Introduction to Hydraulic and Logic Systems in a Controls Course

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Abstract

A four week long module on industrial hydraulics and logic control systems is described. This module is taught in an otherwise conventional senior level controls course that emphasizes feedback control systems. Students are introduced to hydraulic system components and circuit design considerations. Logic control systems, including programmable logic controllers (PLC's), are introduced next. Pneumatic systems are introduced as a special form of hydraulics. Some tutorial introduction to the material is given along with several specific design guidelines for the students. A representative student design project is also described.

Introduction

Many mechanical and electrical engineering programs include a required or elective course in control systems. The topical outlines for these courses typically follow the approaches used in the numerous textbooks available. Closed loop, feedback control system analysis is greatly emphasized, both from the transfer function and state space points of view. Little or no mention is made of another broad class of topics, logic control systems, which are very commonly found in industrial applications.

Logic control systems are used with sensors and actuators that operate in a simple "on/off" mode (for example a light switch). A great deal of simple automation can be accomplished with inexpensive pneumatic cylinders and a few solenoid valves. Unfortunately, many students are never exposed to even the most basic concepts of this powerful and widely used control system technique. Additionally, many students are simply unaware of the wide variety of actuators and sensors that are available for use in control systems. One reason for this is the faculty's lack of familiarity with these subjects. Another is the perception that there is not enough "room" in the course for adding this material. A third reason is that texts and other supporting materials are not as readily available for logic control as for feedback control systems.

The purpose of this paper is to attempt to address some of these concerns by providing a description of the relative simple, but very practical, material that we use. We have successfully incorporated a four week long hydraulics and logic control systems component into our required senior level control systems course (outline given in Table 1). Our focus is on hydraulic and logic control system design, not the selection of specific components, i.e. we work at a "schematic" level. We introduce hydraulic system components first for three reasons.

1. Students learn the available components and can quickly create a schematic of systems to be controlled.
2. Most mechanical engineering students have a better "feel" and appreciation for hydraulic actuators than electric motors.
3. The incompressible nature of hydraulic fluid system makes them somewhat easier to understand than compressible fluid systems (pneumatics), although the much lower cost of pneumatics makes them very attractive in many applications.

The topics in this paper are presented in essentially the same order as in the course. Some portions are presented in an almost tutorial fashion. Other portions give some specific details of examples that we use in our course.

Table 1 - ME 475 Control Systems Course Outline

Week	Material	Week	Material
1	Intro, Industrial Hydraulic Components	7	Block Diagrams
2	Hydraulic Circuit Design, Logic Control Systems	8	Stability
3	Logic Control Systems, Industrial Pneumatics	9	Steady State Errors
4	Industrial Hydraulic System Design Considerations	10-11	Root Locus
5	System Modeling, System Representation,	12-13	Design via Root Locus
6	Time Response	14-16	Frequency Response Methods

Note that our mechanical engineering students are required to take a dynamic systems modeling course prior to the controls course, which means that the topical material for week 5 is a review. The final 11 weeks of the course closely follow the textbook by Nise[1].

Industrial Hydraulic Components

Drive elements (actuators) for industrial automation fall into one of three categories: electrical, hydraulic, or pneumatic. As a very general rule, electrical drive systems are used in high precision, relatively low load applications where control flexibility is paramount. Hydraulic drive systems tend to be used where large loads must be manipulated. Pneumatic drives are generally limited to simple two position operations where low cost and simple programming are necessary.

Hydraulic Drive Systems

A large percentage of heavy-duty industrial applications require the use of hydraulic actuators. Both linear and rotary actuators have large force- or torque-to-weight ratios, which is the primary benefit in many applications. Many of the problems with hydraulic systems are due to the complex system of components required. The minimum set of equipment required to drive even a single axis includes: hydraulic pump and oil supply, electric motor to drive pump, water cooling system for pump, pressure relief valves, safety shut-off valves, filters, directional control valves, hydraulic hoses, and at least one hydraulic actuator. Additional components such as accumulators, manifolds, oil-cooling heat exchangers, or additional reservoirs may be required in some applications. Although the correct selection of many of these components (hydraulic fluid type, hoses and tubing, filters, tanks) is vital to the system operation, they are not directly considered in this course.

Hydraulic Pumps

Hydraulic pumps are required to generate the high fluid pressures of 500 to 3000 psi (3500 kPa to 21000 kPa) used in industrial applications. Three basic types of hydraulic pumps (and motors) are available; piston pumps, vane pumps, and gear pumps. Pumps use an external source of energy (typically an electric motor) to pressurize the hydraulic fluid.

Hydraulic Actuators

Three types of actuators are common in hydraulic applications: hydraulic motors, linear cylinders, and rotary actuators. Hydraulic motors are similar in design and construction to pumps, except that the high-pressure fluid is used as the energy source to drive an external load. In fact, most pumps will act as motors if the flow direction is reversed. Linear cylinders are probably the most common type of hydraulic actuator. Rotary actuators are essentially a hybrid between hydraulic motors (with continuous rotary motion) and linear cylinders (with finite linear motion), since they provide a limited rotary motion.

Valves

Several different types of valves are used in hydraulic systems. Valves can be categorized[2] as either

1. pressure control (pressure relief, sequence, unloading, counterbalance, pressure reducing),
2. flow control (fixed restriction, variable (needle), compensated, flow divider),
3. directional control (check, shuttle, two/three/four way, manual (shut-off), electrohydraulic servovalve)

Pressure relief valves are used to limit the system pressure to a preset limit, and serve a vital safety interest. Pressure control valves that pass flow to other portions of a hydraulic circuit are called either sequence, unloading, or counterbalance valves depending upon the application. A pressure reducing valve is used to provide a downstream source of fluid at a reduced pressure, much like a voltage regulator in an electrical circuit. Flow control valves are used to limit the amount of hydraulic fluid flow. Directional control valves are used to control the path that the hydraulic fluid flow uses as it flows from the pump back to the reservoir. Two-, three-, and four-way directional control valves can be actuated by a variety of different means including manual operation (levers, pedal, or palm buttons), electrical solenoid, cam operation, spring returns, and pilot operation. Check valves are flow control devices that allow fluid flow in one direction, but completely prevent flow in the reverse direction (which is very similar to the action of a diode in an electrical circuit).

Hydraulic Circuit Design

Many useful hydraulic circuits can be constructed by assembling basic building blocks, once the underlying principles are understood. The only example shown here is the manual position control of a double-acting hydraulic cylinder (Figure 1). Four-way, three position valves are commonly used in these applications since the center position allows the cylinder to be stopped at any intermediate position. While the valve is in the center position, the fixed displacement, single direction pump is unloaded. All flow from the pump is immediately returned to the tank reservoir under a relatively low pressure. If the valve is shifted to either of the two end positions, the flow from the pump is routed to the selected end of the cylinder. The pressure will then start to build rapidly until it reaches a pressure that is sufficient to move the load against gravity and friction. The purpose of the pressure relief valve is to set the maximum operating pressure in the system. When the force created by the pressure in the pilot inlet line (shown dashed in the figure) balances the spring force, the relief valve "cracks" and flow is diverted from the cylinder to the tank. This operation is somewhat similar to that of a voltage regulator in an electrical circuit. Different types of pressure relief control valves are available to provide various pressure-flow characteristics. Additional information on hydraulic components and systems can be found in a series of handbooks by Hedges[3].

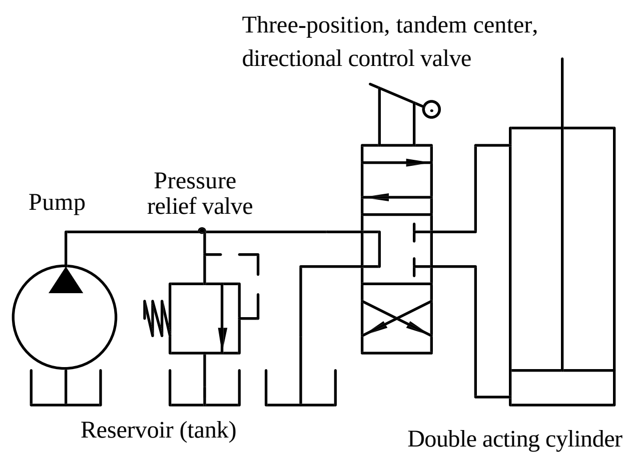

Figure 1. Simple Hydraulic Circuit

Logic Control Systems

To begin the discussion of industrial logic control systems, consider the simple hydraulic system shown in Figure 2. Pressurized hydraulic fluid is available to the simple two position, four-way solenoid valve, as indicated by the dark arrow symbol. In the configuration shown the hydraulic cylinder will retract fully. The solenoid valve shown is activated by an electrical current passing through the solenoid coil. This type of simple ON/OFF programming has traditionally been done by relay control systems, like that shown on the right. This schematic diagram represents a type of “programming” frequently referred to as "ladder logic." The two parts of a relay (coils and contacts) are both shown in this diagram. Electrical current passing through the coil of the relay (denoted by the circle element CR-1) closes one of these sets of contacts (CR-1B) which allows current to flow through the solenoid, SOL-A. Another set of contacts, CR-1A, is used to "hold" the contacts closed once they have been energized. A momentary contact push-button PB-1 (normally open or N.O.) is provided for initiating motion. When PB-1 is pressed, current flows through the actuating circuit of relay CR-1, which closes the output contacts (CR-1A and CR-1B). Relay CR-1 remains energized until the limit switch, LS-1, is activated by the cylinder. When this limit switch is activated, the current flow through the control relay CR-1 is interrupted, and the contacts CR-1A and CR-1B both open. The solenoid SOL-A is de-energized, therefore the spring shifts the solenoid back to the right position, which causes the cylinder to retract. The circuit is inactive until a subsequent pressing of the push-button PB-1.

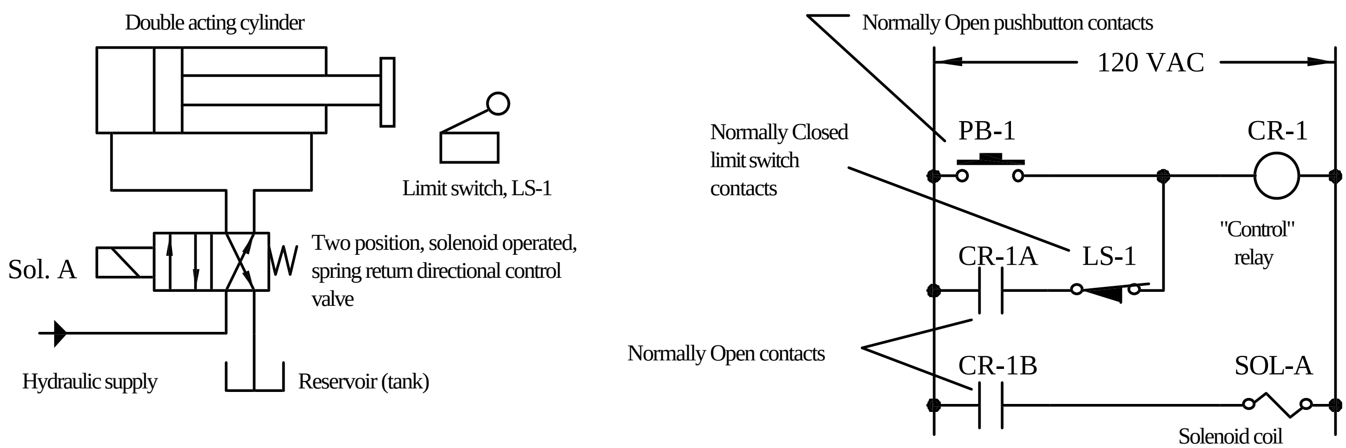

Figure 2. Simple hydraulic and logic control system

<u>Programmable Controllers</u>

One of the disadvantages of the relay logic systems of the previous section is the difficult nature of the "programming." The program logic is "hard-wired" by the interconnection of the relays, limit switches, and pushbutton inputs. Changing the task performed by the simple system of Figure 3 requires that the circuit be physically rewired. For circuits with only three or four components this is not difficult. However, systems containing ten to several hundred individual components are not uncommon in industrial automation systems. The programmable logic controller (PLC) was developed in the early 60's to overcome the deficiencies of relay logic systems. Programmable logic is implemented using a microcomputer instead of the hard-wired logic of the conventional hard-wired relay system. The major advantage of PLC's (frequently referred to as just programmable controllers or PC's) is that the programming can be done in ladder logic, just like relay logic systems.

The major criteria for specifying PLC's are the number of input contacts that can be read and the number of output switches that can be controlled. Small PLC's might have 8 to 12 inputs and outputs, while larger models can use 100 or more I/O (input/ output) points. Inputs are typically 0-120 volts AC or 0-24 volts DC. Output options frequently include relay contacts, triac (120 VAC) or 24 volt (open collector) outputs. Some of the newer PLC models have advanced features such as analog inputs (0 - 10 Volts), PID (proportional-integral-derivative) control loops, and serial (RS-232) communications capabilities.

Figure 3 shows a programmable controller ladder logic diagram for the same simple system of Figure 2. The "internal" contact labeled 0.1 is connected to the input push-button, PB-1. The limit switch, LS-1, is wired to the input contact 0.2. The internal contact 5.0 replaces the control relay CR-1 and its two pairs of contacts. The output solenoid coil, SOL-A, is connected to the output contact 2.0. By comparing this figure to the relay system of Figure 2, the similarities between PLC programming and relay logic is obvious. One simplifying difference is that internal registers (such as 0.1, 0.2, and 5.0) can be used as replacements for inputs and control relay circuits. An essentially unlimited number of input contacts and control relay contacts are therefore available, although the number of actual input devices is limited. A finite number of actual outputs (such as 2.0) are available, but their status can be read as many times as needed on other rungs of the ladder. Also, counters and timers are readily programmed on even the simplest PLC's.

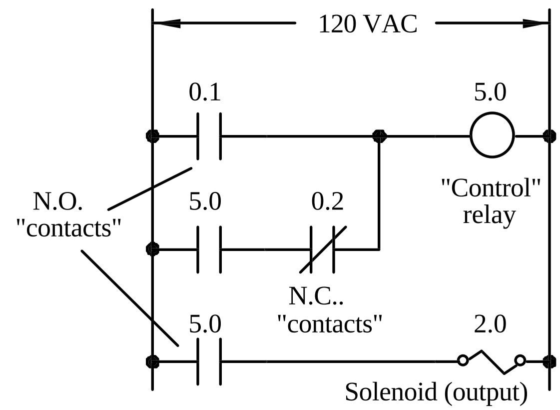

Figure 3. PLC ladder logic

In our course (ME 475) we use a combination of conventional hard-wired relay and PLC logic programming techniques. Rules for designing ladder logic are summarized below.

1. Ladder diagrams are drawn vertically with inputs on the left and outputs on the right.
2. Each rung of the ladder has one (and only one) output.
3. An individual output device can appear on the ladder diagram only once.
4. An individual physical input device (limit switch, push-button, pressure switch, etc.) may be used as many times as necessary on the ladder diagram in both normally open and normally closed configurations, and is drawn using a representative schematic symbol.
5. Internal contacts of the PLC are represented as conventional control relays and contacts.
6. Control relay coils are outputs and can appear on the ladder diagram only once.
7. Control relay contacts are inputs and may be used as many times as necessary on the ladder diagram in both normally open and normally closed configurations.
8. Unlimited "OR"ing of ladder rungs is allowed, but any rung of the ladder diagram may be "OR"ed with a following rung at only one location.

Hard-wired logic systems are drawn in both horizontal and vertical configurations, but PLC diagrams are conventionally drawn vertically with single outputs in the rightmost column. Note that if an output appeared at more than one location on the ladder diagram, then its status would be ambiguous. Physical input devices (limit switches, push-buttons, pressure switches, etc.) and relays have a limited number of normally open and/or normally closed contacts. Hard-wired logic systems can use only as many of these inputs or contacts as are physically available. PLC circuits allow unlimited use of their internal contacts which may also be connected to input devices. Contacts are normally shown for all inputs in a PLC diagram, but we use representative schematic symbols for clarity. A logical "OR" occurs beteween two elements when they are in parallel and a logical "AND" occurs when they are in series. Nested "OR" networks are allowed in hard-wired relay logic systems, but are typically not allowed in PLC diagrams.

<u>Logic Control Circuit Design</u>

Designing new logic control circuits from “scratch” can be a daunting task for a student. Oftentimes a designer can reuse logical blocks from previous successful designs. Unfortunately, this is not always possible, and can sometimes lead to unforeseen interactions between various parts of the logic system. Some broad general guidelines (which must often be violated!) for designing logic systems are given below.

1. Dedicate control relays for specific functions (such as starting the system, activating a solenoid, etc.) and use as many as are necessary. Control relays are essentially "free" once a programmable controller has been purchased, so don't be miserly!
2. Control relays almost always use a holding circuit, so design in terms of both a "turn ON" and a "turn OFF" rung with an "OR" connection between them. Note that some circuits will require multiple rungs for turning ON or OFF, which must be connected through the OR structure.
3. Normally open (N.O.) components are usually used to activate the "turn ON" rung.
4. Normally closed (N.C.) components are usually used to activate the "turn OFF" rung.
5. Be absolutely certain that any holding circuit formed will be actively turned off by your system. Do not depend on a power shutdown to release and holding circuits.
6. Provide safety interlocks either on the "turn ON" rung before the control relay or on the associated solenoid activation rung, depending on the type of interlock required.

Industrial Pneumatics

Pneumatic systems use compressed air as a working fluid instead of hydraulic oil. Many of the design techniques used for hydraulic systems are also applicable to pneumatic ones. However, there are some differences between them::

1. Pressure levels - Pneumatic systems operate at much lower pressures, 50 to 200 psig, whereas hydraulic systems typically operate at pressures from 500 to 3000 psi.
2. Actuating forces - The lower operating pressure of pneumatic systems generally restricts the actuating forces to much lower levels than hydraulic systems, unless extremely large piston diameters are used.
3. Component cost - The higher pressures and oil contamination requirements of hydraulic components creates a cost differential of 3 to 10 times the cost for similar pneumatic components. Pneumatic systems use a "free" fluid, while hydraulic systems require expensive petroleum or water based fluids.
4. Leaks - A leak in a pneumatic system causes an increase in noise levels and lost system efficiency, but is otherwise generally harmless. Hydraulic system leaks are "messy," result in the loss of expensive fluid, and are more difficult to prevent due to the higher pressures.
5. Lines and fittings: Hydraulic lines are typically rigid metal tubing which requires expensive fittings. Pneumatic systems can usually use inexpensive flexible plastic tubing and fittings. Hydraulic systems require return lines to recycle fluid back to the reservoir, while pneumatic systems usually vent air directly to the atmosphere.
6. Speed control - The incompressible nature of hydraulic fluid makes possible precise speed control over a range of operating loads. Pneumatic systems are characterized by relatively poor speed control, but high speeds are readily available at light loads (such as advancing a cylinder before contact with a workpiece).
7. Power source - Hydraulic systems commonly use a simple constant speed pump, which generates a relatively constant flow rate. Maximum system pressure is limited by a pressure relief valve. In pneumatic systems a compressor generates the maximum system pressure and regulators are used to reduce the air pressure to desired levels. Many industrial operations provide a central supply of pneumatic pressure ("shop air") which is piped throughout the plant for use at individual stations.

Design Project

Each student is required to complete an individual design project at the end of the four-week period. A representative project description is given below.

An automatic loading device is to be designed to load sheet metal into a press for forming expanded metal ("X-metal"). The sheets are approximately 4 ft. by 8 ft. and weigh 100 to 200 lbf each. Several sheets of steel are stacked on a pallet on the floor. An overhead "gantry" mechanism has three hydraulic cylinders mounted in three perpendicular directions, Z (up/down), X (left/right) and Y (in/out). The Y cylinder moves out to position the Z cylinder over the stack. The Z cylinder then moves down until a limit switch is tripped at the top of the stack. A vacuum pump is then turned on and the top sheet is held to the Z cylinder with several vacuum cups. After reaching the correct vacuum level, the Z cylinder retracts to the top position at a controlled speed. The Y cylinder then moves a predetermined distance towards the machine at a controlled speed. After reaching this point, the Z cylinder extends downward to position the sheet on the feed table. Upon reaching the feed table, the X cylinder moves in the positive direction at a controlled speed until an "end gage" limit switch is tripped. At this point the vacuum is turned off and the sheet is dropped onto the feed table. The X and Z cylinders then retract to the "home" position at full speed to wait for the next cycle.

The students are asked to take this problem description and develop a conceptual drawing for the proposed system showing an arrangement for the hydraulic cylinders used. They also design hydraulic and electric control circuits to automate the system. Safety considerations include a manual emergency stop and an automatic emergency stop if the sheet is released from the vacuum cups prematurely. The system must also include appropriate position sensing, speed control, manual jogging and safety signals.

Conclusions

A four week long introduction to hydraulic and logic control systems has been described. Some of the topical material from the course has been presented. Students respond positively to the material, since they can immediately see a variety of applications. Hopefully, other faculty members will be encouraged to add this highly relevant and useful material to their own control courses.

Acknowledgments

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