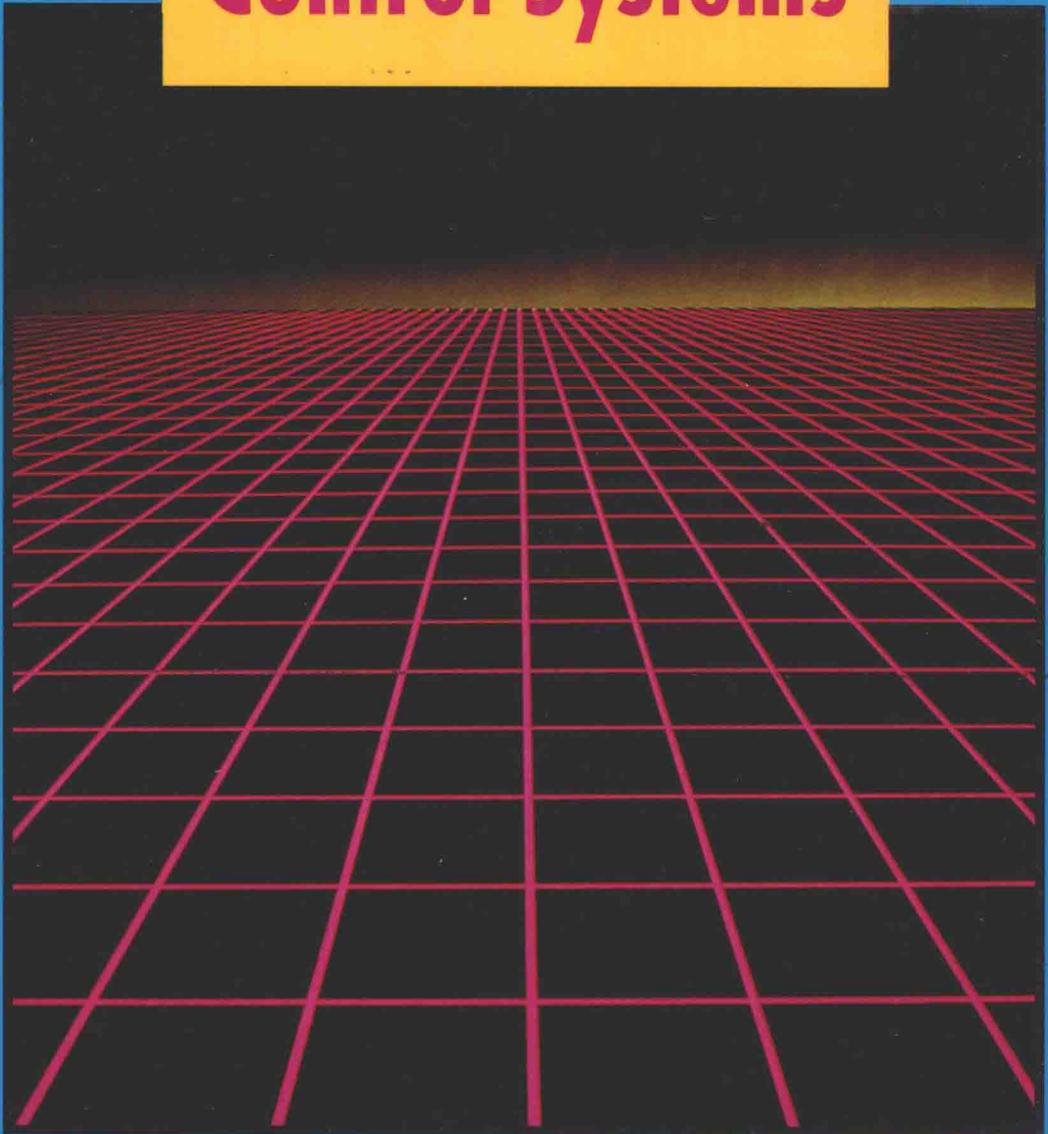


Electrohydraulic Control Systems



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
I. 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.

© 2000 by Prentice-Hall, Inc.
Pearson Education
Upper Saddle River, New Jersey 07458

All rights reserved. No part of this book may be reproduced, in any form or by any means, without permission in writing from the publisher.

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. $F_{\text{ext}} = 21210 \text{ lb}$ $F_{\text{ret}} = 11790 \text{ lb}$
2-5. 7.35 gpm
2-7. 13.6 kW
2-9. $F_{\text{ext}} = 78.54 \text{ kN}$ $F_{\text{ret}} = 40.06 \text{ kN}$
2-11. $v_{\text{ext}} = 0.032 \text{ cm/s}$ $v_{\text{ret}} = 0.062 \text{ cm/s}$
2-13. $2.98 \text{ in}^3/\text{rev}$
2-15. $5.1 \text{ in}^3/\text{rev}$
2-17. $1151 \text{ cm}^3/\text{rev}$
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. $\frac{G_1 G_2}{1 + G_1 G_2 H}$
7-11. $\frac{G_1 G_2 G_3}{1 + G_2 G_3 H_1 H_2 + G_1 G_2 H_3}$
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

Preface	ix	
Chapter 1	An Introduction to the Real World	1
1.1	Introduction	1
1.2	Applications	2
1.3	The Future	4
Chapter 2	A Review of Basic Fluid Power	7
2.1	Introduction	7
2.2	Fluid Power Concepts	8
2.2.1	Flow–Speed Relationship	9
2.2.2	Pressure–Force Relationship	10
2.2.3	Horsepower Calculations	13
2.3	Fluid Power Symbols	17
2.3.1	Rules of Symbol Usage	17
2.3.2	The Language of Graphic Symbols	17
2.3.3	Circuit Diagrams	19
2.4	Summary	21
	Suggested Additional Reading	21
	Review Problems	22
Chapter 3	A Review of Basic Electricity	24
3.1	Introduction	24
3.2	Basic Electrical Concepts	24
3.2.1	Resistance	25
3.2.2	Power	26
3.2.3	Alternating Current Calculations	27
3.3	Symbols for Common Electrical Sensors and Switches	28
3.3.1	Switches	29
3.3.2	Sensors	34
3.4	Electrical Circuit Diagrams	38
3.4.1	General Rules for Electrical Ladder Diagrams	39
3.4.2	Drawing Electrical Ladder Diagrams	40
3.4.3	Relating Wiring Diagrams to Electrical Ladder Diagrams	42
3.4.4	Connecting a Circuit from a Ladder Diagram	44
3.5	Summary	44
	Review Problems	45

Chapter 4	Solenoid Valves	47
4.1	Introduction	47
4.2	Solenoid Valve Construction	48
4.2.1	Valve Section	49
4.2.2	Solenoid	50
4.2.3	Electrical Ratings for Solenoids	55
4.2.4	Transient Suppression	57
4.2.5	Wet-Armature Solenoid	58
4.3	The Solenoid Valve	59
4.4	Solenoid Valve Configurations	61
4.5	Pilot-Operated Solenoid Valves	64
4.6	Valve Shifting Time	69
4.6.1	Pilot Spool	69
4.6.2	Main Spool	72
4.7	Valve Mounting	75
4.8	Transducers for Solenoid Systems	78
4.9	Typical Solenoid Circuits	78
4.10	Solenoid Valve Maintenance and Troubleshooting	85
4.11	Summary	88
	Review Problems	88
	References	89
	Suggested Additional Reading	90
Chapter 5	Electrohydraulic Proportional Control Valve	91
5.1	Introduction	91
5.2	Defining Proportional Control Valves	93
5.3	Directional Control EHPVs	95
5.3.1	Proportional Solenoids	95
5.3.2	Valve Hardware	98
5.4	Throttle (Flow Control) EHPV	100
5.5	Pressure Control EHPV	102
5.6	Electronic Controls	104
5.6.1	Force Control versus Position Control	105
5.6.2	Electronics	107
5.7	Combining Speed and Directional Control	114
5.8	Summary	115
	Review Questions	115
	Suggested Additional Reading	118
Chapter 6	Servoalves	119
6.1	Introduction	119
6.2	Definition of a Servoalve	120
6.2.1	History of Electrohydraulic Servomechanisms	120
6.2.2	Electrohydraulic Servomechanism Concepts	122

6.3	Servovalves	123
6.3.1	Torque Motors	123
6.3.2	Valve Spools	128
6.3.3	Valve Configurations	130
6.3.4	Pressure-Flow Characteristics	134
6.3.5	Valve Performance	138
6.4	Electronics	141
6.4.1	Amplifiers	142
6.4.2	Operational Amplifier	144
6.5	Servopumps and -Motors	151
6.6	System Design Consideration	153
6.7	Summary	157
	References	157
	Review Problems	157

Chapter 7 Electrohydraulic Control System Concepts 159

7.1	Introduction	159
7.2	Rapid Cycling	160
7.2.1	Phase Lag	160
7.2.2	Amplitude Response	162
7.2.3	Step Response	163
7.2.4	Circuit	164
7.2.5	Natural Frequency (Cylinder Circuit)	164
7.2.6	Natural Frequency (Hydraulic Motor Circuit)	171
7.3	Gain and Feedback	174
7.3.1	The Control Ratio Equation	174
7.3.2	Multiple Feedback Systems	177
7.3.3	A System Example	179
7.3.4	Gain Adjustments	184
7.3.5	Repeatable Error	186
7.3.6	Tracking Error	186
7.3.7	Velocity Control Systems	187
7.4	Summary	187
	Suggested Additional Reading	188
	Review Problems	188

Chapter 8 Sensors 191

8.1	Introduction	191
8.2	Transducers versus Sensors	191
8.3	Signal Conditioning	192
8.4	Sensor Characteristics	193
8.4.1	Accuracy	194
8.4.2	Precision	194

8.5	Discrete Sensors and Transducers	195
8.5.1	Limit Switches	195
8.5.2	Pressure Switches	208
8.5.3	Other Discrete Elements	210
8.5.4	Timers and Counters	210
8.6	Continuous Sensors	210
8.6.1	Temperature Sensors	210
8.6.2	Flow Rate Measurement	214
8.6.3	Pressure Measurement	216
8.6.4	Linear Position	220
8.6.5	Rotary Position Measurement	224
8.6.6	Velocity and Acceleration Measurement	227
8.7	Summary	228
	Suggested Additional Reading	229
	References	229
	Review Questions	229
Chapter 9	Programmable Logic Controllers	231
9.1	Introduction	231
9.2	Background	234
9.3	PLC Architecture	235
9.3.1	Central Processing Unit	235
9.3.2	Memory	235
9.3.3	Input/Output Modules	237
9.3.4	Programming Devices	240
9.3.5	PLC Sizes	242
9.4	Programming Languages	243
9.5	The Transition: Relay Logic to PC Logic	244
9.6	Application Examples	245
9.7	Summary	252
	References	252
	Review Questions	253
Chapter 10	Robotics	254
10.1	Introduction	254
10.2	Robotic Devices	255
10.3	Manipulators	257
10.3.1	Cartesian Geometry	257
10.3.2	Polar Coordinates	257
10.3.3	Cylindrical Coordinates	257
10.3.4	Anthropomorphic	257
10.3.5	SCARA	259
10.3.6	Other Configurations	259
10.4	End Effectors	260
10.5	Power Systems	265
10.6	Control	266

10.7	Programming	268
10.8	Safety	269
10.9	Installation Considerations	272
10.10	Summary	272
	Suggested Additional Reading	273
	Review Questions	273
Appendix A	Common Fluid Power Symbols	274
Appendix B	Common Electrical Symbols	277
Index		281
Answers to Selected Problems		287

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.

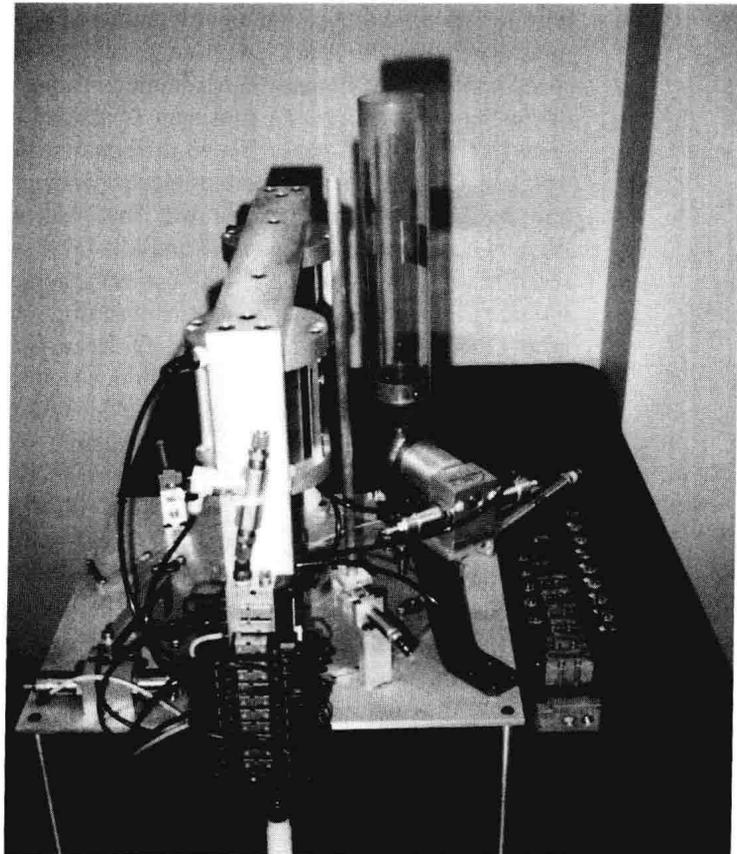




Figure 1.2 A hydraulically operated rock drill. (Courtesy of P&H Mining Equipment)

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.

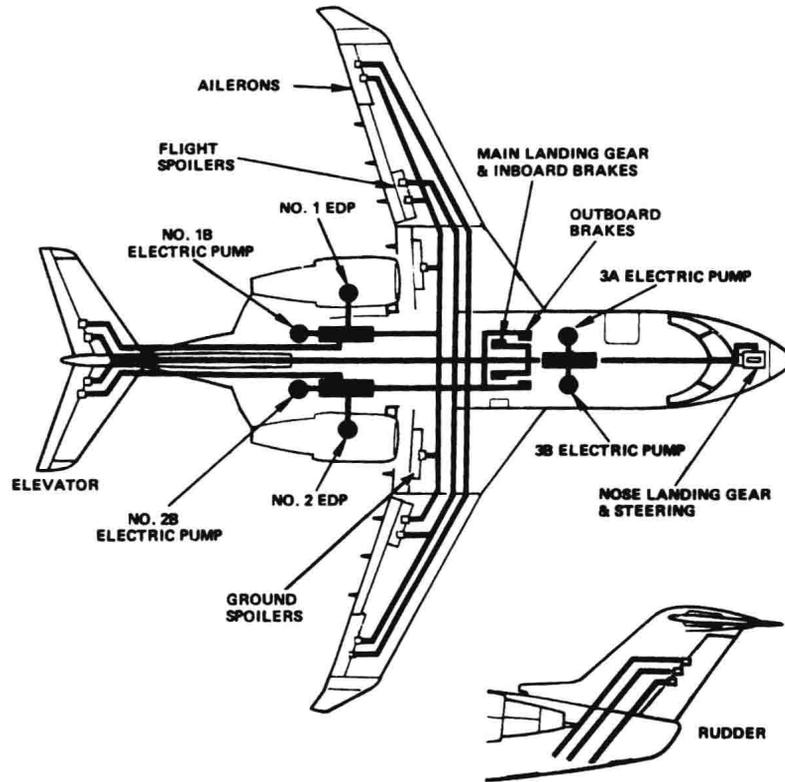


Figure 1.3 A typical aircraft hydraulic system powers the flight controls, landing gear, and nose wheel steering as well as other aircraft functions. (Courtesy of Neese, William A., *Aircraft Hydraulic Systems*, 1991, Krieger Publishing Company, Malabar, Florida)

- 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

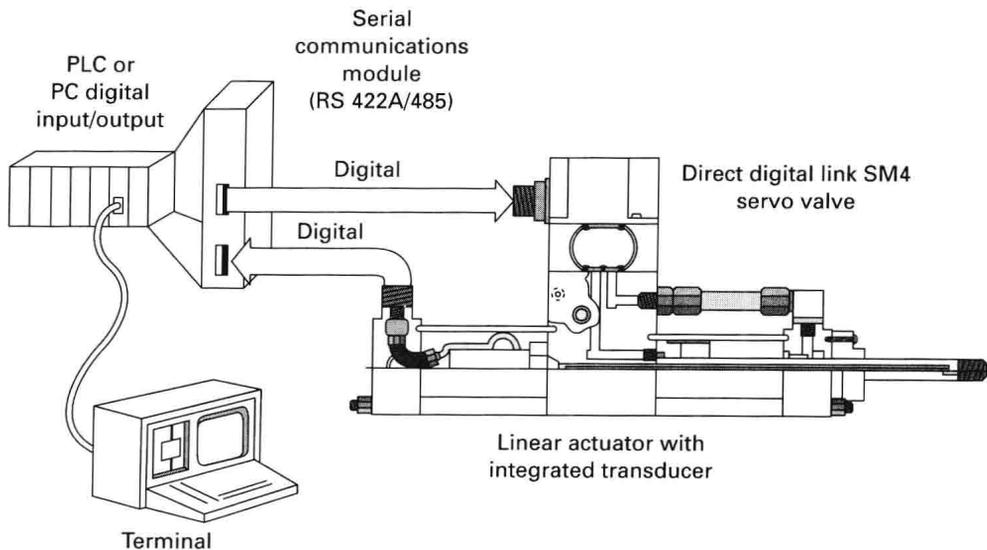


Figure 1.4 A hydraulic servocylinder with the servovalve and controller integrally mounted.