CHAPTER 12 PROPORTIONAL VALVES

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

Introduction

- **Proportional valves** were developed for applications where the precision of a servo valve is not needed, but more accuracy is needed than a conventional valves.

Introduction

TABLE 12.1

Comparison of Characteristics of Proportional Valves and Servo Valves

	Proportional valves	Servo valves
Type of Loop	Open	Closed
Feedback	No	Yes
Accuracy	Moderate error factor $\geq 3\%$	Extremely high error factor $< 1\%$
Frequency response	Low: <10 Hz	Very high: 60–400 Hz
Cost	Moderate	High
Need for auxiliary electronic equipment	Moderate	Substantial
Sensitivity to contamination	Tolerant	High

Types of Proportional Valves

- Types of Proportional valves:
- **Force-Controlled**
  - When a conventional solenoid is energized, the plunger travels it's full stroke and a given force is developed at the moment actuation occurs.
  - With a **Force-Controlled** proportional valve, provision is provided to increase the force output by the solenoid proportional to input current signal.

FIGURE 12.1
Functional diagram of force-controlled proportional valve.

Types of Proportional Valves

- **Stroke-Controlled**
  - With a **Stroke-Controlled** valve, the stroke distance is proportional to the input signal.
  - Both types provide an opening of the valve proportional to the magnitude of the milliamp current applied to the valve.

Types of Proportional Valves

- Force produced by solenoid is almost a linear function of input current.

FIGURE 12.1
Functional diagram of force-controlled proportional valve.

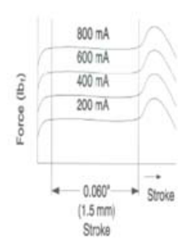

FIGURE 12.2
Force vs. input current developed by Rexroth proportional valve. Reprinted with permission from Mannesmann Rexroth.

Types of Proportional Valves

- **Proportional Pilot-Operated Relief Valve**
  - A functional diagram of Pilot-operated relief valve with a force solenoid replacing the manually adjusted pilot spring.

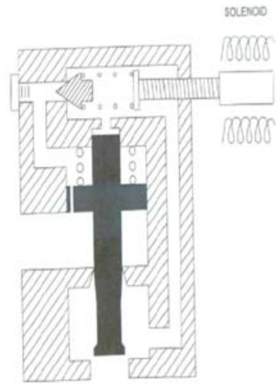

FIGURE 12.3a
Functional diagram of pilot-operated relief valve with a force solenoid in place of a screw adjustment for the pilot spring. Reprinted with permission from Parker Hannifin Corp.

Types of Proportional Valves

- **Proportional Pressure Reducing Valve**
  - Cross-sectional view of proportional pressure reducing valve.

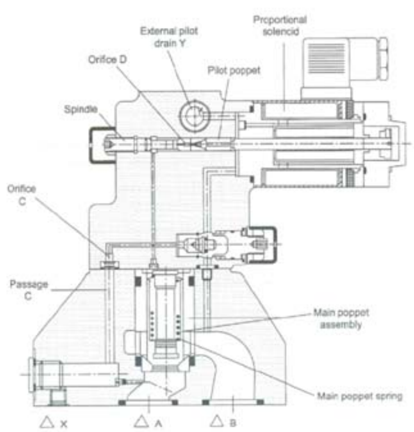

FIGURE 12.3b
Cross-sectional view of proportional pressure relief valve. With permission from Mannesmann Rexroth.

Types of Proportional Valves

- **Proportional Directional Control Valve**

- It has many of the same features of conventional four-way, three position DCV.

- Graphic symbols have orifices to indicate that the spool has been machined to allow metering of the flow.

- Spool in a proportional DCV can be machined with different shaped notches in the spool lands.

Types of Proportional Valves

- Typically these are triangular notches.

- When the spool is shifted, openings are produced as shown in Fig 12.7.

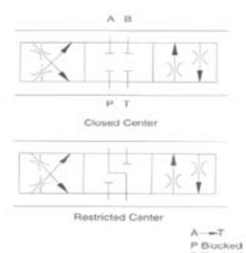

FIGURE 12.6
Graphic symbols used for proportional directional valves.

Types of Proportional Valves

- Note the matched notches, flow is metered when the spool is shifted in both directions.
- Overlap is generally 10% of total spool travel.

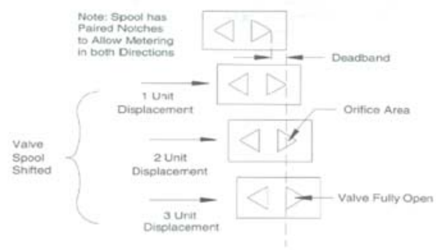

FIGURE 12.7
Openings produced when the spool of a proportional directional control valve is shifted.

Types of Proportional Valves

- In most valves, spool movement stops just short of full open position so that some metering function is maintained.
- Because metering notches are same on both sides of spool lands, pressure drop from P to A is approximately equal to pressure drop from B to T.

FIGURE 12.8
Actual proportional directional control valve spool with triangular notches. Reprinted with permission from Mannesmann Rexroth.

Types of Proportional Valves

- A special spool is needed to control a cylinder with a 2:1 area ratio.
- Flow from the rod end during extension is half the flow to the cap end.
- A spool with equal triangular notches will have unequal pressure drops across the valve because of the unequal flow through equal notch areas.

Types of Proportional Valves

- To control cylinder with 2:1 area ration, a spool is machined with twice the number of notches on one side of the land as the other side.
- Spool configuration keeps total pressure drop on both sides of the proportional DCV fairly equal.
- Good controllability of cylinders with a 2:1 area ratio is maintained.

Types of Proportional Valves

Cross sectional view of proportional DCV (Fig 12.10)

- There is a force solenoid on both ends to produce proportional control in both directions.
- Valve has main spool and a pilot spool like the two-stage servo valve.
- Force solenoid shift the pilot spool to supply pilot pressure to the pilot chambers.

Types of Proportional Valves

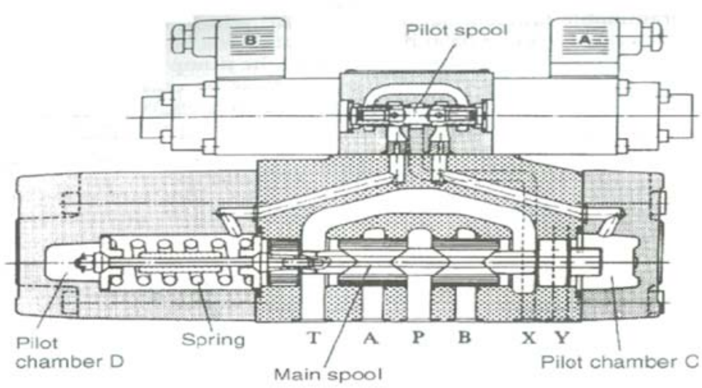

FIGURE 12.10
Cross-sectional view of a proportional directional control valve. Reprinted with permission from Mannesmann Rexroth.

Types of Proportional Valves

- Pressure in Chamber C acts against the right end of the spool causing it to move to the left against the main spool spring.
- The main spool spring is a push-pull spring.
- Pressure in Chamber D acts on the end of the piston that seals the left end of the spring cavity.
- Higher the pilot pressure, greater the spool displacement.

Types of Proportional Valves

- The spring holds the main spool in the center position until it is acted upon by pilot pressure in one of the pilot chambers.
- Similar to the servo valve, a proportional DCV is just a programmable orifice.
- A servo valve (and a proportional DCV) work in conjunction with a relief valve.

Types of Proportional Valves

- The programmable orifice is set to create a ΔP, which, when added to other ΔPs in the circuit, creates a pressure that opens the relief valve.
- Flow to the actuator is controlled by the dumping part of the pump flow across the relief valve.
- A proportional DCV controls flow by converting hydraulic energy to heat energy, thus need to provide for cooling of fluid.

Types of Proportional Valves

- Typical frequency response for a proportional DCV is shown
- The industry standard for rating proportional valves is the frequency at which attenuation is -3dB.

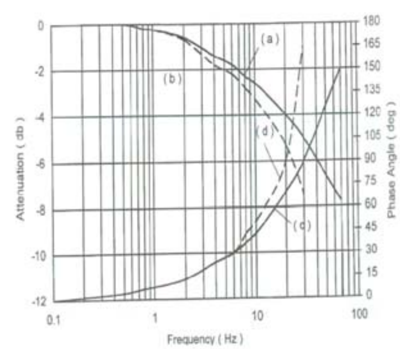

FIGURE 12.11a
Frequency response curves for proportional directional control valve.

Types of Proportional Valves

- Signal used to generate curve (a) was ±25% of rated input current about 50%, and the signal to generate curve (b) was ±50% about 50%.

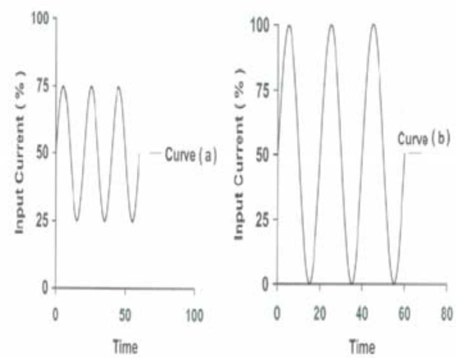

FIGURE 12.11b
Input signals used to obtain frequency response data in Fig. 12.11a.

Types of Proportional Valves

- The rated frequency response using +/- 25% signal is 12 Hz, and using a +/- 50% signal, it is 9 Hz.

- Phase lag curves are plotted for the +/- 25% signal and the +/- 50% signal.

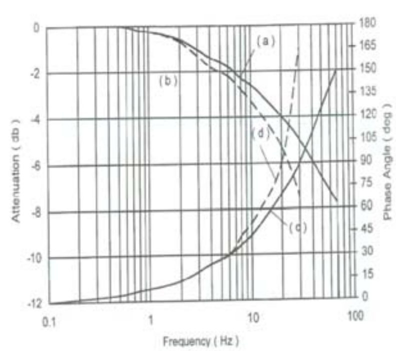

FIGURE 12.11a
Frequency response curves for proportional directional control valve.

Types of Proportional Valves

- At 12 Hz, the phase lag for the +/- 25 % signal is approximately 45^o, meaning that the output lags the input by 45^o.
- Phase lag at 9 Hz is also approximately 45^o for the +/- 50% signal.
- As signal frequency increases, ability of valve to “keep up” decreases and control is lost. If frequency increases to phase angle 180^o meaning the system is unstable.

Analysis of Proportional Directional Control Valve

- Functional Diagram of a proportional valve in a simple cylinder circuit is shown.
- ΔP_1 represents pressure drop between Port P and Port A ,and the pressure drop between Port B and Port T is shown as ΔP_2
- The cylinder has a 2:1 area ratio, and a proportional valve with a 2:1 area ratio is used.

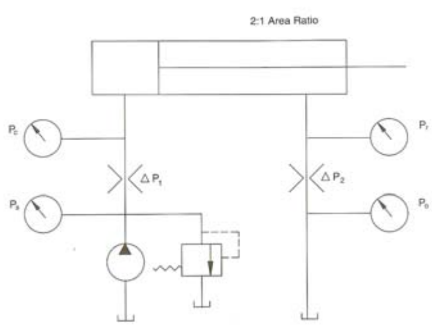

FIGURE 12.14
Functional diagram of a cylinder circuit with proportional valve.

Analysis of Proportional Directional Control Valve

- Flow corresponding to ΔP_1 will be designated Q_1 and the flow corresponding to ΔP_2 will be designated Q_2.

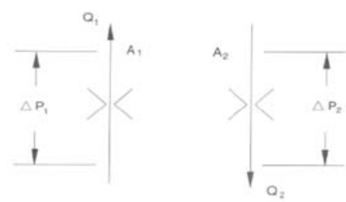

FIGURE 12.15
Orifices created when a proportional valve is opened.

Analysis of Proportional Directional Control Valve

- The Orifice equation applies for both sides of the valve.

$$Q_1 = CA_1\sqrt{\Delta P_1} \qquad Q_2 = CA_2\sqrt{\Delta P_2}$$

Where Q_1= flow into cap end of cylinder (in^3/s)
Q_2 = flow out of rod end of cylinder (in^3/s)
A_1 = area of orifice between Port P and Port A(in^2)
A_2 = area of orifice between Port B and Port T(in^2)
C = orifice coefficient ($in^2.s^{-1}.lb_f^{-0.5}$)
ΔP_1 =pressure drop between Ports P and A (psi)
ΔP_2 =pressure drop between Ports B and T (psi)

Analysis of Proportional Directional Control Valve

- The orifices have the same shape on both sides of the spool land.
- There are just twice as many grooves on one side for a valve with a 2:1 ratio.
- The same orifice coefficient (C) is used for both sides.
- The area ratio of the cylinder is 2:1; therefore during extension $Q_2 = Q_1/2$.

Analysis of Proportional Directional Control Valve

- Flow out rod end for each inch of movement is half the flow into the cap end.

$$A_2 = A_1 / 2$$

- Substituting this value,

$$Q_1 = CA_1\sqrt{\Delta P_1}$$

$$Q_2 = Q_1 / 2 = C(A_1 / 2)\sqrt{\Delta P_2}$$

(or) $$Q_1 = CA_1\sqrt{\Delta P_2}$$ (only if $\Delta P_1 = \Delta P_2$)

Analysis of Proportional Directional Control Valve

Overrunning Load

- Suppose the circuit shown in Fig 12.14 has an overrunning load during extension. (Fig 12.16)

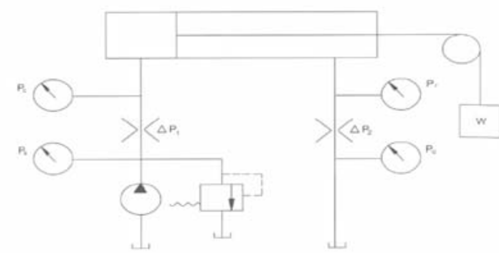

FIGURE 12.16
Cylinder with 2:1 area ratio and valve with 1:1 area ratio controlling an overrunning load.

Analysis of Proportional Directional Control Valve

- Force balance on the cylinder is

$$P_c A_c = P_r A_r + F_f + F_L$$

where F_L=W=load on the cylinder (lb_f)

F_f= friction force (lb_f)

Analysis of Proportional Directional Control Valve

- F_L is negative, since the load is overrunning, i.e., it is acting in the direction of cylinder movement.

- Solving for P_r,

$$P_r = (P_c A_c + F_L - F_f) / A_r$$

- Pressure drop across the Port P to Port A orifice in the proportional valve is

$$\Delta P_1 = P_S - P_C$$

Analysis of Proportional Directional Control Valve

- Neglecting pressure drop between the proportional valve outlet and the reservoir, P_o=0, the pressure drop from Port A to T is

$$\Delta P_2 = P_r - P_o = P_r$$

- With a 1:1 area ratio value, A_1= A_2= A, and the orifice equations become

$$Q_1 = CA\sqrt{\Delta P_1} \qquad Q_2 = CA\sqrt{\Delta P_2}$$

Analysis of Proportional Directional Control Valve

- Solving for CA and equating the two expressions,

$$Q_1/\sqrt{\Delta P_1} = Q_2/\sqrt{\Delta P_2}$$

(or)

$$Q_1/Q_2 = \sqrt{\Delta P_1}/\sqrt{\Delta P_2}$$

- Squaring both sides,

$$Q_1^2/Q_2^2 = \Delta P_1/\Delta P_2$$

(or)

$$\Delta P_2 = \Delta P_1 Q_2^2/Q_1^2$$

Analysis of Proportional Directional Control Valve

- Substituting for ΔP_1 and ΔP_2,

$$\mathrm{P_r} = (P_S - P_C)Q_2^2/Q_1^2$$

- Equating, and solving for pressure at the cap end of the cylinder.

$$\frac{(P_c A_c + F_{L} - F_f)}{A_r} = (P_S - P_C)Q_2^2/Q_1^2$$

$$P_C = \frac{P_S(Q_2^2/Q_1^2) - (F_L - F_f)/A_r}{(A_c/A_r) + (Q_2^2/Q_1^2)}$$

Analysis of Proportional Directional Control Valve

Resistive Load

- A simple circuit with a resistive load is shown.

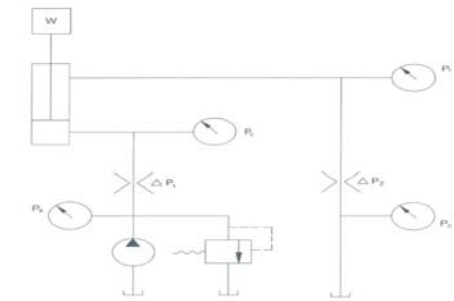

FIGURE 12.18
Cylinder with 2:1 area ratio and valve with 1:1 area ratio controlling a resistive load.

Analysis of Proportional Directional Control Valve

Resistive Load

- Force balance on cylinder gives,

$$P_c A_c = \mathrm{P_r}\, A_r + F_f + F_\mathrm{L}$$

- Solving for P_c,

$$P_c = (\mathrm{P_r}\, A_r + F_f + F_\mathrm{L}) / A_c............(Eq.12.19)$$

Analysis of Proportional Directional Control Valve

- This equation is the same as 12.6 except for the change in sign for F_L .

- Since the value has a 1:1 area ratio,

$$\Delta P_2 = \Delta P_1 Q_2^2 / Q_1^2$$

(or)

$$\Delta P_1 = \Delta P_2 Q_1^2 / Q_2^2 \ldots\ldots\ldots\ldots\ldots (Eq.12.20)$$

Analysis of Proportional Directional Control Valve

- As previously defined,

$$\Delta P_1 = P_S - P_C$$

$$\Delta P_2 = \mathrm{P_r}$$

- Substituting into Eq. 12.20 and solving for P_c,

$$P_c = P_S - \mathrm{P_r} Q_1^2 / Q_2^2 \ldots\ldots\ldots\ldots (Eq.12.21)$$

Analysis of Proportional Directional Control Valve

- Equating Eq. 12.19 and Eq.12.21 and solving for P_r,

$$P_r = \frac{P_S - (F_f + F_L)/A_c}{\frac{A_r}{A_c} + \frac{Q_1^2}{Q_2^2}}$$

End of Chapter 12

Thank You