servo valve would be closed and no fluid would flow to the motor to produce rotational velocity.

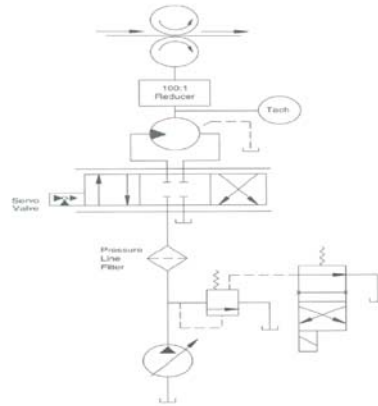


FIGURE 11-31 Servo motor used to control the speed of sheet steel for building for a required ductile.

Types of Servo Systems

- Servo amplifier for a velocity servo is an integrating amplifier.
- Output of an integrating amplifier ramps up when a positive voltage is applied to the input and ramps down when a negative voltage is applied.



Types of Servo Systems

- The non-zero output changes based on the error voltage applied.
- A dc tachometer is widely used as the feedback transducer for a rotary velocity servo, because its high end dc output can be directly connected to the servo amplifier without any need for signal conditioning.
- Spring cavity of pilot –operated relief valve is vented through a two-position, two-way DCV.



Types of Servo Systems

- When this line is blocked the relief valve is set at the pilot-setting.
- When it is open, the pump unloads at low pressure.
- Pressure line filter protects the servo valve. Valve is mounted directly on the motor to create valve motor configuration
- Motor speed is controlled by opening servo valve to provide a given pressure drop.

Types of Servo Systems

- Total pressure at relief valve is

$$\Delta P_{\text{tot}} = \Delta P_f + \Delta P_{\text{sv}} + \Delta P_m$$

where ΔP_f = pressure drop across filter

ΔP_{sv} = pressure drop across servo valve

ΔP_m = pressure drop across the motor

- Relief valve cracks open to divert part of flow back to reservoir, and remaining flow goes to motor.

Servo Amplifiers

- A servo amplifier has two main functions.
 - It provides a mA current proportional to an input voltage. Typical designs fall in the range 5mA/V to 100 mA/V.
 - It saturates at the rated current of the servo valve. The amplifier is designed so that it cannot deliver enough current to the torque motor to burn out coils.

Servo Amplifiers

- Why is an amplifier needed for a pot-pot servo system? Why not connect a torque motor between two potentiometers? (Refer Fig 11.32a)
- Suppose command and feedback potentiometers both have a resistance of 40Ω. Analysis shows that current through the coil would be 30 mA per inch of feedback pot movement. If servo valve has a deadband of 5% , and rated current is 30 mA, the deadband is $0.05 \times 30 = 1.5$ mA. This deadband corresponds to following position error.

$$\text{Error} = (1.5 \text{ mA}) / (30 \text{ mA/in}) = 0.05 \text{ in}$$

Servo Amplifiers

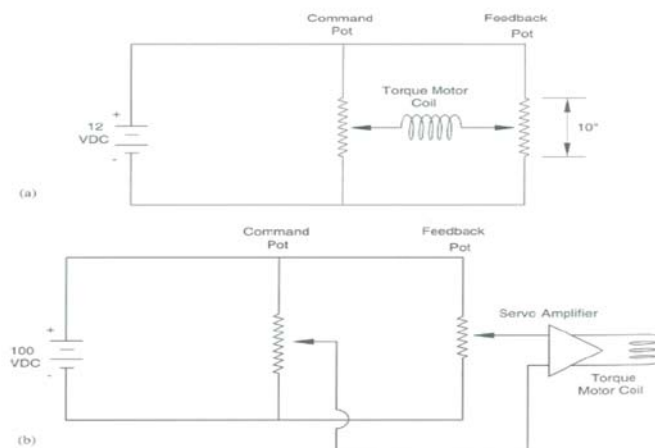


FIGURE 11.32
 (a) Potential electrical circuit for a pot-pot servo and (b) electrical circuit for a pot-pot servo that includes a servo amplifier.

Servo Amplifiers

- A servo amplifier has a very high input impedance, meaning that almost no current flows into the amplifier at the input.
- This feature allows the use of high-resistance pots and high supply voltage. (Fig 11.32 b)
- If feedback pot travel is 10 in., the feedback transfer function (TF) is $100\text{V} / 10 \text{ in.} = 10\text{V/in.}$

Servo Amplifiers

- Suppose the amplifier gain is 1000 mA/V. Total current is defined by

$$G_1 = G_a \times H$$

Where G_1 = total current gain (mA/in)

G_a = amplifier gain (mA/V)

H = feedback gain (V/in)

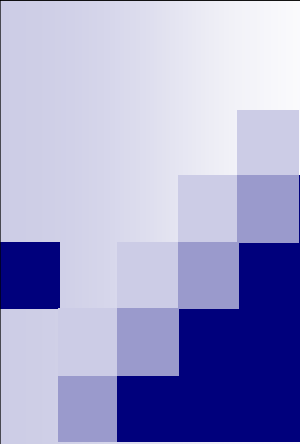
In this case ,

$$G_1 = 1000 \times 10 = 10,000 \text{ mA/in}$$

Assuming same servo value deadband, position error is

$$\text{Error} = 1.5 \text{ ma} / (10,000 \text{ mA/in}) = 0.00015 \text{ in}$$

As compared to 0.05 in. without servo amplifier. So, a servo amplifier provides opportunity to reduce position error.



Chapter 11 (contd.)

Refer slide Ch 11b