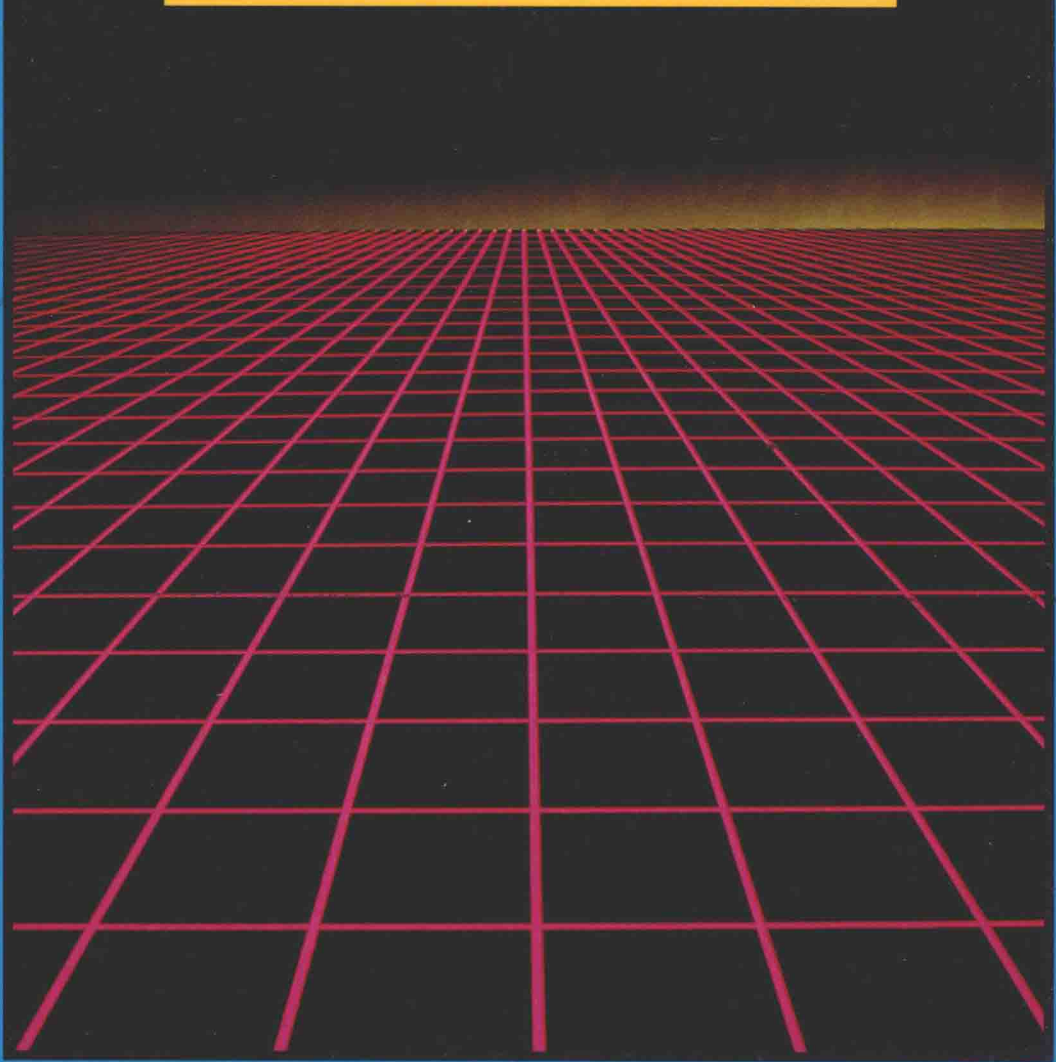
Electrohydraulic Control Systems



F. D. Norvelle

Electrohydraulic Control Systems

F. Don Norvelle

Oklahoma State University

Prentice Hall

Upper Saddle River, New Jersey   Columbus, Ohio

Library of Congress Cataloging-in-Publication Data

Norvelle, F. Don.
Electrohydraulic control systems/F.D. Norvelle.
p. cm.
Includes bibliographical references and index.
ISBN 0-13-716359-2
1. Hydraulic control. I. Title.

TJ843 .N57 2000
629.8'042--dc21

99-053027

Publisher: Charles E. Stewart, Jr.
Production Editor: Alexandrina Benedicto Wolf
Production Coordinator: Karen Fortgong, *bookworks*
Cover Design Coordinator: Karrie Converse-Jones
Cover Designer: Jeff Vanik
Cover photo: © Michael Simpson, FPG International
Production Manager: Matthew Ottenweller
Marketing Manager: Ben Leonard

This book was set in Times Roman by York Graphics and was printed and bound by R. R. Donnelley & Sons Company. The cover was printed by Phoenix Color Corp.

Printed in the United States of America
10 9 8 7 6 5 4 3 2

ISBN: 0-13-716359-2

Prentice-Hall International (UK) Limited, *London*
Prentice-Hall of Australia Pty. Limited, *Sydney*
Prentice-Hall of Canada, Inc., *Toronto*
Prentice-Hall Hispanoamericana, S. A., *Mexico*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Prentice-Hall (Singapore) Pte. Ltd., *Singapore*
Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*

PREFACE

This textbook is aimed specifically at students enrolled in two- and four-year college-level programs in engineering technology, especially in those programs where motion control is taught. Its primary objective is to provide the student with a very broad introduction to the concepts of electrohydraulic control systems specifically and motion control in general, and to do so in a one-semester course. It also attempts to bridge the gap between the traditional electronics and mechanical curricula.

The second objective is really not new. There are several texts that attempt to close the gap in specific areas. Servomechanisms and proportional control valves are good examples of electrohydraulic systems for which there are several bidiscipline references. These texts, however, are highly theoretical and are intended more as references for engineers than as textbooks for engineering technologists. There are also numerous texts on control theory, but these tend to deal almost entirely with electronics.

In this text I have attempted to present both the mechanical and electronic aspects of the various types of valves and illustrate methods of controlling those valves. It is important to note that although the title of the text implies that it is specifically concerned with hydraulic systems, most of the concepts presented in the discussion of controls (ladder diagrams, programmable logic controllers, sensors, and operational amplifiers) are applicable to all motion systems. Only the power sections of the systems are different.

This text assumes a basic knowledge of fluid power, so Chapter 2 provides only a brief review of that subject. A full treatment of hydraulics is well beyond the scope of this text, and is, in fact, the subject of numerous textbooks and college courses.

Chapter 3, likewise, assumes a basic knowledge of electrical circuitry, so the first part of the chapter offers only a brief review of the subject. However, many of the electronics courses taught in current curricula are very heavy on electronics and light on electrical circuitry. For this reason the concepts of common electrical switches and relays are introduced in this chapter. The chapter then continues with a fairly detailed discussion of ladder diagrams. This discussion lays the groundwork for solenoid valve control circuits in Chapter 4 and PLC programming in Chapter 9.

Chapters 5 and 6 deal with proportional control valves and servovalves, respectively. In both chapters the mechanical aspects of the valves, the valve actuation mechanisms, and the control circuit boards are discussed. Valve performance is also discussed.

The calculations for determining the natural frequencies of hydraulic motor and cylinder systems are demonstrated in Chapter 7. This chapter also includes the concepts of gain, transfer functions, and feedback and control using a "running" example.

Chapter 8 expands on the basic switching elements that were introduced in Chapter 3. Sensor properties such as accuracy and precision are addressed, along with analog to digital conversion. There is extensive discussion of discrete sensors, including proximity, photoelectric, Hall effect, and reed switches. Continuous sensors for temperature, flow rate, pressure, linear and rotary position, and velocity and acceleration are discussed as well.

Programmable logic controllers are the subject of Chapter 9, which begins with an introduction to the basic concepts of PLCs, architecture, and programming languages. A section on ladder logic programming follows, which facilitates the transition from the relay logic diagrams of Chapters 3 and 4 to the ladder logic required for programming PLCs. The chapter ends with some programming examples.

The final chapter (Chapter 10) is a brief introduction to robotics. It discusses robot geometries, end effectors, and control and programming.

Obviously, this is very much an introductory text. The subject of virtually every chapter has been treated extensively in numerous books. The purpose here is simply to introduce the student to the concepts in considerable breadth but limited depth. To my knowledge, this is the first textbook to approach electrohydraulic control in this manner.

Some chapters include more depth than might be desired for a specific curriculum. The structure of the text caters to those cases. Each chapter begins with basic descriptions and proceeds to more analytical material. It is a simple matter, then, to use only specific parts of a chapter if the depth is not needed for the course.

The material is generally presented in a fashion that facilitates associated laboratory exercises where lab facilities are available. For example, the solenoid valve circuits presented in Chapter 4 lend themselves nicely to basic hydraulic training stands. The PLC programming examples can be used directly as laboratory exercises. (Where PLCs other than the OMRON are used, it would make sense to translate these examples into the appropriate programming language.)

A unique feature that will help demonstrate the relationship between the hydraulic circuit and the control circuit is the inclusion of the Automation Studio CD-ROM with the instructor's manual. This software allows the student to draw both the hydraulic circuit and the electrical ladder diagram and then simulate the system operation. When the START button is "pushed" on the screen, the appropriate electrical components are energized (change color), the valves move, and the cylinder or hydraulic motor operates. It is an easy transition, then, to take the proven circuit from the "drawing board" to the training bench.

This text will not make the student a controls expert, but it will provide a solid basis on which to build. Industry badly needs people with this type of academic background.

ACKNOWLEDGMENTS

So many people have contributed to the preparation of this book that I am almost afraid to start listing them for fear of overlooking someone. Special thanks, though, must be given to several people: Frank Garner of the Vickers Training Center; Randy Nobles of Womack Machine Supply in Tulsa, Oklahoma; Tom Nelson and Rob Bartling of Racine Federated; Glenn Haueter of Automated Dynamics in Tulsa; Larry Schrader of the Parker Fluid Power Training Center; and Jim Green of Control Dynamics in Oklahoma City.

These people, with the permission of their respective companies, have provided literature, hardware, and even opportunities for training that have allowed me to gain the knowledge, understanding, and experience necessary to write this text. A special acknowledgment goes to Stewart Atkin of FAMIC Technologies 2000 of St. Laurent, Quebec, Canada, for providing the Automation Studio Demo CD-ROMs.

My heartfelt thanks go to my wife, Evelyn, who got so tired of watching me struggle with the keyboard that she pushed me aside and typed (and retyped) the manuscript. I also appreciate the efforts of my daughters, Babs and Cery, who proofread the manuscript and very seldom laughed (out loud, anyway) at my mistakes. I also thank my electrohydraulics students at Oklahoma State University for patiently struggling through the manuscript. Their suggestions were very useful.

I also thank the following who reviewed the manuscript and made so many excellent suggestions: Ciso Macia, Arizona State University; David Pacey, State University of Kansas; Bill Reeves, Ohio University; Wajiha Shireen, University of Houston; and Gang Tao, University of Virginia. I took those suggestions to heart and incorporated most of them.

Finally, my sincere thanks to the staff of Prentice Hall Publishing Company. They were very patient with me and provided invaluable help and encouragement.

F. Don Norvelle

Answers to Selected Problems

Chapter 2

2-1. 6280 lb
2-3. $F_{ext} = 21210$ lb $F_{ret} = 11790$ lb
2-5. 7.35 gpm
2-7. 13.6 kW
2-9. $F_{ext} = 78.54$ kN $F_{ret} = 40.06$ kN
2-11. $v_{ext} = 0.032$ cm/s $v_{ret} = 0.062$ cm/s
2-13. 2.98 in^3/rev
2-15. 5.1 in^3/rev
2-17. 1151 cm^3/rev
2-19. 2.73 hp
2-21. 11.4 hp
2-23. 5 kW

Chapter 3

3-15. 5000 V
3-17. 600 W
3-19. 38.4 W 15Ω
3-21. 750 W
3-23. 0.87 W 36 mA

Chapter 4

4-11. 6.28 N 1.42 lb
4-13. 3.5 lb
4-15. 32.1 ms

Chapter 6

6-13. 7.5 V 300 mA 2.25 W
6-15. 1.74×10^4
6-17. 13.3 hp 564.3 Btu/min 5.5°F

Chapter 7

7-1. - 2.5 dB
7-3. 10.27 in 8.24 Hz
7-5. 9.49 in 9.78 Hz
7-7. 13.2 Hz
7-9. $\dfrac{G_1G_2}{1 + G_1G_2H}$
7-11. $\dfrac{G_1G_2G_3}{1 + G_2G_3H_1H_2 + G_1G_2H_3}$
7-13. 0.25 V/deg
7-15. 60 rpm/gpm
7-17. 0.02 V/rpm
7-19. 11.16 gpm
7-21. b. 0.499 in/V
c. 1.23 in
d. 1.5 in

CONTENTS

CHAPTER 1

An Introduction to the Real World

1.1 INTRODUCTION

Fluid power is involved in virtually every phase of industry, including manufacturing, transportation, and construction. Hydraulic systems are required in heavy-load applications, whereas pneumatic systems are generally employed in light-load, short-stroke, high-speed applications. In many cases, simple manual control systems are totally adequate for the operation, even where a considerable amount of complexity is required. However, the "real world" of fluid power lies in the domain of electric and electronic command, control, and sensing. The marriage of electronics and hydraulics has produced a hybrid system that has both brains and brawn. The electronics can utilize digital devices such as limit switches, pressure switches, and low-level switches to provide nearly instantaneous reaction to limiting situations. The use of tachometer-generators, linear variable differential transformers, piezoelectric pressure sensors, turbine flow meters, accelerometers, and other continuously sensing devices with electronic outputs allows very precise control of both linear and rotational speed, position, acceleration, and deceleration as well as force. The hydraulic system concomitantly provides the same stiffness, accuracy, power, and reliability for which it has always been known.

With the advent of programmable logic controllers (PLCs), the scope of automating with electrohydraulics has become virtually unlimited. The concept of a fully automated manufacturing facility controlled from a single location is now a reality. With PLCs, not only is the manufacturing process control fully automated, it is also readily changed. Previously, many types of piece-part manufacturing (gears, for instance) were limited to large-batch quantities because of the changes that were required from one batch to the next. That is no longer the case. With all the processes stored in the PLC memory, if a single gear of one type is needed, the operator need only call up that program and load the gear blank.

Of course, PLC control is not limited to hydraulics. Every phase of the process—heat treating temperatures and times, surface finishes, painting, packaging—can be handled by a PLC network using a master computer with slave or satellite units for the individual processes.

1.2 APPLICATIONS

Even the simplest industrial systems use electrohydraulics to cause cylinders to stop at a certain position, reciprocate automatically, or operate in a certain sequence. The most common method for achieving these functions is to use solenoid valves activated by limit switches or some other type of digital device. Figure 1.1 shows a bank of solenoid valves that control the operation of cylinders in a manufacturing process.

The use of electrohydraulics in mobile and construction equipment enhances operator safety and reduces operator fatigue while providing improved controllability. The use of a joystick to control electrically actuated valves located on or near the output power actuators removes the high-pressure hydraulic lines from the operator's station and reduces the physical effort that was previously required to manipulate large valve handles. The rock drill in Figure 1.2 utilizes this type of system.

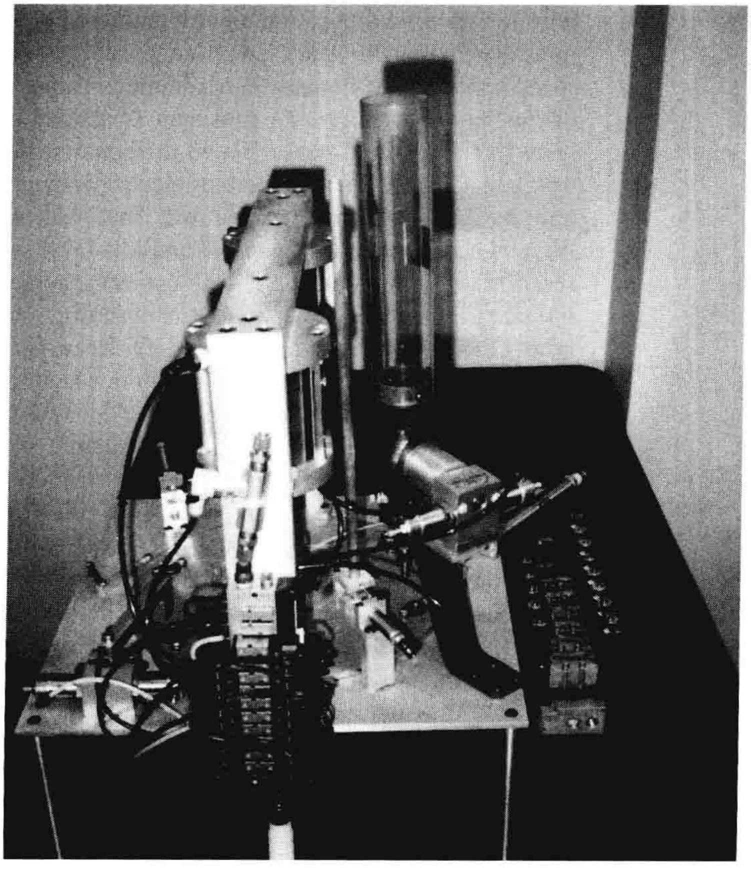


Figure 1.1 A bank of solenoid-operated valves.

Figure 1.2 A hydraulically operated rock drill. (Courtesy of P&H Mining Equipment)

Modern high-performance aircraft commonly use "fly-by-wire" flight control systems. In these aircraft the pilot, rather than operating valves to port fluid to the control-surface actuators, sends electrical signals to a flight control computer. These signals tell the computer what the pilot wants the airplane to do. The computer then sends the necessary commands to the appropriate actuators to achieve the desired maneuver. Because most of today's fighter aircraft are aerodynamically unstable, they are virtually impossible to control by conventional methods; therefore, computer control is an absolute necessity. A typical aircraft hydraulic system is shown in Figure 1.3.

Other electrohydraulic applications include:

- Passenger-car leveling systems for high-speed trains.
- Railroad track sensing and alignment equipment for straightening bent rails.
- Roll-control systems for oceangoing ships.
- Ship propeller pitch and speed controls.

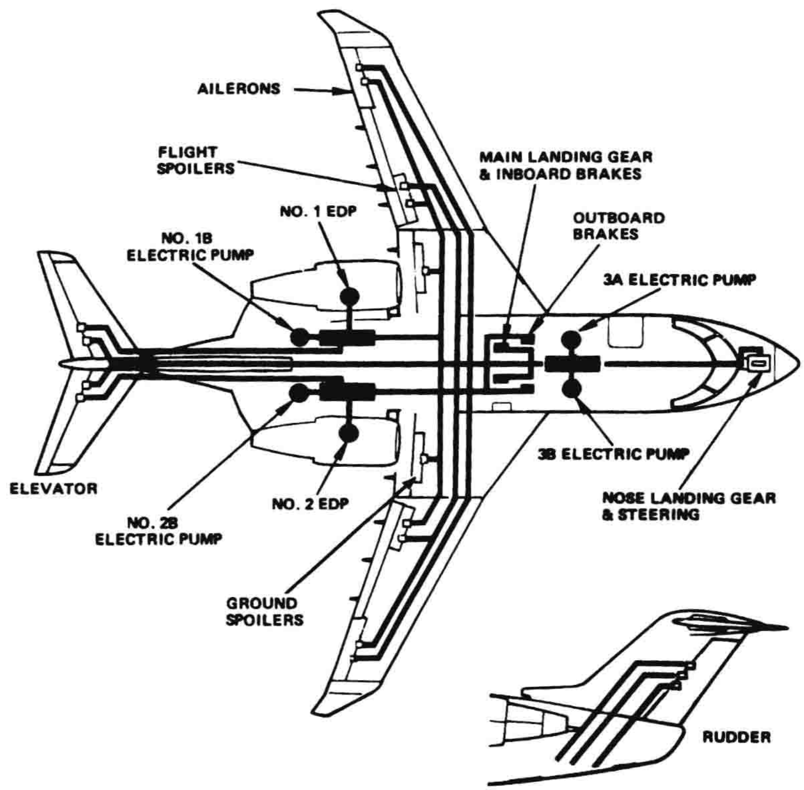


Figure 1.3 A typical aircraft hydraulic system powers the flight controls, landing gear, and nose wheel steering as well as other aircraft functions. (Courtesy of Neese, William A., *Aircraft Hydraulic Systems,* 1991, Krieger Publishing Company, Malabar, Florida)

- Steam valve control for electrical generators.
- Roll control for offshore drilling rigs.
- Automobile transmissions.
- Thrust vectoring nozzles for spacecraft.

The list is nearly endless. Virtually every machine that moves or is used for manufacturing has either hydraulics or pneumatics, and most have some sort of electrical or electronic control.

1.3 THE FUTURE

Fluid power is considered a "mature technology." That term implies that although there may be small, evolutionary advances, no revolutionary changes can be expected. Although this *may* be true, the future of electrohydraulics and electropneumatics is, nonetheless, exciting.

Certainly, evolutionary advances are being seen constantly. Researchers are continually working to improve standard solenoids to provide higher forces and faster operation. Proportional solenoid performance has already reached levels of control and frequency response that rival some servovalves, and the work is continuing. Command and feedback electronics for servovalves are advancing in step with all other areas of electronics, and the valve torque motors and the valves themselves are constantly being improved to keep pace with the electronics.

Improved transducers, digital electronics, and fiber-optic devices are making their way into the electrohydraulic world. "Smart" components, such as the servocylinder shown in Figure 1.4, servopumps, and servomotors are being developed. In these devices, the servovalve, the cylinder, the feedback unit, and the servo electronics are combined in a single package. The only external electrical connections are a power lead and a single command line from the master computer. The unit in Figure 1.4 is digitally addressed from the central command computer, which can control eight such units simultaneously.

All these advances, however, are evolutionary. So far, we have witnessed the marriage of separate electrical/electronic devices and fluid power devices—two separate sets of hardware combined to perform a specific function. The future will bring us the offspring of that marriage—a truly hybrid electrohydraulic device in which there will be no demarcation between the electronics and hydraulics. Rather than being simply a control valve bolted to a cylinder, a unit will be fully integrated, and the separate components will be virtually indistinguishable. *That* will be revolutionary and will open a new world for electrohydraulic applications.

I encourage you to be a part of the revolution. This book is a good start, but it is only the beginning. Other texts will be referenced in subsequent chapters that contain

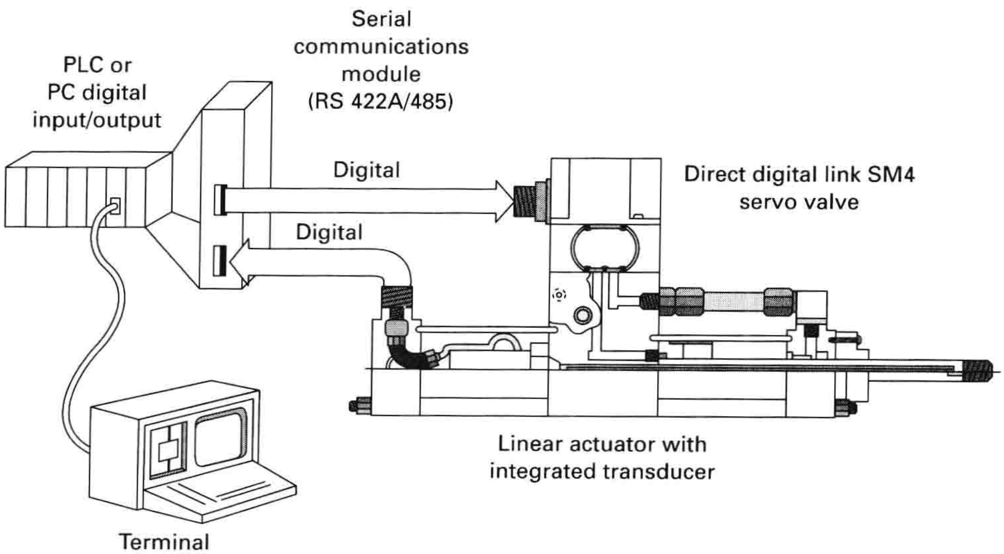


Figure 1.4 A hydraulic servocylinder with the servovalve and controller integrally mounted.