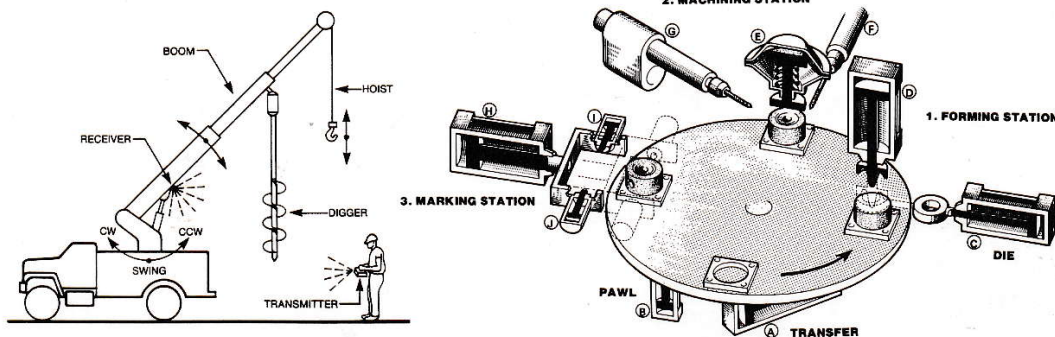


FLUID POWER DESIGN HANDBOOK

FRANK YEAPLE

Second Edition, Revised and Expanded



Fluid Power Design Handbook

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Frank Yeaple

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Electrohydraulic Valves and Servosystems

The marriage of electronics with hydraulics can save energy and therefore money. The choice is among simple on-off solenoid directional valves, proportional pressure- and flow-control valves, servovalves, and digitally modulated valves. The last are the newest and are based on microprocessor-controlled stepping motors built into each valve.

The aerospace industry long ago swung over to electrohydraulics (EH) because it was impossible to control powerful aircraft with lengthy high-pressure plumbing or mechanical linkages from the cabin. In contrast, industrial users of hydraulics fought off electrohydraulic systems, particularly servo systems, for decades. It always had been possible to control most machines and vehicles, without the complexity and initial high expense of electronics, by clever arrangements of purely hydro-mechanical elements.

Now designers are playing a different tune. Energy is too expensive to waste, and it's worth a buck or two to put more options at the fingertips of the operator or to replace him or her with a black box. An equally important reason for electrohydraulics is that the control can be remote.

FIVE LEVELS OF CONTROL

Simple *solenoids* are widely used to turn valves on and off, and this is the most basic electrohydraulic control. The flow and pressure are well defined by the size and nature of the circuit elements, but modulation is minimal.

A second level of sophistication is to modulate flow by rapidly opening and closing the solenoid valves. Some engineers call this *pulse-width modulation*. In effect, the variation in length of on-time vs. off-time establishes an average flow of any amount desired.

A typical system uses two valves, one for each direction of motion. If each valve is cycled in the open position for an equal time, the net motion of a cylinder or motor driven by these valves will be zero. Motion in one direction or the other is

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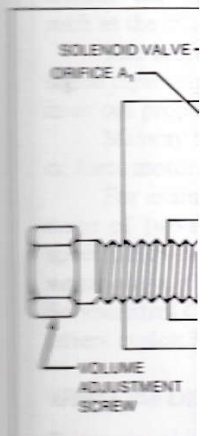


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achieved by leaving the valve open for a longer period in that direction. (See Chap. 15, 18, and 26 for examples of the art.)

A third level of electrical control is the *proportional valve*. It can be as simple as a linear-response solenoid valve, meaning only that spool position varies in direct proportion to the electrical current fed to the solenoid. Or it can be a complex EH valve that regulates either pressure or flow under close control of the input electrical signal. A sophisticated proportional valve is in many respects a servovalve except that it is not as likely to be used in a feedback system.

The fourth level of control is the true electrohydraulic *servovalve*. The accompanying tables, graphs, and illustrations help define servovalves and compare them with the very similar proportional valves.

The fifth level is the *digital valve*, wherein a microprocessor sends discrete signal pulses to a stepping motor, which in turn positions the pilot or spool of a valve. This is a technology in itself and is discussed in detail in Chap. 26, "Microprocessors in Design and Control."

PULSE-WIDTH MODULATION

Engineers at Electro-Flo Division of Applied Power Inc. (New Berlin, WI) developed a novel PWM (pulse-width-modulated) valve system. It exploits an on-off solenoid valve that feeds hydraulic supply pressure into a small holding chamber. At the same time, a fixed-bleed orifice drains oil from the same chamber (Fig. 5.1).

Chamber mean effective pressure (MEP) is determined by what percentage of time the input solenoid valve is held open. The jargon for "percentage of time on" is *modulation ratio*. It's on-time divided by on-time plus off-time, in percent. If on-time is 5 msec and off-time 25 msec, the modulation ratio is $(5)/(5+25)$ or 16.7%.

In the initial tests, oil flow from the valve passed through an 0.024-in. orifice

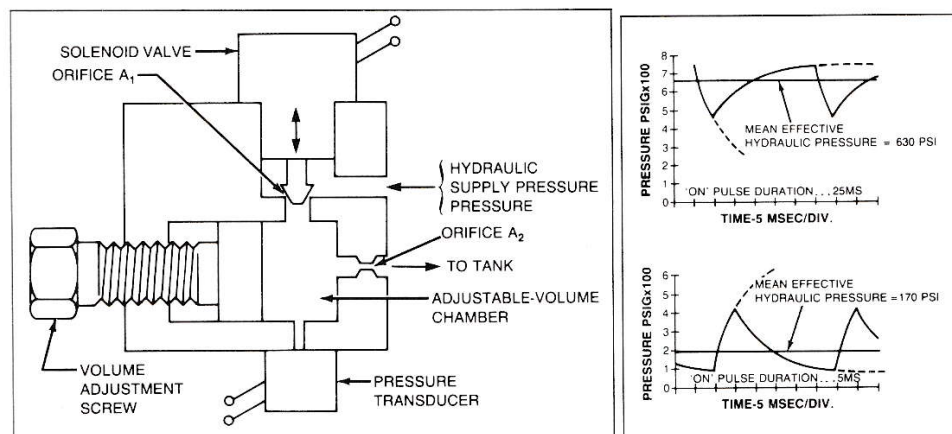


Fig. 5.1 Pulse-width modulation (PWM) of solenoid valve, with continuous bleed to tank, creates adjustable mean effective hydraulic pressure. (Courtesy of Electro-Flo, New Berlin, WI.)

into the chamber and through an 0.018-in. bleed orifice out of the chamber. With 800 psig inlet pressure and 16.7% modulation ratio, mean effective pressure in the chamber was 170 psig.

Two such solenoid valves, pressurizing opposite ends of a four-way directional control valve, create a flow-control valve. The company calls the combination a "pulsar" valve. Microprocessor-controlled PC boards (see Chap. 26) can provide the electrical pulses to operate the solenoids. A typical application is on manlifts.

PROPORTIONAL VALVES

Let's start with the electrical solenoid. There are special breeds that adjust armature position with variable electrical input, usually against a spring load or hydraulic pressure. Europeans use more of them than Americans do, but a trend in the United States indicates growing acceptance.

A potential big application of *proportional solenoids* is the direct operation of spool valves. The coil current is high enough to move the spool reliably against friction and hydraulic forces.

HPI/Nichols (Sturtevant, WI) developed a two-solenoid pressure regulator pilot. It has a proportional solenoid at each end of a special spool (Fig. 5.2). Spool motion in one direction opens the supply port to pressurize the spool in the opposite direction, balancing the solenoid force. The controlled output pressure, up to 2000 psi, is used to position the spring-loaded spool of a separate flow-control valve.

Ledex (Vandalia, OH) developed a proportional solenoid (Fig. 5.3) whose plunger position is a function of the average current in the coil.

The current controller delivers a pulse-width-modulated signal that is full-on or full-off, and the average solenoid coil current is established by the percentage of on-

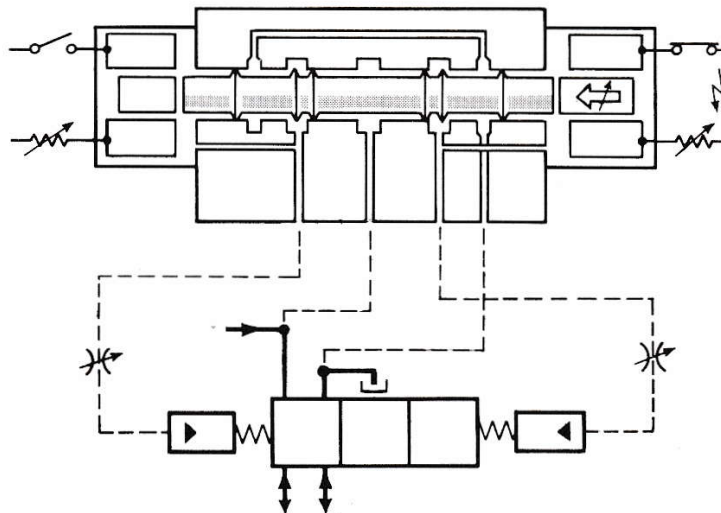


Fig. 5.2 Proportional solenoids (top picture) regulate pressure pilot of hydraulic flow-control valve. (Courtesy of HPI/Nichols, Sturtevant, WI.)

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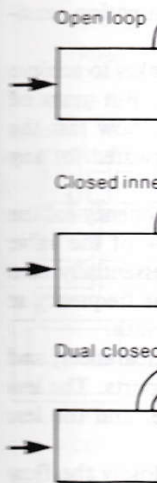


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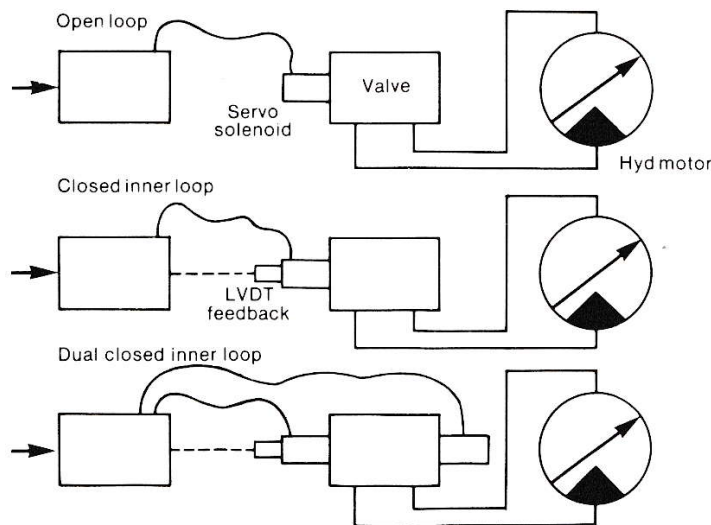


Fig. 5.3 Typical proportional solenoid systems. (Courtesy of Ledex, Inc., Vandalia, OH.)

vs. off-time. It's efficient because the transistors doing the controlling are full-on or full-off, avoiding the higher voltage drops that occur at partial loads. Solenoid power is sufficient to directly move the spool of a 3000-psi 150-gpm valve if the spool is balanced.

The solenoid plunger will position itself open loop (schematic), but better accuracy is possible with inner-loop or outer-loop feedback. Inner loop means to monitor the solenoid plunger position; outer loop means to monitor the final output such as the cylinder stroke or pump swashplate angle.

The loop feedback position signal is compared with the called-for position signal input; the error between the two tells the solenoid control to move the plunger in or out proportionally.

Midway between simple proportional valves and servovalves are torque motors or force motors used to operate valves directly (Figs. 5.4 and 5.5).

For example, *torque motors* usually operate flappers or jet pipes in the pilot stage of two-stage and three-stage servovalves: force motors usually drive pilot spools. However, some designs are powerful enough to regulate flow or pressure in a single stage. One example is the torque-motor-flapper design made by Hydraulic Servocontrol Corp. (Buffalo, NY). Some users make it the first stage of a servovalve; others exploit it as a single-stage pressure controller.

What's the Difference

Proportional valves, particularly the two-stage variety, are similar to servovalves, but there are recognizable performance differences. Richard Woodring, while engineering manager at Parker Hannifin's Manatrol Division (Elyria, OH), noted four parameters that separate one from the other: overall response time; crossover character-

istics of the spool; hysteresis, repeatability and threshold; and contamination sensitivity.

Response time can be defined in many ways, such as the time it takes to achieve some percent of rated flow after being given a step electrical input. But years of experience have shown that the best comparative technique is to see how fast the valve will respond to a sine wave electrical input: The test is easily repeated for any valve, and the results are readily analyzed.

So-called frequency response is generally considered to be the frequency (of the sine wave electrical command signal) at which the peak output flow of the valve decreases to 70.7% of the flow it would have if the frequency were essentially zero (about 0.1 Hz). That drop in flow (29.3%) is equivalent to 3 dB, so the frequency at which it occurs is called the minus 3 dB frequency, or the valve bandwidth.

Crossover characteristics are just a measure of the dimensions, clearances, and tolerances of the finely machined edges of the spool and the mating ports. The less precise they are, the greater the deadband, the slower the response, and the less accurate the valve will be.

Hysteresis, repeatability, and threshold are measures of how closely the flow follows the theoretical flow-vs.-input curves, and how small a signal will effect a measurable change.

Contamination tolerance is important if the oil supply is from an ordinary reservoir.

Table 5.1 compares typical proportional flow valves with servovalves. An improper choice either won't work or will cost too much.

Proportional valves should always be considered first. Compared with servovalves, their manufacturing tolerances are more easily met, the parts are more interchangeable, and the costs can be from half to one-tenth as much.

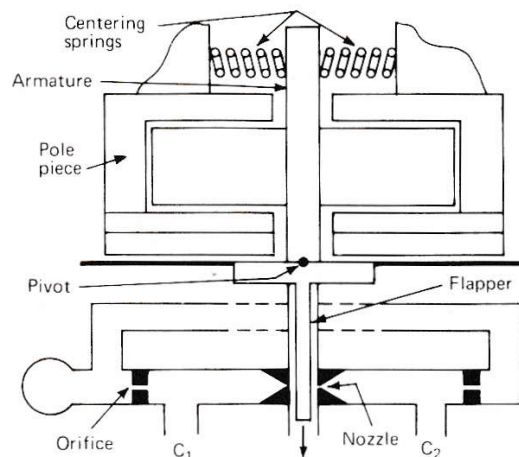


Fig. 5.4 Pressure-control pilot valve, with torque motor and flapper, regulates in one stage. (Courtesy of Honeywell, Bloomington, MN.)

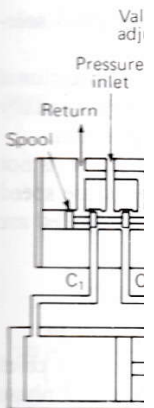


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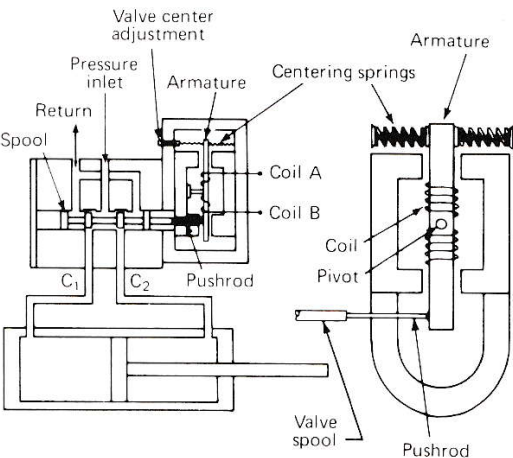


Fig. 5.5 One-stage flow-control servovalve is powered directly by the force of the torque motor. (Courtesy of Honeywell, Bloomington, MN.)

Furthermore, with good microprocessor control, even poor performance can be enhanced. Hard-to-predict effects of contamination, flow shear forces, pilot pressure variations, and temperature can be countered by incorporating position feedback at the main spool. LVDTs and other position transducers have come down in cost, and economical microprocessors, along with support electronics, can interpret much information and react quickly.

Electrical “offsets” can be programmed to make corrections to the input-vs.-output response, so that the valve spool shifts quickly and automatically across the deadband region near the null (crossover) point. Called a “deadband eliminator,” the control makes the plot of electrical input vs. flow output resemble the accurate plot of a carefully lapped servovalve. Also, the rate of position change can be controlled by programming.

Many manufacturers offer novel or improved versions of electronically controlled proportional valves. The Manatrol Div. of Parker Hannifin, for example, has adopted the company’s Berteau electrical servovalve pilot as an optional pilot for most

Table 5.1 Proportional Valve vs. Servovalve (Typical Performance)

	Proportional	Servovalve
Response (frequency at 29.3% flow reduction)	2 to 10 Hz	10 to 300 Hz
Spool center condition (deadband)	10 to 30%	Nil
Hysteresis/repeatability/threshold	Up to 10%	Less than 3%
Filtration requirements	10 micron	3 micron

sizes of its proportional valves. It has better performance than proportional solenoids and uses less signal power.

Rexroth (Bethlehem, PA), Vickers (Troy, MI), and others offer directional valves that not only provide multiple flow paths but throttle the flow proportionally as well. It is done with proportional solenoids that control valve spool position.

There are limitations to proportionals. Control at the deadband region is not likely to be stable, unless the spool merely passes through it. Also, response speed cannot match that of a fast servovalve, and the pressures and forces controlled are not as high.

THE ART OF SERVOVALVES

Servo implies feedback control, and it's as much an art as a science. The chief difficulty is in keeping the system stable when the output is too much out of phase with the input or with the system disturbances. A 90-deg phase lag, based on an arbitrary sinusoidal input signal, is one measure of performance for individual components (see Fig. 5.6).

Manufacturers of servovalves and designers of servo systems have established simplified guidelines to encourage wider acceptance of their products. The details of proprietary designs are in company catalogs and manuals. We'll just point out areas of importance. Much of the discussion is based on comments by James Stegner of Moog Inc. (East Aurora, NY). Figures 5.7 through 5.11 are from many sources. Most of the comments apply to proportional valves as well as to servovalves.

Hydraulic Amplifier Stages. Servovalves generally are multistage devices of two or three stages. The largest share of the industrial/mobile market is served with two-stage servovalves.

The first stage is an electromechanical actuator and a hydraulic amplifier. Typical actuators are torque motors, force motors, or solenoids. The torque motor often is preferred because it has more usable output power per unit of input power. Also, it has low moving mass and therefore has high natural frequency and fast response. A low natural frequency limits the response of a servovalve.

Special design features in torque motors can enhance performance. For example, a flexure tube instead of a sliding bearing provides a limited-motion frictionless pivot for armature rotation. Symmetrical magnetic circuit design minimizes temperature-induced variations. Dual coils permit redundancy, choices of rated current, and choice of operation from two isolated command signal sources.

Two other frictionless amplifiers are the flapper-nozzle valve and the momentum jet valve. They are "open center," however, and consume a small hydraulic flow continuously.

The first-stage hydraulic amplifier also can be a sliding metering member such as a spool or plate, but dirt, friction, and wear can be a problem. Hydura/Oilgear (Milwaukee, WI) has solved the problem of friction and wear of sliding-plate valves by mounting the plate on flexure supports. The supports hold the plate next to the valve ports without quite touching. The torque motor and valve are immersed.

Sliding spools are popular for the second and subsequent stages. They are variable orifices and can be configured to provide linear or nonlinear flow in various circuit arrangements such as closed center and open center.

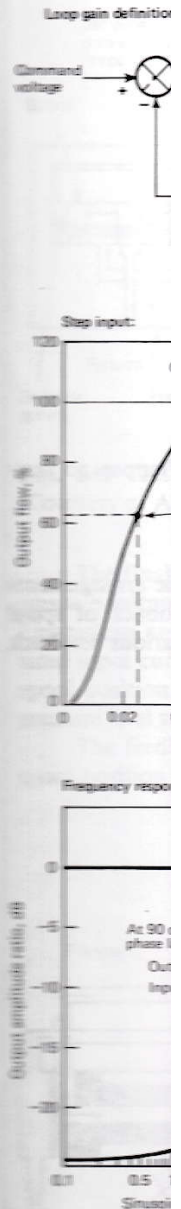


Fig. 5.6 Flow characteristics of a servovalve. (Moog Inc., East Aurora, NY.)