plicated constitutive laws than those shown in Fig. 13-6, but the general idea of a modulator and a source combining into an amplifier still applies. Let us consider an example of such an amplifier made out of hydraulic valves.

**Example 13-2** Figure 13-7 shows a schematic diagram of an amplifier constructed of a four-way valve connected to a hydraulic pressure source. The unique feature of this valve, shown as a spool valve, is that four hydraulic resistances are modulated by the spool position $z$ simultaneously. (Note that the normalized position $y = z/z_{max}$, which varies between $+1$ and $-1$, is sometimes more convenient in making plots than $z$ itself.) The resistances are formed by the four edges of the spool lands, $A$, $B$, $C$, and $D$, and corresponding lands in the valve body. For $z > 0$, the flow $Q_s$ passes through $B$, through the motor, and to the sump through $D$. For $z < 0$ the motor flow $Q_m$ reverses.

The four resistors are connected in a Wheatstone-bridge circuit, and you can recognize the benzene-ring pattern in the bond graph of Fig. 13-7*b*. The $R$ elements are put on the inside of the ring this time so that the common modulating variable $z$ can be indicated easily. Assuming that the return pressure is zero, there are only three distinct pressures in the valve, $P_s$, $P_1$, and $P_2$, and each appears on a 0-junction. The motor pressure is $P_m = P_1 - P_2$. At the top of the ring $Q_B$ is a function of $P_s - P_1$, and $Q_A$ is a function of $P_s - P_2$. At the bottom of the graph $Q_m$ is given by two expressions, $Q_B - Q_C$ and $Q_D - Q_A$. From our assumption that the return pressure is zero, $Q_C$ is a function only of $P_1$, and $Q_D$ is a function of $P_2$. With these considerations you can see that the junction structure corresponds to the schematic diagram.

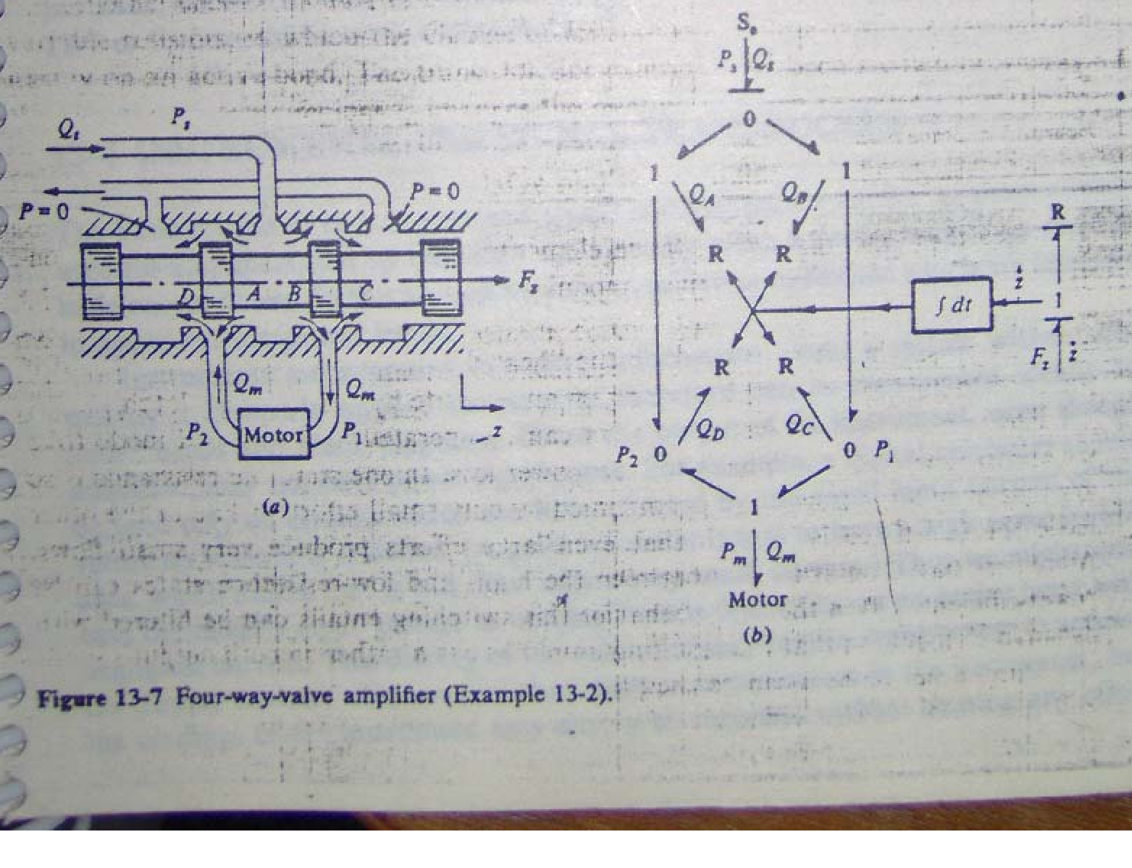


**Figure 13-7** Four-way-valve amplifier (Example 13-2).

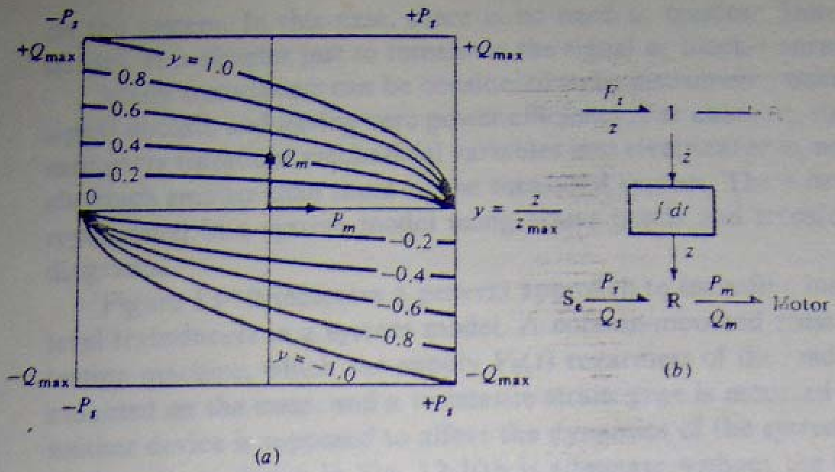


**Figure 13-8** Reduced form of hydraulic amplifier.

In practice, $Q_C$ and $Q_A$ practically vanish for positive $z$ while $Q_D$ and $Q_B$ vanish for negative $z$, simplifying the analysis. The individual resistors are nonlinear, the pressure drops being proportional to flow squared (or the flow proportional to the square root of pressure). For a closed-center valve, i.e., one which blocks the flows $Q_A$ and $Q_B$ when $z = 0$, one can work out the relationships between $P_m$ and $Q_m$ with $z$ as a parameter; this is plotted in Fig. 13-8*a*. The algebraic reduction of the bridge circuit can be represented in a simplified way (Fig. 13-8*b*). The constitutive laws for the modulated 2-port $R$ are just those shown in Fig. 13-8*a*. In both bond-graph representations we show not only the active modulation but also a piece of structure indicating that the force required to stroke the valve $F_z$ is not really zero. In our simple model we just show that at least $F_z$ must overcome seal friction to move the spool. More detailed models would include other force components.

**Example 13-3** An even simpler model of our amplifier can be found by considering normal operation fairly near the point $P_m = 0$, $Q_m = 0$. Then you can see that $y$ (or $z$) sets the flow if $P_m = 0$. For values of $P_m$ not too large compared with $P_s$, the effect of $P_m$ is to change $Q_m$ somewhat along curves which are fairly straight until $P_m$ and $P_s$ are almost equal. This allows us to make a linearized approximation appropriate for preliminary system design.

Figure 13-9 shows the middle portion of the $P_m$, $Q_m$ plane for an open-center valve. Such valves can have a steady small flow through both sides of the valve when $z = 0$ because the spool lands do not quite fill the grooves in the body. This has the disadvantage of a steady power loss, which the closed-center valve did not have, but it has the advantage of increasing the size of the approximately linear region. In the region we can write

$$Q_m \approx Q(y) - \frac{1}{R} P_m \approx K_y y - \frac{1}{R} P_m \approx K_z z - \frac{1}{R} P_m \qquad (13\text{-}16)$$

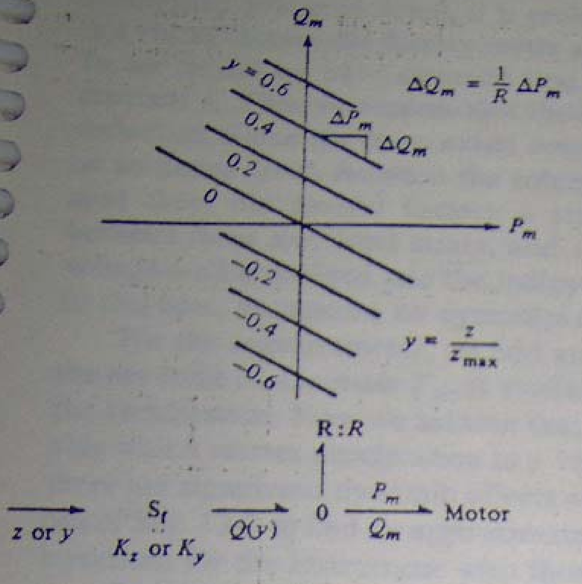


**Figure 13-9** A linearized hydraulic-amplifier model for an open-centered valve.

where $Q(y)$, $K_y y$, or $K_z z$ represents the flow at $P_m = 0$ as a function of spool position and $1/R$ is the slope of the $Q_m$-versus-$P_m$ curves near $P_m = 0$. (The slope $1/R$ is more nearly constant for open- than for closed-center valves.) The bond-graph representation of this approximation is quite simple. A position-controlled flow source is attached to a hydraulic resistance which enforces Eq. (13-16). Here we see the typical amplifier as a controlled-source model. This model would be good for many purposes, but for extreme fluctuations in pressure and flow one of the models of Fig. 13-7 or 13-8 would be more accurate.

## 13-4 INSTRUMENTS AND SIGNAL TRANSDUCERS

The basic models of instruments and signal transducers are similar to those already used for amplifiers, but by amplifier we normally mean a device with large controllable output power. In this section we restrict ourselves to devices which are intended to operate at low power levels.

Instruments are supposed to extract information about a system without disturbing it. Properly applied instruments therefore can be represented ideally by active bonds and block diagrams. Often the output of an instrument, even though amplified, may not have power significance. For example, a digital voltmeter should be used only on circuits which are little affected by the small input current of the voltmeter when it is attached. (A good voltmeter is said to have a high *input impedance,* which means that it will draw only a very small current.) Thus we might indicate the meter's input voltage as coming from a 0-junction on an active bond with negligible current. This display of the voltmeter may require some power to actuate the display devices, which means that there is amplification in the instrument, but the readings of the instrument may simply be recorded without causing any effect