

FUNDAMENTALS OF FLUID POWER CONTROL

This exciting new reference text is concerned with fluid power control. It is an ideal reference for the practicing engineer and a textbook for advanced courses in fluid power control. In applications in which large forces and/or torques are required, often with a fast response time, oil-hydraulic control systems are essential. They excel in environmentally difficult applications because the drive part can be designed with no electrical components, and they almost always have a more competitive power–weight ratio than electrically actuated systems. Fluid power systems have the capability to control several parameters, such as pressure, speed, and position, to a high degree of accuracy at high power levels. In practice, there are many exciting challenges facing the fluid power engineer, who now must have a broad skill set.

John Watton entered industry in 1960 working on the design of heat exchangers. He then studied Mechanical Engineering at Cardiff University, obtaining his BSc degree followed by his PhD degree. In 1969, he returned to industry as a Senior Systems Engineer working on the electrohydraulic control of guided pipe-laying machines. Following a period at Huddersfield University, he returned to Cardiff University in 1979 and was appointed Professor of Fluid Power in 1996, receiving his DSc degree in the same year. He was awarded the Institution of Mechanical Engineers Bramah Medal in 1999 and a special award from the Japan Fluid Power Society in 2005, both for outstanding research contributions to fluid power.

Professor Watton has been continually active as a researcher and consultant with industry in the past 40 years. He has worked on components and systems design, manufacturing plant monitoring, and the design of new mobile machines, and he has acted as an Expert Witness on a variety of fluid power issues. He is a Chartered Engineer, a Fellow of the Institution of Mechanical Engineers, and was elected a Fellow of the Royal Academy of Engineering in 2007.

Cambridge University Press
978-0-521-76250-2 - Fundamentals of Fluid Power Control
John Watton
Frontmatter
[More information](#)

Fundamentals of Fluid Power Control

John Watton, DSc FREng
Cardiff University, School of Engineering



Cambridge University Press
978-0-521-76250-2 - Fundamentals of Fluid Power Control
John Watton
Frontmatter
[More information](#)

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore,
São Paulo, Delhi, Dubai, Tokyo

Cambridge University Press
32 Avenue of the Americas, New York, NY 10013-2473, USA
www.cambridge.org
Information on this title: www.cambridge.org/9780521762502

© John Watton 2009

This publication is in copyright. Subject to statutory exception
and to the provisions of relevant collective licensing agreements,
no reproduction of any part may take place without the written
permission of Cambridge University Press.

First published 2009

Printed in the United States of America

A catalog record for this publication is available from the British Library.

Library of Congress Cataloging in Publication data

Watton, J., 1944–
Fundamentals of fluid power control / John Watton.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-521-76250-2 (hardback)
1. Fluid power technology. 2. Hydraulic control. 3. Component analysis. I. Title.
TJ843.W383 2009
629.8'042 – dc22 2008054781

ISBN 978-0-521-76250-2 Hardback

Cambridge University Press has no responsibility for the persistence or
accuracy of URLs for external or third-party Internet Web sites referred to in
this publication and does not guarantee that any content on such Web sites is,
or will remain, accurate or appropriate.

Contents

<i>Preface</i>	<i>page xi</i>
1 Introduction, Applications, and Concepts	1
1.1 The Need for Fluid Power	1
1.2 Circuits and Symbols	8
1.3 Pumps and Motors	11
1.4 Cylinders	16
1.5 Valves	17
1.6 Servoactuators	25
1.7 Power Packs and Ancillary Components	26
1.8 References and Further Reading	31
2 An Introduction to Fluid Properties	33
2.1 Fluid Types	33
2.2 Fluid Density	39
2.3 Fluid Viscosity	40
2.4 Bulk Modulus	41
2.5 Fluid Cleanliness	49
2.6 Fluid Vapor Pressure and Cavitation	50
2.7 Electrorheological (ER) Fluids and Magnetorheological (MR) Fluids	54
2.8 References and Further Reading	58
3 Steady-State Characteristics of Circuit Components	61
3.1 Flow Through Pipes	61
3.1.1 The Energy Equation	61
3.1.2 Laminar and Turbulent Flow in Pipes; the Effect of Fluid Viscosity	62
3.1.3 The Navier–Stokes Equation	62
3.1.4 Laminar Flow in a Circular Pipe	64
3.1.5 The General Pressure-Drop Equation	66
3.1.6 Temperature Rise in 3D Flow	68
3.1.7 Computational Fluid Dynamics (CFD) Software Packages	69

vi	Contents
3.2	Restrictors, Control Gaps, and Leakage Gaps 74
3.2.1	Types 74
3.2.2	Orifice-Type Restrictors 74
3.2.3	Flow Between Parallel Plates 80
3.2.4	Flow Between Annular Gaps 81
3.2.5	Flow Between an Axial Piston Pump Slipper and Its Swash Plate 82
3.2.6	Flow Between a Ball and Socket 89
3.2.7	Flow Between Nonparallel Plates – Reynolds Equation 90
3.2.8	Flow Through Spool Valves of the Servovalve Type and the Use of a CFD Package for Analysis 95
3.2.9	Flow Characteristics of a Cone-Seated Poppet Valve 100
3.2.10	A Double Flapper–Nozzle Device for Pressure-Differential Generation 104
3.2.11	The Jet Pipe and Deflector-Jet Fluidic Amplifier 109
3.3	Steady-State Flow-Reaction Forces 112
3.3.1	Basic Concepts 112
3.3.2	Application to a Simple Poppet Valve 112
3.3.3	Application to the Main Stage of a Two-Stage Pressure-Relief Valve 113
3.3.4	Application to a Spool Valve 115
3.3.5	Application to a Cone-Seated Poppet Valve 117
3.3.6	Application to a Flapper–Nozzle Stage 119
3.4	Other Forces on Components 120
3.4.1	Static and Shear-Stress Components 120
3.4.2	Transient Flow-Reaction Forces 121
3.5	The Electrohydraulic Servovalve 122
3.5.1	Servovalve Types 122
3.5.2	Servovalve Rating 123
3.5.3	Flow Characteristics, Critically Lapped Spool 125
3.5.4	Servovalve with Force Feedback 127
3.5.5	Servovalve with Spool-Position Electrical Feedback 129
3.5.6	Flow Characteristics, Underlapped Spool 130
3.6	Positive-Displacement Pumps and Motors 133
3.6.1	Flow and Torque Characteristics of Positive-Displacement Machines 133
3.6.2	Geometrical Displacement of a Positive-Displacement Machine 137
3.6.3	Flow Losses for an Axial Piston Machine 142
3.6.4	Torque Losses for an Axial Piston Machine 148
3.6.5	Machine Efficiency – Axial Piston Pump 152
3.6.6	Machine Efficiency – Axial Piston Motor 155
3.7	Pressure-Relief Valve Pressure–Flow Concepts 158
3.8	Sizing an Accumulator 159
3.9	Design of Experiments 161
3.10	References and Further Reading 163

Contents	vii
4 Steady-State Performance of Systems	171
4.1 Determining the Power Supply Pressure Variation during Operation for a Pump–PRV–Servovalve Combination: A Graphical Approach	171
4.2 Meter-Out Flow Control of a Cylinder	172
4.3 A Comparison of Counterbalance-Valve and an Overcenter-Valve Performances to Avoid Load Runaway	174
4.4 Drive Concepts	177
4.5 Pump and Motor Hydraulically Connected: A Hydrostatic Drive	179
4.6 Pump and Motor Shaft Connected: A Power Transfer Unit (PTU)	183
4.7 Servovalve–Motor Open-Loop and Closed-Loop Speed Drives	189
4.7.1 Open-Loop Control	189
4.7.2 Closed-Loop Control	192
4.8 Servovalve–Linear Actuator	195
4.8.1 Extending	195
4.8.2 Retracting	196
4.8.3 A Comparison of Extending and Retracting Operations	198
4.9 Closed-Loop Position Control of an Actuator by a Servovalve with a Symmetrically Underlapped Spool	200
4.10 Linearization of a Valve-Controlled Motor Open-Loop Drive: Toward Intelligent Control	203
4.11 References and Further Reading	207
5 System Dynamics	209
5.1 Introduction	209
5.2 Mass Flow-Rate Continuity	211
5.3 Force and Torque Equations for Actuators	211
5.4 Solving the System Equations, Computer Simulation	213
5.5 Differential Equations, Laplace Transforms, and Transfer Functions	216
5.5.1 Linear Differential Equations	216
5.5.2 Nonlinear Differential Equations, the Technique of Linearization for Small-Signal Analysis	219
5.5.3 Undamped Natural Frequency of a Linear Actuator	221
5.5.4 Laplace Transforms and Transfer Functions	223
5.6 The Electrical Analogy	225
5.7 Frequency Response	229
5.8 Optimum Transfer Functions, the ITAE Criterion	235
5.9 Application to a Servovalve–Motor Open-Loop Drive	239
5.9.1 Forming the Equations	239
5.9.2 An Estimate of Dynamic Behavior by a Linearized Analysis	239
5.9.3 A Comparison of Nonlinear and Linearized Equations Using the Phase-Plane Method	244
5.10 Application to a Servovalve–Linear Actuator Open-Loop Drive	245
5.10.1 Forming the Equations	245
5.10.2 An Estimate of Dynamic Behavior by a Linearized Analysis	247

5.10.3 Transfer Function Simplification for a Double-Rod Actuator	248
5.11 Further Considerations of the Nonlinear Flow-Continuity Equations of a Servovalve Connected to a Motor or a Double-Rod Linear Actuator	249
5.12 The Importance of Short Connecting Lines When the Load Mass Is Small	250
5.13 A Single-Stage PRV with Directional Damping	253
5.13.1 Introduction	253
5.13.2 Forming the Equations, Transient Response	255
5.13.3 Frequency Response from a Linearized Transfer Function Analysis	257
5.14 Servovalve Dynamics	259
5.15 An Open-Loop Servovalve–Motor Drive with Line Dynamics Modeled by Lumped Approximations	261
5.16 Transmission Line Dynamics	265
5.16.1 Introduction	265
5.16.2 Lossless Line Model for Z and Y	267
5.16.3 Average and Distributed Line Friction Models for Z and Y	270
5.16.4 Frequency-Domain Analysis	271
5.16.5 Servovalve-Reflected Linearized Coefficients	275
5.16.6 Modeling Systems with Nonlossless Transmission Lines, the Modal Analysis Method	278
5.16.7 Modal Analysis Applied to a Servovalve–Motor Open-Loop Drive	282
5.17 The State-Space Method for Linear Systems Modeling	285
5.17.1 Modeling Principles	285
5.17.2 Some Further Aspects of the Time-Domain Solution	291
5.17.3 The Transfer Function Concept in State Space	292
5.18 Data-Based Dynamic Modeling	293
5.18.1 Introduction	293
5.18.2 Time-Series Modeling	294
5.18.3 The Group Method of Data Handling (GMDH) Algorithm	296
5.18.4 Artificial Neural Networks	297
5.18.5 A Comparison of Time-Series, GMDH, and ANN Modeling of a Second-Order Dynamic System	300
5.18.6 Time-Series Modeling of a Position Control System	304
5.18.7 Time-Series Modeling for Fault Diagnosis	306
5.18.8 Time-Series Modeling of a Proportional PRV	309
5.18.9 GMDH Modeling of a Nitrogen-Filled Accumulator	311
5.19 Some Comments on the Effect of Coulomb Friction	314
5.20 References and Further Reading	318
6 Control Systems	323
6.1 Introduction to Basic Concepts, the Hydromechanical Actuator	323
6.2 Stability of Closed-Loop Linear Systems	326

Contents

6.2.1	Nyquist’s Stability Criterion	326
6.2.2	Root Locus Method	330
6.2.3	Routh Stability Criterion	332
6.2.4	The State-Space Approach	334
6.2.5	Servo valve–Motor Closed-Loop Speed Control	335
6.2.6	Servo valve–Linear Actuator Position Control	338
6.2.7	The Effect of Long Lines on Closed-Loop Stability, Speed Control of a Motor	343
6.2.8	The Effect of Long Lines on Closed-Loop Stability, Position Control of a Linear Actuator	345
6.2.9	The Effect of Coulomb Friction Damping on the Response and Stability of a Servo valve–Linear Actuator Position Control System	349
6.3	Digital Control	352
6.3.1	Introduction	352
6.3.2	The Process of Sampling	353
6.3.3	The <i>z</i> Transform	356
6.3.4	Closed-Loop Analysis with Zero-Order-Hold Sampling	356
6.3.5	Closed-Loop Stability	360
6.4	Improving the Closed-Loop Response	362
6.4.1	Servo valve Spool Underlap for Actuator Position Control, a Linearized Transfer Function Approach	362
6.4.2	Phase Compensation, Gain and Phase Margins	365
6.4.3	Dynamic Pressure Feedback	371
6.4.4	State Feedback	374
6.5	Feedback Controller Implementation	384
6.5.1	Analog-to-Digital Implementation	384
6.5.2	Generalized Digital Filters	385
6.5.3	State Estimation, Observers, and Reduced-Order Observers	390
6.5.4	Linear Quadratic (LQ) Optimal State Control	394
6.6	On–Off Switching of Directional Valves	399
6.6.1	PWM Control	400
6.6.2	Valves Sized in a Binary Flow Sequence	405
6.7	An Introduction to Fuzzy Logic and Neural Network Control	407
6.8	Servo valve Dither for Improving Position Accuracy	414
6.9	References and Further Reading	416
7	Some Case Studies	421
7.1	Introduction	421
7.2	Performance of an Axial Piston Pump Tilted Slipper with Grooves	421
7.2.1	Introduction	421
7.2.2	Flow and Pressure Distribution, Mathematical Analysis	422
7.2.3	Simplification for the Nontilted Case, No-Rotation Condition	426
7.2.4	Experimental Method	427

x	Contents
7.2.5	Some Results with Slipper Tilt Included and for No Rotation 433
7.2.6	The Effect of Tilt and Rotation, Measurement, and CFD Simulation 434
7.3	Modeling a Forge Valve and Its Application to Press Cylinder Control 438
7.3.1	Introduction 438
7.3.2	Developing the Component Equations 440
7.3.3	Developing the System Equations 443
7.3.4	System Dynamics for Closed-Loop Control 446
7.3.5	The Use of PWM Control of a Pair of Fast-Acting Solenoid Valves 448
7.4	The Modeling and Control of a Vehicle Active Suspension 448
7.4.1	Introduction 448
7.4.2	Determining the Open-Loop Fluid Power Model 451
7.4.3	Actuator Dynamic Stiffness 455
7.4.4	The Introduction of Feedback, the One-Degree-of-Freedom (1 DOF) Test to Identify Actuator Viscous Damping B_v and Leakage Resistance R_i 455
7.4.5	The Introduction of Feedback, the Two-Degree-of-Freedom (2 DOF) Test to Identify Tire Viscous Damping B_t and Validate Tire Stiffness k_t 457
7.4.6	A State-Space Model for the Active Suspension 460
7.4.7	Closed-Loop Control Design by Computer Simulation 461
7.4.8	Experimental Validation of the Preferred LQC System 468
7.5	The Performance of a Car Hydraulic Power-Steering System 470
7.5.1	Introduction 470
7.5.2	Experimental Setup and Operation 471
7.5.3	Steady-State Characteristics of the Steering Valve 472
7.5.4	Dynamic Behavior of the Power-Steering Unit 475
7.5.5	Results 477
7.6	Onboard Electronics (OBE) for Measurement and Intelligent Monitoring 478
7.7	References and Further Reading 484
Index	489

Preface

This book is aimed at undergraduate students as a second-year and beyond entry stage to fluid power. There is much material that will also appeal to technicians regarding the background to fluid power and the operation of components and systems. Fluid power is often considered a specialist subject but should not be so given that the same would not be said for electrical power. In fact, there are many applications for which fluid power control is the only possibility because of force/torque/power/environmental demands. In the past 20 years, a number of groups around the world have made significant steps forward in both the understanding and the application of theory and control, complementing the R&D activity undertaken within the manufacturing industry. Details of just one organization involving many participating fluid power centers around the world are available at www.fluid.power.net. I embarked on this book ostensibly as a replacement for my first book, *Fluid Power Systems – Modelling, Simulation, Analog and Microcomputer Control*, published by Prentice-Hall in 1989 and now out of print. However, the result is a much different book and perhaps not surprising, given the developments in fluid power in the past 20 years. Following many constructive comments by undergraduate students, friends in industry, and academic friends who still use my first book for teaching, it was clear that a new book was needed. It was felt that a new book should integrate far more fundamental background theory with its application to real components and systems, but without the book becoming research orientated; this is the intention. Validation of theory has been significantly aided by advances in computer modeling of fluid mechanics and system dynamic issues, together with advances in sensors and instrumentation for experimental validation of component and systems performance. These aspects are introduced where appropriate.

Chapter 1 introduces fluid power, indicating its need, circuit symbols, various standard circuits, and associated components. Practical examples of fluid power control are given with the intention of conveying the power-level breadth and application breadth of the subject, varying from precision micrometer position control to primary processing of materials and products. Some common circuit components are presented with their operating concepts, and a further reading list includes textbooks and related industrial literature.

Chapter 2 introduces fluid physical properties for different applications that now must seriously begin to consider the use of less mineral-oil content as both

supply and environmental issues begin to dominate many new applications. Fluid bulk modulus issues are presented in some detail, particularly for flexible-hose applications for which its reduction can be dramatic. Fluid cleanliness is also introduced, as is the importance of understanding the effects of cavitation conditions on material erosion. Electrorheological and magnetorheological fluids are now emerging in fluid power applications following many years of awareness, and this is presented for a student racing car suspension real-time control application. A further reading list is included.

Chapter 3 is the first substantial chapter; it discusses the steady-state characteristics of circuit components. It begins with essentials of fluid flow theory and moves on to applications involving restrictors, control gaps, and leakage gaps used in components. Unique solutions are presented where appropriate, with practical data and supporting computation fluid dynamics simulations introduced for the first time. A section on flow-reaction forces is essential and considered in some detail. Developments in servovalves are also briefly discussed and their characteristics analyzed. Positive-displacement pumps and motors are discussed with respect to generic losses and supported by measurements, particularly with respect to efficiency. A section on servovalve behavior is included, together with other control valves and accumulators commonly used in circuits. Finally, the concept of design of experiments is introduced to aid experimental testing to determine performance characteristics. Many worked examples are also included, together with a further reading list.

Chapter 4 is concerned with the steady-state performance of drive systems; it discusses the interconnection of valves, servovalves, pumps, and motors in a variety of configurations. The relatively unknown theory of power transfer units for aircraft applications is discussed and compared with practice in a qualitative sense. This chapter covers graphical and explicit design approaches to understanding steady-state behavior. Several worked examples are also included as well as a further reading list.

Chapter 5, the second substantial chapter, is concerned with system dynamics – that is, time-varying behavior. The philosophy of this chapter is to derive the basic mass flow and force–torque continuity equations, integrate them into typical components and circuits, and then consider solutions to determine the dynamic response of common components and circuits. Linear differential equations are considered, together with frequency response and transfer function concepts. The concept of linearizing equations is introduced to aid analysis when components have nonlinear pressure–flow characteristics such as servovalves. Transmission-line effects are covered in some detail with practical validation. State-space analysis is introduced as a basis for control-theory developments in the next chapter. Finally, an overview of data-based modeling is considered as a means of growing importance when considering the determination of a dynamic model with some knowledge of its probable form. Various methods are introduced, such as the group method of data handling, artificial neural networks, and time-series modeling, with practical validation. Many additional worked examples are also included, together with a further reading list.

Chapter 6 is concerned with controlling fluid power systems and therefore calls on the work of previous chapters. The third substantial chapter, it brings together basic background theory for closed-loop stability, digital control, closed-loop response improvement, and feedback control implementation. The concepts are applied to typical circuits, including the effect of long lines. State feedback is developed for both analog and digital feedback control and extended to include

Preface

xiii

state estimation for state control and linear quadratic control. Again, many examples and additional worked examples are included. On–off switching of valves is then considered as an alternative to conventional control techniques because this is gaining popularity, particularly for high-water-content fluid applications. This part of the chapter is dominated by the practical aspect, but real application results are shown. Finally, an introduction to fuzzy-logic and neural network control is added to whet the appetite for these relatively new approaches for hydraulic systems control. Developing these aspects further is beyond the scope of this book, although some practical results are shown to allow the reader to obtain a feel for the approaches used. Again, a further reading list is included.

Chapter 7 is the final substantial chapter; it consists of just five of the many advanced studies undertaken by me, colleagues, and undergraduate students who have worked with me on a range of applications. The idea here is to develop existing concepts presented in the previous chapters, not to present a collection of research papers but to show a continuing thread of what usually happens in practice. Hence, many aspects of each study are not included but may be taken further from the references given. The first study is concerned with extending hydrostatic pump slipper theory to the case in which the slipper has a groove, rotation, and tilt, the last giving rise to hydrodynamic effects. The second study is concerned with modeling and real control of a forging press cylinder, including both proportional and switched valve systems. The third study is concerned with the modeling and control of a real vehicle wheel active suspension and includes model identification, control by computer simulation, and practical computer control. The fourth study is concerned with the performance of a commercially used car power-steering unit and, in particular, the crucial performance of the power-steering valve. The fifth study is concerned with progress toward intelligent monitoring of pump cylinder pressures using onboard electronics. These five studies embrace theory and practice with practical data to show the effectiveness and limitations of the approaches taken.

John Watton
jwatton@fluidpowerconsultants.com
Llandaff, Cardiff, July 2008