INTRODUCTION TO FLUID POWER CIRCUITS AND SYSTEMS

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PART 1

INTRODUCTION TO FLUID POWER CIRCUIT DESIGN

CHAPTER 1

ENERGY TRANSFER

The final step toward competence in fluid power technology is the study of circuits and systems. The diverse information acquired by the student of fluid power in the earlier stages of his training is here synthesized and put to use in the development of workable systems to perform useful functions.

Fluid power circuits can be considered from two points of view:

1. Design. Design of a circuit implies synthesis of an energy transfer system to perform a specific task.

2. Analysis. Analysis of a circuit implies the existence of a circuit to be analyzed with respect to its performance characteristics.

Design is a deductive process; analysis is inductive. This book provides a step-by-step approach to the deductive process of design. The student will find that he can minimize the difficulty of the subject by studying the topics carefully in the order in which they are presented.

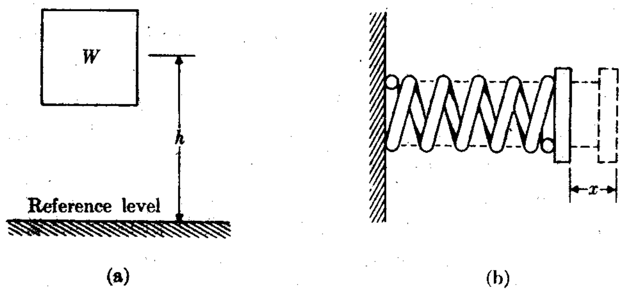
THE ENERGY TRANSFER PROCESS

Fluid power technology deals with energy transfer systems. Such systems are used to transfer energy from a source, called the *prime mover*, to a load for the purpose of doing useful work. The work might involve moving an object from one position to another (for example, on an automated transfer line), driving a machine tool spindle, powering the table on a milling machine, or raising the bucket on a front-end loader.

The simplest definition of *work* is as follows:

$$\text{work} = \text{force} \times \text{distance} = \text{pounds} \times \text{feet} = \text{ft}\cdot\text{lb}.$$

In this definition of mechanical work, the energy unit is the foot-pound (ft·lb). No distinction is made between work that involves linear motion and work that involves rotational motion.



1.1

There are two kinds, or *states*, of mechanical energy: *potential energy* and *kinetic energy*. Potential energy is stored energy; essentially, it is energy at rest. The term connotes the ability of energy to do work when released from its stored state. The easiest way to visualize potential energy is as a weight W (measured in pounds) held at some elevation h (measured in feet) above a reference level. We may then say that the weight has $W \times h$ ft·lb of potential energy relative to the reference level. (See Fig. 1.1a.)

A compressed spring provides another illustration of potential energy. If a spring with spring constant k lb/in. is deflected through a distance x, the potential energy (PE) of the spring is $\frac{1}{2}kx^2$. (See Fig. 1.1b.)

Kinetic energy is energy of motion, energy that is due to an object's velocity. The expression for kinetic energy is $KE = \frac{1}{2}mv^2$, where m is the mass of the object and v is its velocity. Note that $m = W/g$, where W is the weight of the object (in pounds) and g is the acceleration due to gravity. Since g is expressed in ft/sec^2 and v is expressed in ft/sec, the units for kinetic energy are lb/ft/sec^2 $\times$ ft^2/sec^2, which reduces to ft·lb, the same units that are used for potential energy.

There is a significant relationship between these kinds of energy. The law of conservation of energy states that the total energy content of a system is constant: $KE + PE = C$. Therefore, if the potential energy between any two points in a fluid power system changes, there must be a corresponding change in kinetic energy: $\Delta PE = \Delta KE$.

In a fluid power system, energy transfer occurs as a change in *potential energy*. Consider a fluid power circuit consisting of a source of fluid, an input device (a pump), conducting lines, and an output device (a cylinder or a motor) that uses the energy of the fluid to perform work before the fluid returns to the tank. For comparison's sake, suppose the fluid in the circuit is oil with a specific gravity of 0.8. Let's say that the fluid flows through the lines at a rate of 10 gpm at a pressure of 3000 psi, and assume that the lines are sized so that the flow velocity is 30 ft/sec. If we recall that water weighs 8.345 lb/gal, we can then write

$$\begin{aligned} W &= 10 \text{ gpm} \times 8.345 \text{ lb/gal} \times 0.8 \\ &= 66.6 \text{ lb/min} = 11.1 \text{ lb/sec} \end{aligned}$$

and

$$m = \frac{W}{g} = \frac{11.1 \text{ lb/sec}}{32.2 \text{ ft/sec}^2} = 0.345 \text{ slug/sec}.$$

Then

$$\begin{aligned} KE &= \tfrac{1}{2}mv^2 = \tfrac{1}{2} \times 0.0345 \times 900 \\ &= 15.5 \text{ ft·lb/sec} \end{aligned}$$

and

$$\begin{aligned} PE &= W \times 2.32p/0.8 \\ &= 1.11 \text{ lb/sec} \times 2.32 \times 3000/0.8 \\ &= 9650 \text{ ft·lb/sec}. \end{aligned}$$

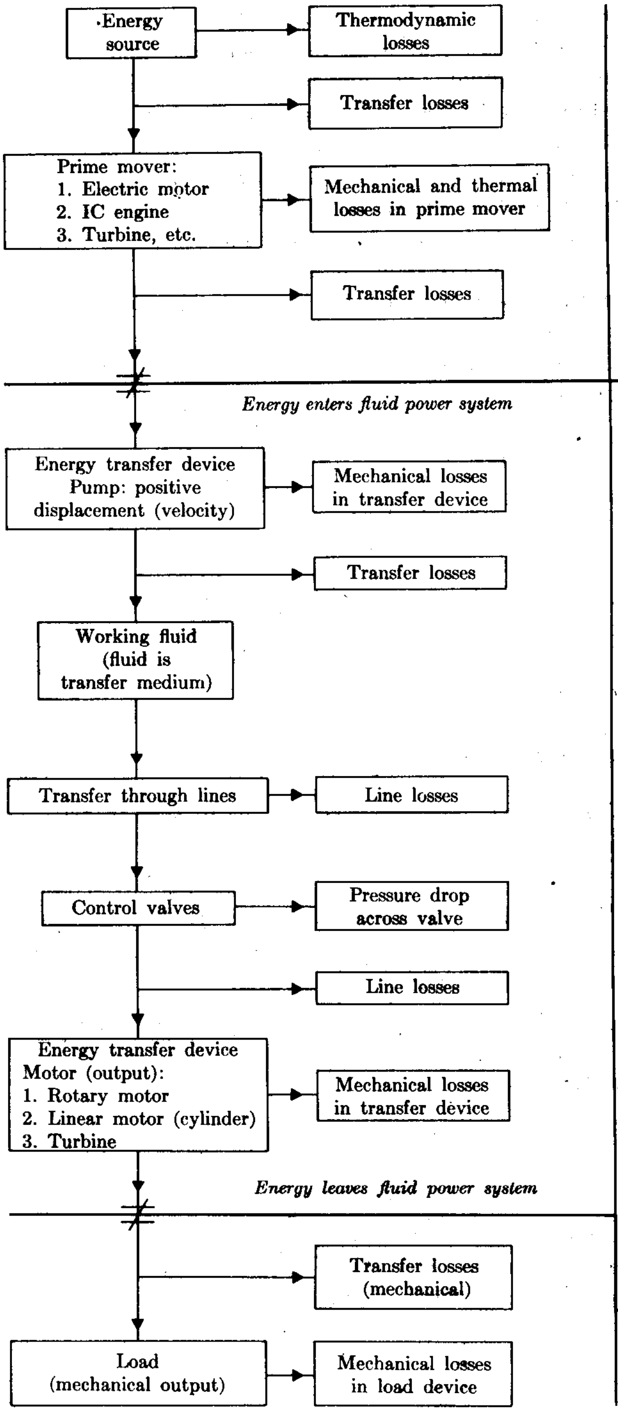
Thus the fluid stream has about 600 times as much potential energy as kinetic energy.

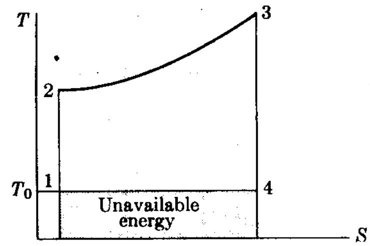
If we neglect area differentials in the cylinder, we can see that the velocity of the flow to the circuit output device is about the same as the velocity of the flow from it. In other words, the cylinder or motor at the end of the circuit returns the fluid to the tank with kinetic energy of about the same order of magnitude as it had when it left the pump. Thus $\Delta KE \simeq 0$ around the circuit.

On the other hand, the potential energy of the fluid leaving the output device is at a level greatly reduced from that at which it entered the device. Where this device is a cylinder, the piston of the cylinder acts as an interface between the high-energy fluid entering it and the low-energy fluid returning to the tank. The potential energy of the incoming fluid is first transferred to the piston; then the *force* developed by the piston rod moves through a *distance* equal to the stroke of the piston, and the potential energy of the fluid is thus converted into a work output: ΔPE = work. The same sort of energy transfer occurs where the output device is a rotary motor rather than a cylinder, except that the mechanical output is then a torque instead of a linear force.

The flow-diagram technique helps one to visualize the process of energy transfer as it occurs in a fluid power circuit. The left-hand side of Fig. 1.2 is a flow diagram; the four curves on the right-hand side of Fig. 1.2 are graphical representations of the events that occur during the various phases of the flow.

The flow diagram begins with the energy source, which supplies energy to the prime mover. The process of supplying energy to the prime mover entails a thermodynamic energy conversion; the curve to the right illustrates a typical thermodynamic cycle. The flow diagram next indicates the transfer of energy from the prime mover to the fluid. The device which performs this transfer is the pump.

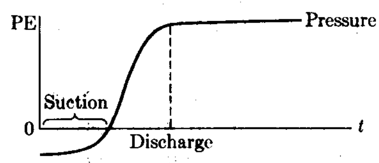




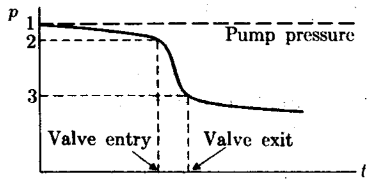
It can be demonstrated that all the energy in the system is *not* available. Also there are transfer losses in passing from one state to another.

1. Energy input to pump is mechanical, either by shaft rotation or a plunger stroke.

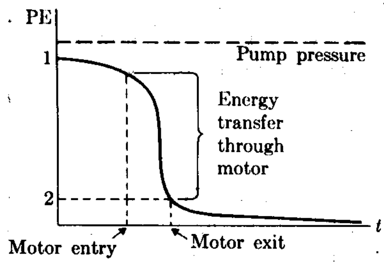
2. The potential-energy level of the fluid is raised in passing through the pump:



3. a) Slope from 1 to 2 illustrates line losses; b) Δp_{2-3} indicates pressure drop across valve:

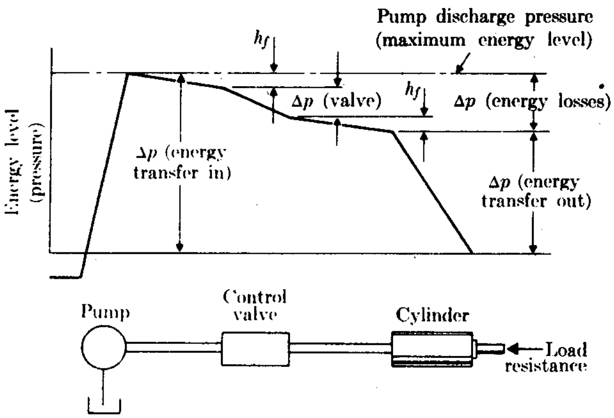


4. Potential-energy "flow" arriving at the output device will be less than that transferred to the fluid at the pump, by the amount of the losses:



5. There will be further losses in the mechanical output device, regardless of what it is. The magnitude of these losses depends on the particular situation.

1.2
Flow diagram of energy transfer in a fluid power system.



1.3

The second curve on the right-hand side of the figure shows the change in the potential energy of the fluid as it passes through the pump.

After the transfer losses indicated below the pump, we note a loss of energy due to flow losses of the fluid as it passes through the circuit piping; these are referred to as line losses. Then comes an energy loss due to a pressure drop across a control valve. Both of these losses are reflected in the third curve.

After further line losses, the flow diagram indicates an energy transfer to the load. The energy that is transferred constitutes the output from the circuit. The corresponding curve shows the energy transfer across the mechanical interface (i.e., the output device) as a pressure differential.

If you compare Fig. 1.2 with Fig. 1.3, you will recognize Fig. 1.2 as an amplification of the familiar pressure-energy diagram for a simple fluid power circuit. (In Fig. 1.3, h_f stands for head losses.)

RATE OF DOING WORK

Now that we have reviewed the concepts of potential and kinetic energy and introduced the flow-diagram technique, we can return to the subject of work and discuss the *rate of doing work* in a fluid power system. We express rate of work in horsepower, and in the English system one horsepower is equal to 550 ft·lb/sec or 33,000 ft·lb/min. Recall that when we calculated potential energy, we converted pressure in psi to feet of head ($h = 2.32p/S_g$, where S_g is the specific gravity of the fluid). We also converted the flow rate in gpm to pounds per minute ($W = 8.345 \times Q \times S_g$, where Q is the flow rate in gpm). If we multiply these two quantities and divide by the rate of work equivalent to one horsepower, we have the familiar formula used for calculating hydraulic horsepower:

$$\text{HP} = \frac{8.345 \times Q \times S_g \times 2.32p}{S_g \times 33{,}000} = \frac{19.4pQ}{33{,}000} = \frac{pQ}{1714}.$$

It is evident from this formula that the horsepower, and therefore the rate of energy transfer, in a fluid power system is a function of the flow rate and the pressure level in the system.

Important Terms

Fluid power technology deals with the transfer, control, and storage of energy by means of a pressurized fluid.

Work is the utilization of energy. It is generally considered to be the product of a force (lb) and the distance (ft) through which it acts.

Potential energy is energy of state, or stored energy. It is the capability for doing work. It is expressed by PE = Wh.

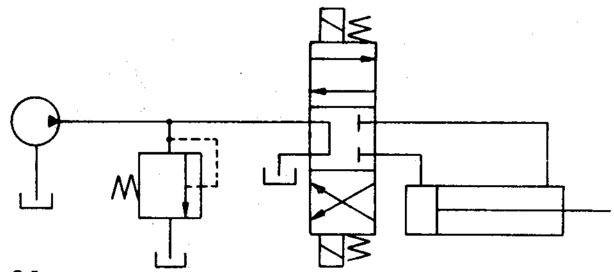
Kinetic energy is energy of motion, the energy that a mass (W/g) transmits by virtue of its velocity. It is expressed by KE = $\frac{1}{2}mv^2$.

Horsepower is the rate of doing work, or the rate of energy transfer. One horsepower is equal to 550 ft·lb/sec or 33,000 ft·lb/min.

CHAPTER 2

DEFINITIONS AND A SYSTEM OF CLASSIFICATION OF CIRCUITS

Now that we have established the concept of fluid power systems as energy transfer systems, we must develop a language to use in talking about them. In this chapter we shall outline a basic vocabulary that will make it possible for us to approach the design of fluid systems in a formal and definitive manner.

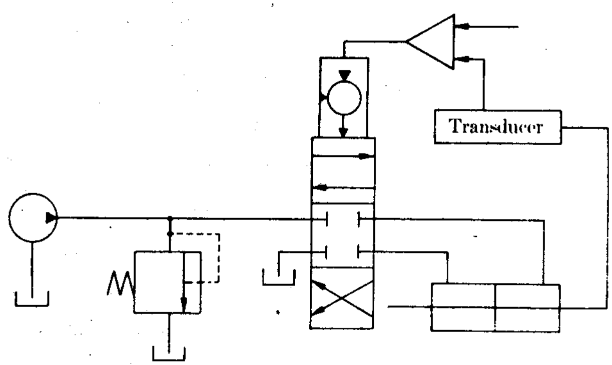


2.1

OPEN-LOOP AND CLOSED-LOOP CIRCUITS

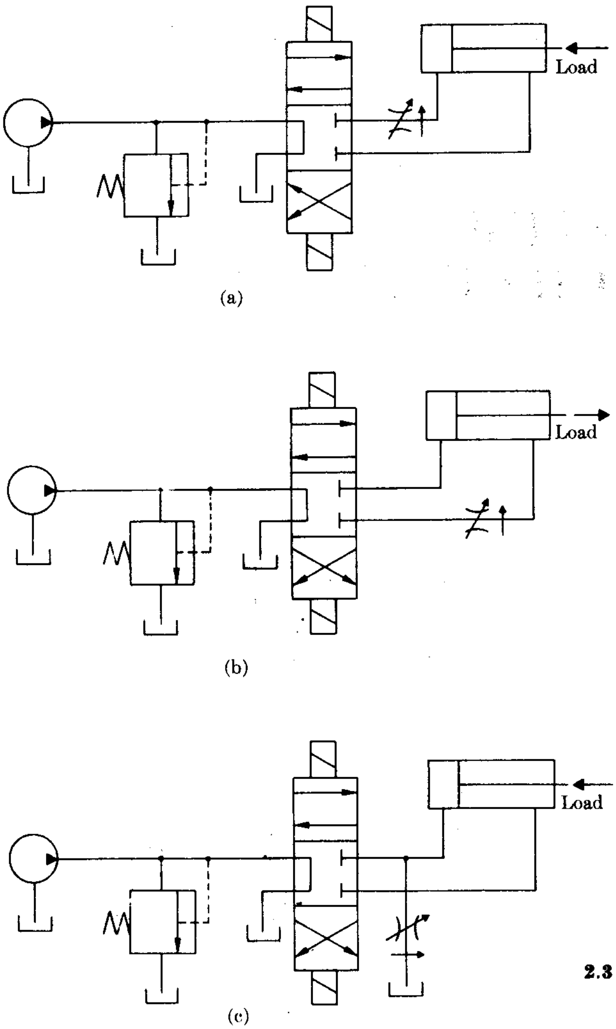
Fluid power systems may be divided into two majar classes: open-loop and closed-loop systems. A closed-loop system is one that employs *feedback*, which is the technique of sampling the state of the output from the system, generating a signal proportional to this output, and comparing it to an input or command signal. If there is a difference between the command signal and the feedback signal, action is taken automatically to correct the output so that it matches the requirements of the command. We shall deal with closed-loop systems in Part 3.

An open-loop circuit or system is one in which feedback is not employed. The performance characteristics of the circuit are determined by the characteristics of the individual components used and their interaction in the circuit. Figure 2.1 illustrates such a circuit. Most so-called industrial circuits are of this type.



2.2

We might mention one more type of system before we proceed with the classification of open-loop circuits. A *servo system* is a feedback system in which the output is a mechanical position. (See Fig. 2.2.) We shall discuss servo systems in Part 3.



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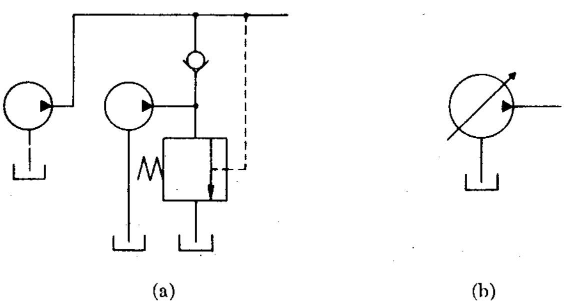


2.4

CLASSIFICATIONS OF OPEN-LOOP CIRCUITS

There are many ways to classify open-loop circuits. For example, they may be classified by

a) the *function* they are to perform,
b) the *method* by which they achieve control,
c) *system type*, or
d) *application* area.

All of these circuit classifications are in common use today.

Functions of Open-Loop Circuits

Classifications by function of open-loop circuits are related to the basic areas of control:

1. Flow control. The purpose of flow control is to regulate the energy transfer *rate* by regulating the flow rate in a circuit or branch of a circuit.

2. Pressure control. The purpose of pressure control may be either (i) to regulate energy transfer by regulating pressure level or (ii) to use a specific pressure level as a signal to initiate a secondary action.

3. Direction control. This is control of the distribution of energy in a fluid power circuit.

Methods by which Open-Loop Circuits Achieve Control

Control can be achieved in a fluid power circuit by one of these three fundamental methods:

1. Valve control. Valving is applied to give the desired mode of control.

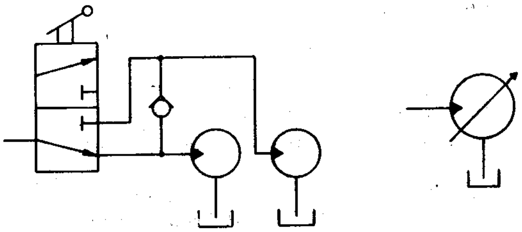
2. Pump control. The pump itself, almost of necessity a variable-volume pump, provides control.

3. Actuator control. The displacement of the actuator (most frequently a rotary motor) is varied to provide control.

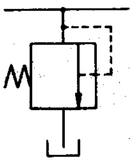
These three methods apply within the functional classes of control as follows:

1. Flow control

a) Valve control utilizes one of the several types of compensated or uncompensated flow control valves.



(a) (b) 2.5



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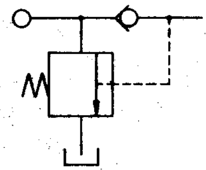

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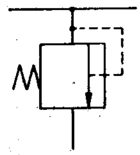

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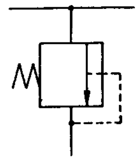

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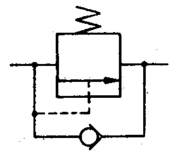

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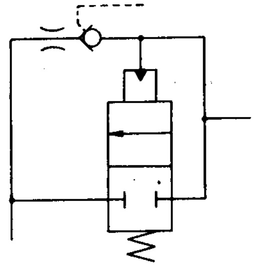


2.11

The position of the flow control valve in the circuit determines the appropriate type to use:

i) *Meter-in:* The valve is placed between the source of energy and the actuator. (See Fig. 2.3a.)

ii) *Meter-out:* The valve is placed in the return line from the actuator. It controls the energy transfer by limiting the rate of flow out of the the actuator. (See Fig. 2.3b.)

iii) *Bleed-off:* The valve is placed in parallel with the actuator. It limits the rate of energy transfer to the actuator by controlling the amount bypassed through the parallel circuit. (See Fig. 2.3c.)

b) Pump control implies one of two control methods, depending on which type of pump is used. *Multiple* pumps give a step variation in flow rate (see Fig. 2.4a); *variable-volume* pumps give infinite variation in flow rate (see Fig. 2.4b).

c) Actuator control uses the same techniques as pump control and thus involves the use of multiple motors (see Fig. 2.5a) for step variation or variable-displacement motors (see Fig. 2.5b) for infinite variation in output speed.

2. Pressure control

a) Valve control uses one or more of the types of pressure control valves. There are six important types that we shall encounter:

i) *Relief* valves limit the maximum energy level of the system by limiting the maximum pressure. (See Fig. 2.6.)

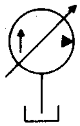
ii) *Unloading* valves regulate the pressure level by providing a bypass for the circuit flow, so that it is carried back to the tank at a low energy level. Unloading valves are activated when the pressure reaches a certain "set" level. (See Fig. 2.7.).

iii) *Sequence* valves react to a pressure signal to switch flow to a secondary circuit. Thus they divert energy from the primary circuit to the secondary. (See Fig. 2.8.)

iv) *Reducing* valves react to a pressure signal to throttle flow to a secondary circuit, thereby delivering energy at a lower level than that in the primary circuit. (See Fig. 2.9.)

v) *Counterbalance* valves control the potential energy differential across an actuator by maintaining a back pressure in the return line. These are not truly pressure control or pressure-actuated valves in the sense of the four previous types. (See Fig. 2.10.)

vi) *Decompression* valves provide controlled release of energy stored in high-pressure systems because of elasticity in the system. These also are not true pressure control valves. (See Fig. 2.11.)



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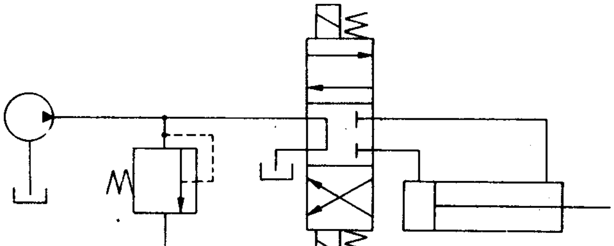

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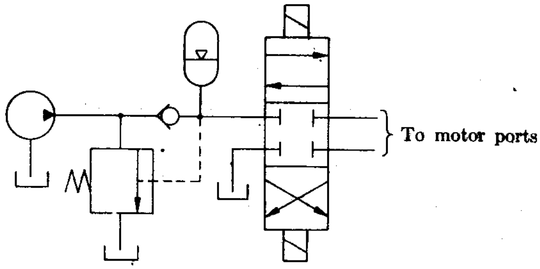

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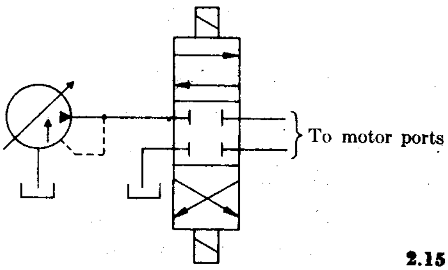


2.15

b) Pump control of pressure in open-loop circuits is generally effected by pressure-compensated variable-volume pumps. Energy transfer is controlled by varying the flow rate from the pump in response to a pressure-level signal impressed across the compensator. (See Fig. 2.12.)

c) Actuator control of pressure is not generally used.

3. Direction control

a) Valve control uses one of the many types of direction control valves to regulate the distribution of energy throughout the circuit. These valves switch the flow streams entering and leaving the valve.

b) Pump control is limited to reversal of direction of flow from a variable-volume reversible pump.

c) Actuator control is similar to pump control; it uses reversible, variable-volume motors.

Types of Open-Loop Circuits

There are two basic types of open-loop circuits, *open-center* and *closed-center*. Figure 2.13 shows a typical open-center circuit. Such circuits have the following characteristics:

1. A direction control valve unloads the pump, bypassing fluid to the tank when the valve is in the centered or neutral position.

2. A fixed-displacement pump is most commonly used.

3. Energy transfer starts from a low level (essentially zero) when the valve is in neutral, and builds up as the valve is shifted. This shifting of the valve causes the fluid stream to move into the actuator and therefore to exert itself against the load resistance.

4. Internal leakage is minimal when the valve is in centered position, unless the actuator is supporting a load in an elevated position.

5. In general, open-center circuits are the least expensive, provided they meet performance requirements.

Figure 2.14 shows a typical closed-center circuit. Note that such a circuit uses a fixed-displacement pump, an unloading valve, and an accumulator. Closed-center circuits have the following characteristics:

1. All ports are blocked when the direction control valve is in its centered or neutral position.

2. If a fixed-displacement pump is used, ordinarily an accumulator is also used and an unloading valve is required.

3. Energy transfer starts from a high level, from the maximum pressure setting of the system. The energy is available to the actuator as soon as the valve is shifted.

4. Internal leakage is of more concern here than in open-center circuits, since the valve is holding against full system pressure at all times.

Figure 2.15 shows a second version of the closed-center circuit. This circuit uses a pressure-compensated variable-volume pump instead of the fixed-displacement pump, accumulator, and unloading valve used in the circuit of Fig. 2.14. The characteristics of this circuit are the same as the ones noted for the first version of the closed-center circuit.

Applications of Open-Loop Circuits

The final method of classifying circuits is by their applications. This is a very broad and very flexible type of classification. The following outline illustrates the method and suggests the range of current industrial applications. The student can easily expand this list.

1. **Machine-tool applications**

a) *Feed circuits.* These provide flow control by regulating the speed of the actuator.

b) *Transfer circuits.* These provide direction control primarily. They are used where it is desirable to regulate acceleration, velocity, or deceleration. A transfer circuit also provides secondary flow control.

c) *Clamping circuits.* These provide direction control, and possibly pressure control as a secondary function.

d) *Spindle-drive circuits.* These provide flow control primarily, but they may be used for secondary pressure control.

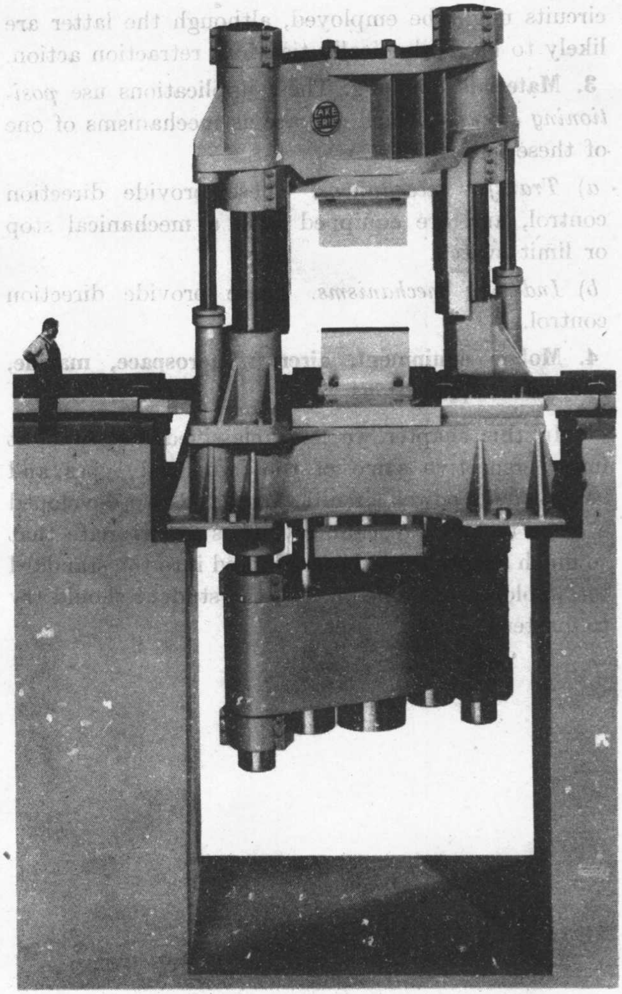
2. **Press applications** (see Fig. 2.16)

a) *Heavy stamping presses*

i) Prefill circuits (primarily direction control)

ii) Work-stroke circuits (pressure control)

iii) Retraction circuits (primarily direction control, but their function includes decompression)



2.16
Hydraulically powered forming press such as is used throughout industry for forming metal shapes. Columns on either side of press opening are hydraulic cylinders which generate tons of force between the blocks in the press opening.

iv) Knockout circuits (auxiliary circuit applications, and also direction control)

v) Transfer circuits (direction control)

b) *Die-casting and plastic-molding presses.* The type of circuit used in these presses depends on the size of machine. Work-stroke, retraction, and knockout circuits might be employed, although the latter are likely to be mechanically tied into retraction action.

3. Materials handling. These applications use *positioning circuits*, which operate as mechanisms of one of these two kinds:

a) *Transfer mechanisms.* These provide direction control, and are equipped with a mechanical stop or limit switch.

b) *Indexing mechanisms.* These provide direction control.

4. Mobile equipment, aircraft, aerospace, marine, and other applications

In this chapter we have classified and brought into perspective some of the industrial types and uses of fluid power circuits. We have also developed a basic technical vocabulary. It is unfortunate that so much shoptalk has been adopted into the standard terminology; but since it has, the student should try to master it at the outset.

Important Terms

Open-loop circuit is one that does not employ feedback.

Closed-loop circuit is one that does use feedback.

Valve control is control exercised by valving components.

Pump control is control exercised by pump components.

Actuator control is control exercised by motor components.

Open-center circuit is an open-loop circuit in which the direction control valve directs the flow from the pump to the tank instead of to the actuator when the valve is in the neutral position.

Closed-center circuit is an open-loop circuit in which all ports of the direction control valve are blocked when the valve is in the neutral position.