Lecture 24

HYDRAULIC CIRCUIT DESIGN AND ANALYSIS

Learning Objectives

Upon completion of this chapter, the student should be able to:

- Identify the graphic symbols for various types of hydraulic components.
- Explain various hydraulic circuits to control single-acting and double-acting cylinders.
- Explain a regenerative circuit and determine the load-carrying capacities.
- Describe the working of a double-pump circuit along with its advantages.
- Explain the working of a sequencing circuit and a counterbalancing circuit.
- Differentiate between series and parallel synchronization circuits.
- Calculate the speed, pressure and load-carrying capacity of hydraulic circuits.
- Evaluate the performance of hydraulic circuits using various hydraulic elements.

1.1 Introduction

A hydraulic circuit is a group of components such as pumps, actuators, control valves, conductors and fittings arranged to perform useful work. There are three important considerations in designing a hydraulic circuit:

1. Safety of machine and personnel in the event of power failures.
2. Performance of given operation with minimum losses.
3. Cost of the component used in the circuit.

1.2Control of a Single-Acting Hydraulic Cylinder

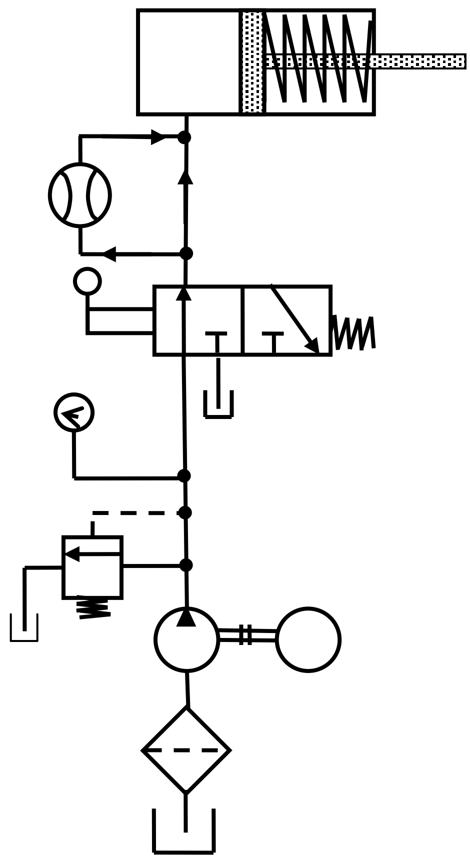

Figure 1.1 Control of a single-acting cylinder.

Figure 1.1 shows that the control of a single-acting,spring return cylinder using a three-way two-position manually actuated, spring offset direction-control valve (DCV). In the spring offset mode, full pump flow goes to the tank through the pressure-relief valve (PRV). The spring in the rod end of the cylinder retracts the piston as the oil from the blank end drains back into the tank. When the valve is manually actuated into its next position, pump flow extends the cylinder.
After full extension, pump flow goes through the relief valve. Deactivation of the DCV allows the cylinder to retract as the DCV shifts into its spring offset mode.

1.3Control of a Double-Acting Hydraulic Cylinder

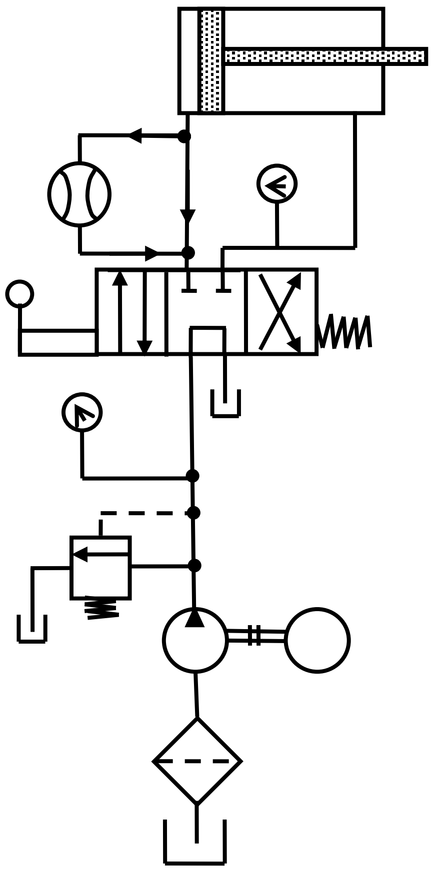

Figure 1.2 Control of a double-acting cylinder.

The circuit diagram to control double-acting cylinder is shown in Fig. 1.2. The control of a double-acting hydraulic cylinder is described as follows:

1. When the 4/3 valve is in its neutral position (tandem design), the cylinder is hydraulically locked and the pump is unloaded back to the tank.
2. When the 4/3 valve is actuated into the flow path, the cylinder is extended against its load as oil flows from port P through port A. Oil in the rod end of the cylinder is free to flow back to the tank through the four-way valve from portB through portT.
3. When the 4/3 valve is actuated into the right-envelope configuration, the cylinder retracts as oil flows from port P through port B. Oil in the blank end is returned to the tank via the flow path from port A to port T.

At the ends of the stroke, there is no system demand for oil. Thus, the pump flow goes through the relief valve at its pressure level setting unless the four-way valve is deactivated.

1.4Regenerative Cylinder Circuit

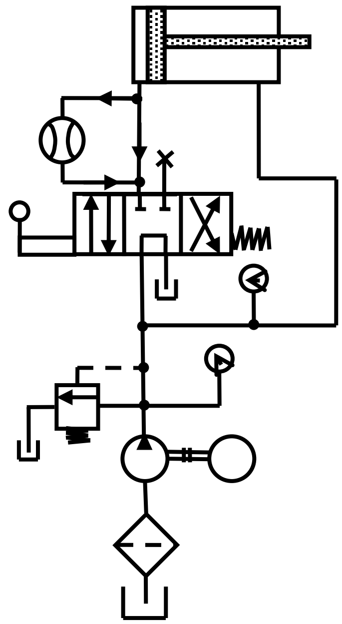

Figure 1.3 Regenerative circuit.

Figure 1.3 shows a regenerative circuit that is used to speed up the extending speed of a double-acting cylinder. The pipelines to both ends of the hydraulic cylinder are connected in parallel and one of the ports of the 4/3 valve is blockedby simply screwing a thread plug into the port opening. During retraction stroke, the 4/3 valve is configured to the right envelope. During this stroke, the pump flow bypasses the DCV and enters the rod end of the cylinder. Oil from the blank end then drains back to the tank through the DCV.

When the DCV is shifted in to its left-envelope configuration, the cylinder extends as shown in Fig. 1.3.The speed of extension is greater than that for a regular double-acting cylinder because the flow from the rod end regenerates with the pump flow Q_{p} to provide a total flow rate Q_{T} .

1.4.1 Expression for the Cylinder Extending Speed

The total flow rate Q_{T} entering the blank end of the cylinder is given by

$$Q_{\mathrm{T}} = Q_{\mathrm{p}} + Q_{\mathrm{r}}$$

where Q_{p} is the pump flow rate and Q_{r} is the regenerative flow or flow from the rod end.Hence,

$$\text{Pump flow rate } (Q_{\mathrm{p}}) = Q_{\mathrm{T}} - Q_{\mathrm{r}}$$

But the total flow rate acting on the blank rod end is given by

$$(Q_{\mathrm{T}}) = A_{\mathrm{p}} v_{\mathrm{ext}}$$

Similarly, theflow rate from the rod end is given by

$$(Q_{\mathrm{r}}) = (A_{\mathrm{p}} - A_{\mathrm{r}}) v_{\mathrm{ext}}$$

So pump flow rate is

$$Q_{\mathrm{p}} = A_{\mathrm{p}} v_{\mathrm{ext}} - (A_{\mathrm{p}} - A_{\mathrm{r}}) v_{\mathrm{ext}}$$

$$\Rightarrow Q_p = A_r v_{ext}$$

The extending speed of the piston is given as

$$v_{ext} = \frac{Q_p}{A_r}$$

Thus, a small area provides a large extending speed. The extending speed can be greater than the retracting speed if the rod area is made smaller. The retraction speed is given by

$$v_{ret} = \frac{Q_p}{A_p - A_r}$$

The ratio of extending and retracting speed is given as

$$\frac{v_{ext}}{v_{ret}} = \frac{Q_p / A_r}{Q_p / (A_p - A_r)} = \frac{A_p - A_r}{A_r} = \frac{A_p}{A_r} - 1$$

When the piston area equals two times the rod area, the extension and retraction speeds are equal. In general, the greater the ratio of the piston area to rod area, the greater is the ratio of the extending speed to retraction speed.

1.4.2 Load-Carrying Capacity During Extension

The load-carrying capacity of a regenerative cylinder during extension is less than that obtained from a regular double-acting cylinder.The load-carrying capacity $F_{\text{load-extension}}$ for a regenerative cylinder during extension equals pressure times the piston rod area. This is because system pressure acts on both sides of the piston during extension. Then

$$F_{\text{load-extension}} = pA_r$$

Thus, wedo not obtain more power from the regenerative cylinder during extension because the extension speed is increased at the expense of reduced load-carrying capacity.

1.5Pump-Unloading Circuit

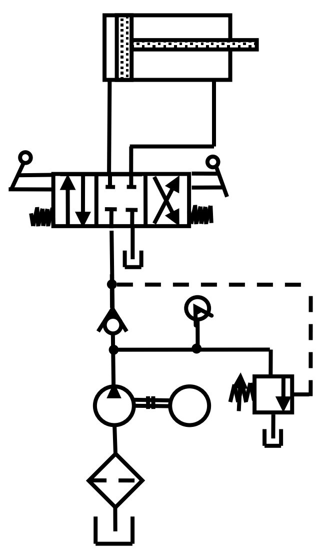

Figure 1.4 Pump-unloading circuit.

Figure 1.4 shows a hydraulic circuit to unload a pump using an unloading valve.When the cylinder reaches the end of its extension stroke, the pressure of oil rises because the check valve keeps the high-pressure oil. Due to high-pressure oil in the pilot line of the unloading valve, it opens and unloads the pump pressure to the tank.

When the DCV is shifted to retract the cylinder, the motion of the piston reduces the pressure in the pilot line of the unloading valve. This resets the unloading valve until the cylinder is fully retracted. When this happens, the unloading valve unloads the pump due to high-pressure oil. Thus, the unloading valve unloads the pump at the ends of the extending and retraction strokes as well as in the spring-centered position of the DCV.

1.6 Double-Pump Hydraulic System

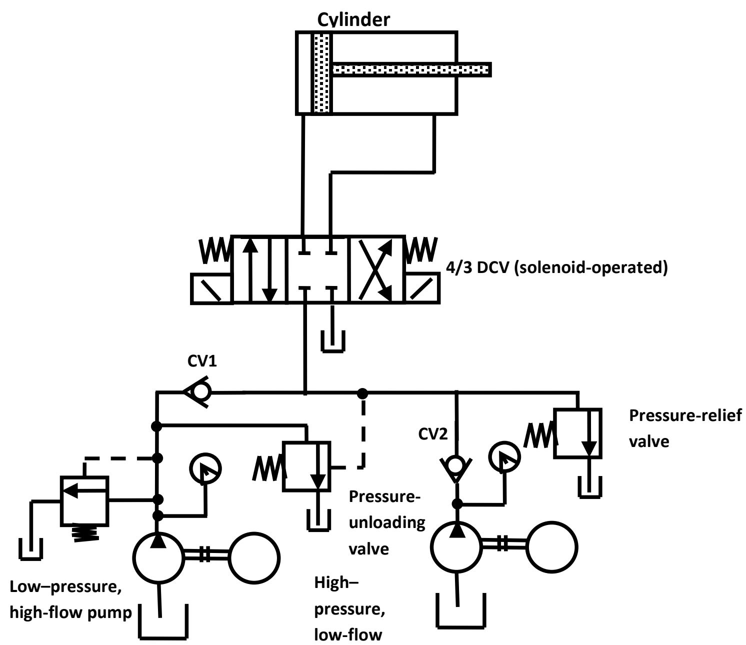

Figure 1.5 Double-pump circuit.

Figure 1.5 shows an application for an unloading valve. It is a circuit that uses a high-pressure, low-flow pump in conjunction with a low-pressure, high-flow pump. A typical application is a sheet metal punch press in which the hydraulic cylinder must extend rapidly over a great distance with low-pressure but high-flow requirements. This occurs under no load. However during the punching operation for short motion, the pressure requirements are high, but the cylinder travel is small and thus the flowrequirementsare low. The circuit in Fig. 1.5 eliminates the necessity of having a very expensive high-pressure, high-flow pump.

When the punching operation begins, the increased pressure opens the unloading valve to unload the low-pressure pump. The purpose of relief valve is to protect the high-pressure pump from over pressure at the end of cylinder stroke and when the DCV is in its spring-centered mode. The check valve protects the low-pressure pump from high pressure, which occurs during punching operation, at the ends of the cylinder stroke and when the DCV is in its spring-centered mode.

1.7Counterbalance Valve Application

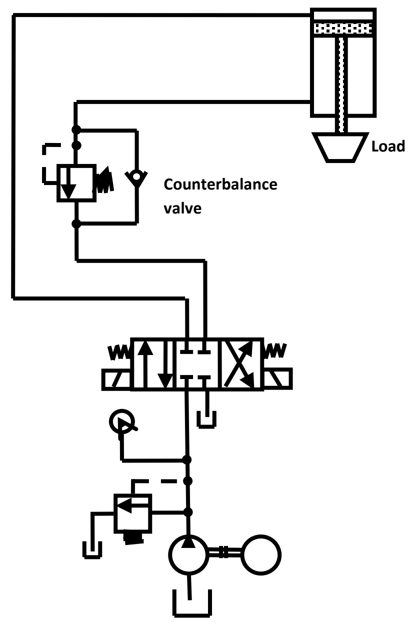

Figure 1.6 Counterbalance valvein circuit.

A counterbalance valve (Fig. 1.6) is applied to create a back pressure or cushioning pressure on the underside of a vertically moving piston to prevent the suspended load from free falling because of gravity while it is still being lowered.

1.7.1 Valve Operation (Lowering)

The pressure setting on the counterbalance valve is set slightly higher than the pressure required to prevent the load from free falling. Due to this back pressure in line A, the actuator piston must force down when the load is being lowered. This causes the pressure in line A to increase, which raises the spring-opposed spool, thus providing a flow path to discharge the exhaust flow from line A to the DCV and then to the tank. The spring-controlled discharge orifice maintains back pressure in line A during the entire downward piston stroke.

1.7.2Valve Operation (Lifting)

Asthe valve is normally closed, flow in the reverse direction (from port B to port A) cannot occur without a reverse free-flow check valve. When the load is raised again, the internal check valve opens to permit flow for the retraction of the actuator.

1.7.3 Valve Operation (Suspension)

When the valve is held in suspension, the valve remains closed. Therefore, its pressure setting must be slightly higher than the pressure caused by the load. Spool valves tend to leak internally under pressure. This makes it advisable to use a pilot-operated check valve in addition to the counterbalance valve if a load must be held in suspension for a prolonged time.

1.8 HydraulicCylinder Sequencing Circuits

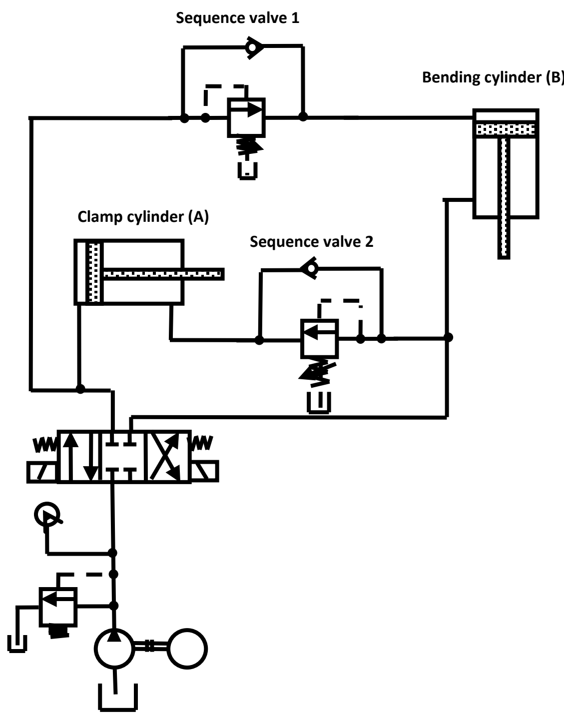

Figure 1.7 Sequencing circuit.

Hydraulic cylinders can be operated sequentially using a sequence valve. Figure 1.7 shows that two sequence valves are used to sequence the operation of two double-acting cylinders. When the DCV is actuated to its right-envelope mode, the bending cylinder (B) retracts fully and then the clamp cylinder (A) retracts.

This sequence of cylinder operation is controlled by sequence valves. This hydraulic circuit can be used in a production operation such as drilling. Cylinder A is used as a clamp cylinder and cylinder B as a drill cylinder. Cylinder A extendsand clamps a work piece. Then cylinder B extends to drive a spindle to drill a hole. Cylinder B retracts the drill spindle and then cylinder A retracts to release the work piece for removal.

1.9Automatic Cylinder Reciprocating System

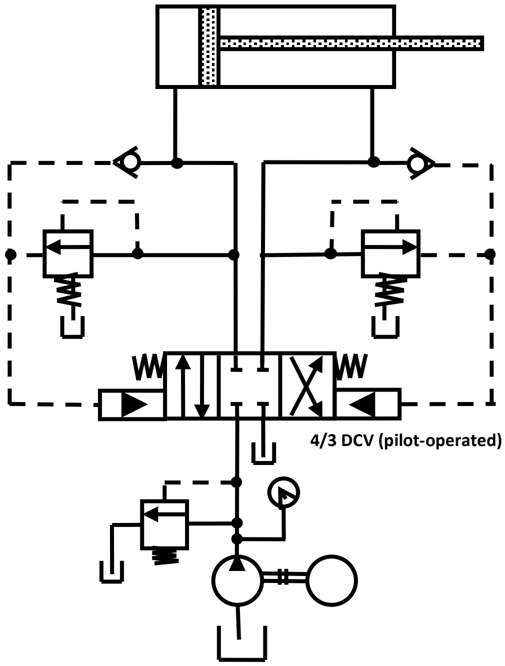

Figure 1.8 Sequencing circuit.

The hydraulic circuit shown in Fig. 1.8 produces continuous reciprocation of a double-acting cylinder using two sequence valves. Each sequence valve senses the completion of stroke by the corresponding build-up pressure. Each check valve and the corresponding pilot line prevent the shifting of the four-way valve until the particular stroke of the cylinder is completed.
The check valves are needed to allow pilot oil to leave either end of the DCV while the pilot pressure is applied to the opposite end. This permits the spool of the DCV to shift as required.

1.10Locked Cylinder Using Pilot Check Valves

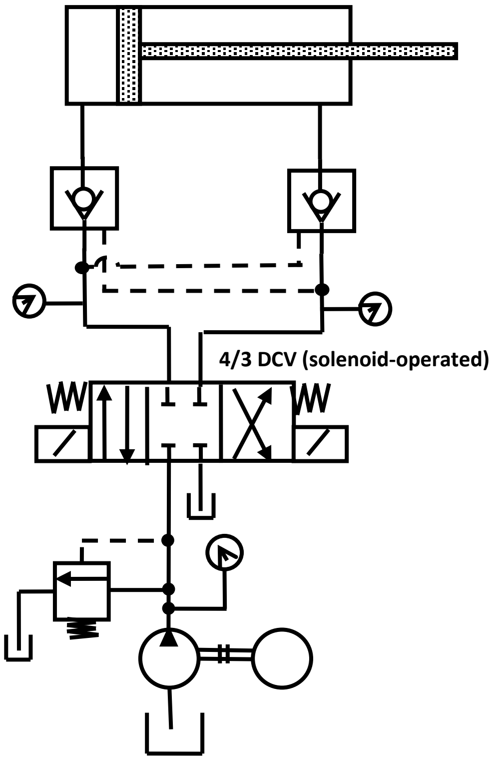

Figure 1.9 Locked cylinders with pilot check valves.

A check valve (Fig. 1.9) blocks flow in one direction but allows free flow in the opposite direction. A pilot-operated check valve permits flow in the normally blocked opposite direction when pilot pressure is applied at the pilot pressure port of the valve.

Pilot-operated check valves are used to lock the cylinder, so that its piston cannot be moved by an external force. The cylinder can be extended and retracted by the DCV. If regular check valves are used, the cylinder could not extend or retract. External force acting on the piston rod does not move the piston in either direction thus locking the cylinder.

1. 11Cylinder Synchronizing Circuits

In industry, there are instances when a large mass must be moved, and it is not feasible to move it with just one cylinder. In such cases we use two or more cylinders to prevent a moment or moments that might distort and damage the load. For example, in press used for molding and shearing parts, the platen used is very heavy. If the platen is several meter wide, it has to be of very heavy construction to prevent the damage when it is pressed down by a single cylinder in the middle. It can be designed with less material if it is pressed down with two or more cylinders. These cylinders must be synchronized. There are two ways that can be used to synchronize cylinders: Parallel and series.

1.11.1 Cylinders in Parallel

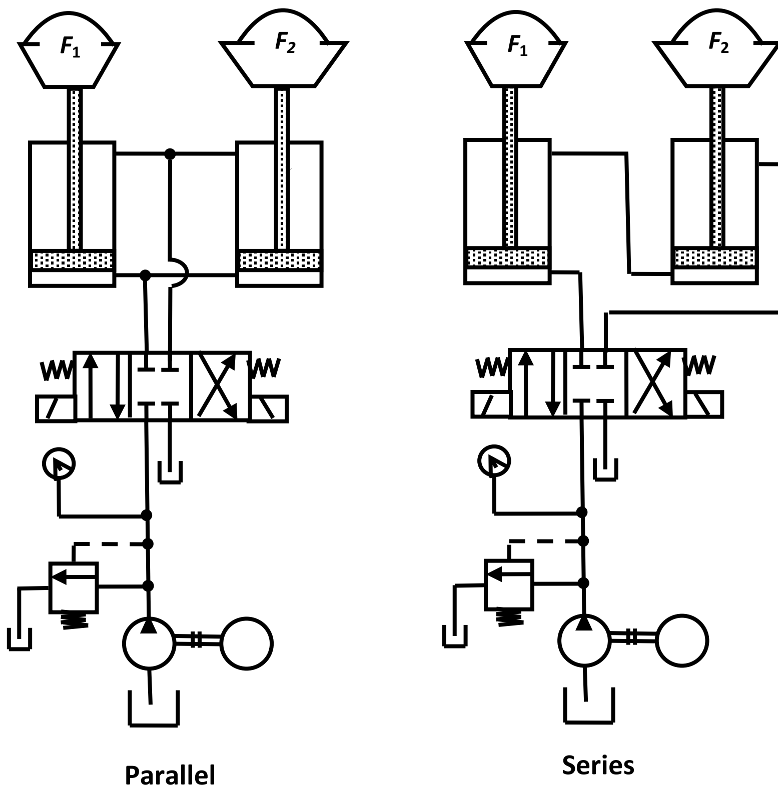

Figure 1.10 Cylinders in parallel and series.

Figure 1.10shows a hydraulic circuit in which two cylinders are arranged in parallel. When the two cylinders are identical, the loads on the cylinders are identical, and then extension and retraction are synchronized. If the loads are not identical, the cylinder with smaller load extends first. Thus, the two cylinders are not synchronized. Practically, no two cylinders are identical, because of packing(seals)friction differences. This prevents cylinder synchronization for this circuit.

1.11.2 Cylinders in Series

During the extending stroke of cylinders, fluid from the pump is delivered to the blank end of cylinder 1. As cylinder 1 extends, fluid from its rod end is delivered to the blank end of cylinder 2 causing the extension of cylinder 2. As cylinder 2 extends, fluid from its rod end reaches the tank.
For two cylinders to be synchronized, the piston area of cylinder 2 must be equal to the difference between the areas of piston and rod for cylinder 1. Thus, applying the continuity equation,

$$Q_{\text{out (cylinder1)}} = Q_{\text{in (cylinder 2)}}$$

we get

$$(A_{\text{p1}} - A_{\text{r1}})v_1 = A_{\text{p2}}v_2$$

For synchronization, $v_1 = v_2$. Therefore,

$$(A_{\text{p1}} - A_{\text{r1}}) = A_{\text{p2}} \quad (1.1)$$

The pump must deliver a pressure equal to that required for the piston of cylinder 1 by itself to overcome loads acting on both extending cylinders. We know that the pressure acting at the blank end of cylinder 2 is equal to the pressure acting at the rod end of cylinder 1.

Forces acting on cylinder 1 give

$$p_1 A_{\text{p1}} - p_2 (A_{\text{p1}} - A_{\text{r1}}) = F_1$$

Forces acting on cylinder 2 give

$$p_2 A_{\text{p2}} - p_2 (A_{\text{p2}} - A_{\text{r2}}) = F_2$$

UsingEq. (1.1)and noting that $p_3 = 0$ (it is connected to the tank), we have

$$p_1 A_{\text{p1}} - p_2 (A_{\text{p2}}) = F_1 \quad (1.2)$$

$$p_2 (A_{\text{p2}}) - 0 = F_2 \quad (1.3)$$

Now, Eq. (1.2) + Eq. (1.3) gives

$$p_1 A_{\text{p1}} = F_1 + F_2 \quad (1.4)$$

If Eqs. (1.1) and (1.4) are met in a hydraulic circuit, the cylinders hooked in series operate in synchronization.

1.12SpeedControl of a Hydraulic Cylinder

The speed control of a hydraulic cylinder circuit can be done during the extension stroke using a flow-control valve (FCV). This is done on a meter-in circuit and meter-out circuit as shown in Fig. 1.11. Refer to Fig. 1.11(a). When the DCV is actuated, oil flows through the FCV to extend the cylinder. The extending speed of the cylinder depends on the FCV setting. When the DCV is deactivated, the cylinder retracts as oil from the cylinder passes through the check valve. Thus, the retraction speed of a cylinder is not controlled. Figure 1.11(b) shows meter-out circuit; when DCV is actuated, oil flows through the rod end to retract the cylinder.

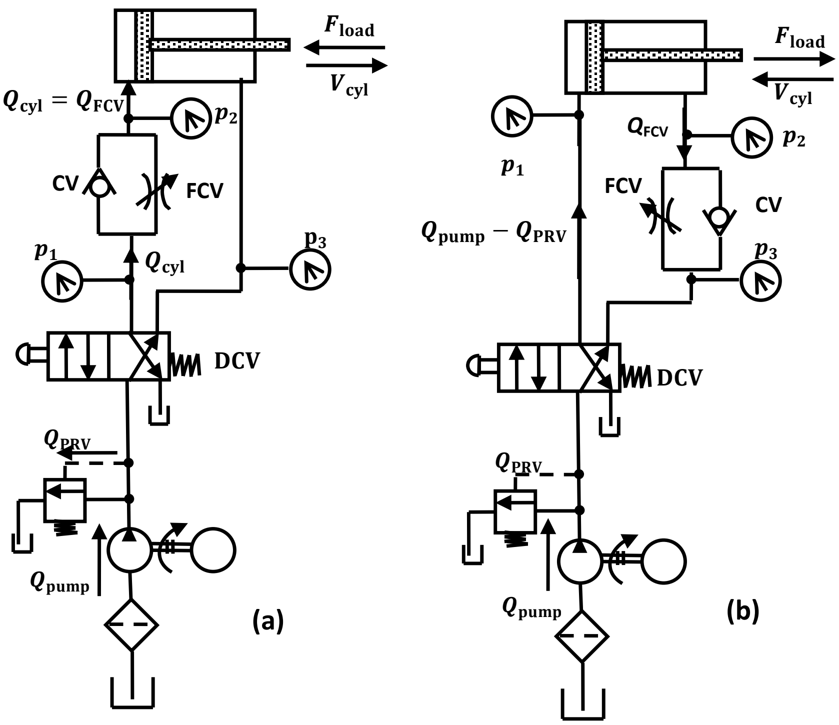

Figure 1.11 Speed control of cylinders:(a) Meter in and (b)meter out.

1.12.1 Analysis of Extending Speed of Cylinder (Controlled)

When theFCV is fully open during extension, all the flow from the pump goes to the cylinder to produce a maximum cylinder speed.When the FCV is partially closed, its pressure drop increases across the FCV. This causes an increase in pressure p_1. If closing is continued, pressure p_1 reaches and exceeds the cracking pressure of the PRV. This results in a slower cylinder speed because part of the pump flow goes through the PRV.

The flow rate to the cylinder Q_{cyl} is given by

$$Q_{cyl} = Q_{pump} - Q_{PRV} \tag{1.5}$$

where Q_{pump} is the flow rate of the pump and Q_{PRV} is the flow rate through the PRV. The flow rate through the FCV is given by

$$Q_{FCV} = C_V \sqrt{\frac{\Delta p}{SG}} = C_V \sqrt{\frac{p_1 - p_2}{SG}} \tag{1.6}$$

where Δp is the pressure drop across the FCV, C_V is the capacity coefficient of the FCV and SG is the specific gravity of oil.The pressure p_1 can be determined by summing forces on the hydraulic cylinder:

$$p_2 A_p = F_{load}$$

$$\Rightarrow p_2 = \frac{F_{load}}{A_p}$$

The extending velocity (controlled speed) of the cylinder is given by

$$v_{\text{cyl}} = \frac{Q_{\text{cyl}}}{A_{\text{p}}} = \frac{Q_{\text{FCV}}}{A_{\text{p}}}$$

$$\Rightarrow v_{\text{cyl}} = \frac{C_{\text{V}}}{A_{\text{p}}} \sqrt{\frac{p_{\text{PRV}} - \frac{F_{\text{load}}}{A_{\text{p}}}}{\text{SG}}}$$

1.12.2 Meter-In Versus Meter-Out Flow-Control Valve Systems

In Section 1.12, the FCV is placed in the line leading to the inlet port of the cylinder. Thus, it is called the meter-in control of speed. Meter-in flow controls the oil flow rate into the cylinder.

A meter-out flow control system is one in which the FCV is placed in the outlet line of the hydraulic cylinder. Thus, a meter-out flow control system controls the oil flow rate out of the cylinder.

Meter-in systems are used primarily when the external load opposes the direction of motion of the hydraulic cylinder. When a load is pulled downward due to gravity, a meter-out system is preferred. If a meter-in system is used in this case, the load would drop by pulling the piston rod, even if the FCV is completely closed.

One drawback of a meter-out system is the excessive pressure build-up in the rod end of the cylinder while it is extending. In addition, an excessive pressure in the rod end results in a large pressure drop across the FCV. This produces an undesirable effect of a high heat generation rate with a resulting increase in oil temperature.

1.12.3 Speed Control of a Hydraulic Motor

Figure 1.12shows the speed control circuit of a hydraulic motor using a pressure-compensated FCV.The operation is as follows:

- In a spring-centered position of the tandem four-way valve, the motor is hydraulically blocked.
- When the valve is actuated to the left envelope, the motor rotates in one direction. Its speed can be varied by adjusting the throttle of the FCV. Thus, the speed can be infinitely varied and the excess oil goes through the PRV.
- When the valve is deactivated, the motor stops suddenly and becomes locked.
- When the right envelope is in operation, the motor turns in the opposite direction. The PRV provides overload protection if, for example, the motor experiences an excessive torque load.

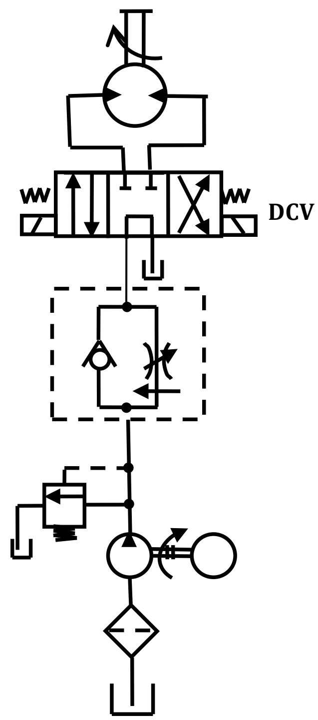

Figure 1.12 Speed control of a motor.

1.13Fail-Safe Circuits

Fail-safe circuits are those designed to prevent injury to the operator or damage to the equipment. In general, they prevent the system from accidentally falling on an operator and also prevent overloading of the system. In following sections we shall discuss two fail-safe circuits: One is protection from inadvertent cylinder extension and other is fail-safe overload protection.

1. **Protection from inadvertent cylinder extension:** Figure 1.13 shows a fail-safe circuit that is designed to prevent the cylinder from accidentally falling in the event when a hydraulic line ruptures or a person inadvertently operates the manual override on the pilot-actuated DCV when the pump is not working. To lower the cylinder, pilot pressure from the blank end of piston must pilot open the check valve to allow oil to return through the DCV to the tank. This happens when the push button is actuated to permit the pilot pressure actuation of DCV or when the DCV is directly manually actuated when the pump operates. The pilot-operated DCV allows free flow in the opposite direction to retract the cylinder when this DCV returns to its offset mode.

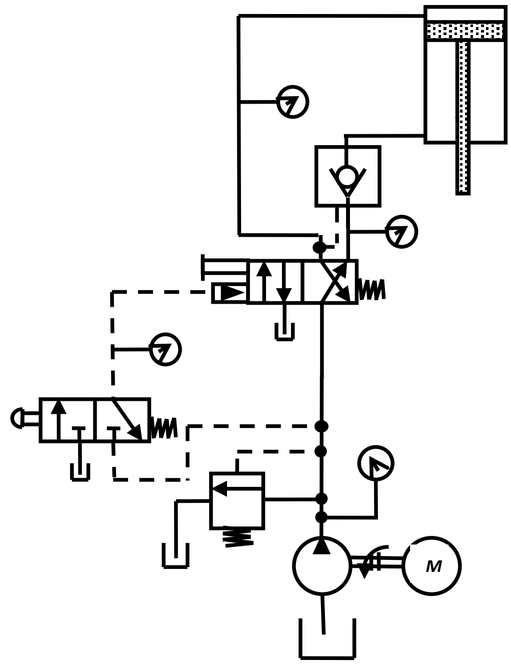

Figure 1.13 Fail-safe circuits – inadvertent cylinder extension.

2. Fail-Safe System with Overload Protection: Figure 1.14 shows a fail-safe system that provides overload protection for system components. The DCV V_1 is controlled by the push-button three-way valve V_2. When the overload valve V_3 is in its spring offset mode, it drains the pilot line of valve V_1. If the cylinder experiences excessive resistance during the extension stroke, sequence valve V_4 pilot-actuates overload valve V_3. This drains the pilot line of valve V_1 causing it to return to its spring offset mode. If a person then operates the push-button valve V_2 nothing happens unless overload valve V_3 is manually shifted into its blocked-port configuration. Thus, the system components are protected against excessive pressure due to an excessive cylinder load during its extension stroke.

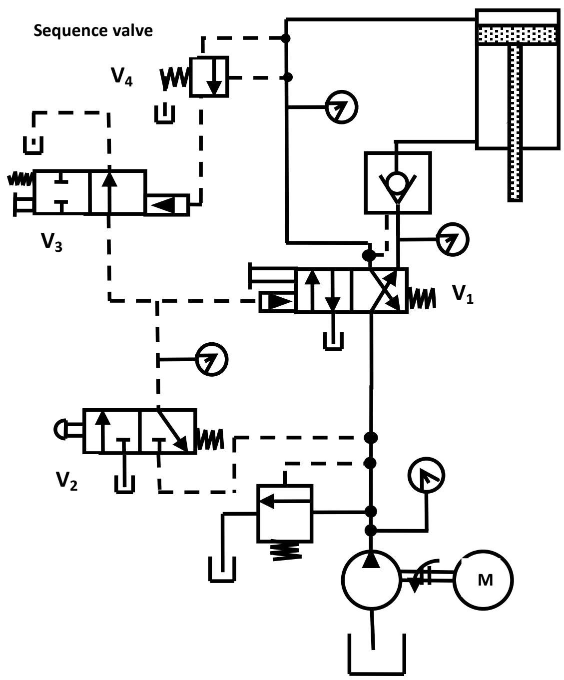

Figure 1.14 Fail-safe circuits –overload protection.