

Modern Control Engineering

Fifth Edition

Katsuhiko Ogata

Prentice Hall

Boston Columbus Indianapolis New York San Francisco Upper Saddle River

Amsterdam Cape Town Dubai London Madrid Milan Munich Paris Montreal Toronto

Delhi Mexico City Sao Paulo Sydney Hong Kong Seoul Singapore Taipei Tokyo

VP/Editorial Director, Engineering/Computer Science: Marcia J. Horton Assistant/Supervisor: Dolores Mars Senior Editor: Andrew Gilfillan Associate Editor: Alice Dworkin Editorial Assistant: William Opaluch Director of Marketing: Margaret Waples Senior Marketing Manager: Tim Galligan Marketing Assistant: Mack Patterson Senior Managing Editor: Scott Disanno Art Editor: Greg Dulles Senior Operations Supervisor: Alan Fischer Operations Specialist: Lisa McDowell Art Director: Kenny Beck Cover Designer: Carole Anson Media Editor: Daniel Sandin

Credits and acknowledgments borrowed from other sources and reproduced, with permission, in this textbook appear on appropriate page within text.

MATLAB is a registered trademark of The Mathworks, Inc., 3 Apple Hill Drive, Natick MA 01760-2098.

Copyright © 2010, 2002, 1997, 1990, 1970 Pearson Education, Inc., publishing as Prentice Hall, One Lake Street, Upper Saddle River, New Jersey 07458. All rights reserved. Manufactured in the United States of America. This publication is protected by Copyright, and permission should be obtained from the publisher prior to any prohibited reproduction, storage in a retrieval system, or transmission in any form or by any means, electronic, mechanical, photocopying, recording, or likewise. To obtain permission(s) to use material from this work, please submit a written request to Pearson Education, Inc., Permissions Department, One Lake Street, Upper Saddle River, New Jersey 07458.

Many of the designations by manufacturers and seller to distinguish their products are claimed as trademarks. Where those designations appear in this book, and the publisher was aware of a trademark claim, the designations have been printed in initial caps or all caps.

Library of Congress Cataloging-in-Publication Data on File

www.pearsonhighered.com

10 9 8 7 6 5 4 3 2 1

Prentice Hall is an imprint of



ISBN 10: 0-13-615673-8

ISBN 13: 978-0-13-615673-4



Preface	ix
Chapter 1 Introduction to Control Systems	1
1–1 Introduction 1	
1–2 Examples of Control Systems 4	
1–3 Closed-Loop Control Versus Open-Loop Control 7	
1–4 Design and Compensation of Control Systems 9	
1–5 Outline of the Book 10	
Chapter 2 Mathematical Modeling of Control Systems	13
2–1 Introduction 13	
2–2 Transfer Function and Impulse-Response Function 15	
2–3 Automatic Control Systems 17	
2–4 Modeling in State Space 29	
2–5 State-Space Representation of Scalar Differential Equation Systems 35	
2–6 Transformation of Mathematical Models with MATLAB	39

2–7	Linearization of Nonlinear Mathematical Models 43	
	Example Problems and Solutions 46	
	Problems 60	
Chap	pter 3 Mathematical Modeling of Mechanical Systems and Electrical Systems	63
3–1	Introduction 63	
3–2	Mathematical Modeling of Mechanical Systems 63	
3–3	Mathematical Modeling of Electrical Systems 72	
	Example Problems and Solutions 86	
	Problems 97	
Chap	pter 4 Mathematical Modeling of Fluid Systems and Thermal Systems	100
4–1	Introduction 100	
4–2	Liquid-Level Systems 101	
4–3	Pneumatic Systems 106	
4–4	Hydraulic Systems 123	
4–5	Thermal Systems 136	
	Example Problems and Solutions 140	
	Problems 152	
Chap	pter 5 Transient and Steady-State Response Analyses	159
5–1	Introduction 159	
5–2	First-Order Systems 161	
5–3	Second-Order Systems 164	
5–4	Higher-Order Systems 179	
5–5	Transient-Response Analysis with MATLAB 183	
5–6	Routh's Stability Criterion 212	
5–7	Effects of Integral and Derivative Control Actions on System Performance 218	
5–8	Steady-State Errors in Unity-Feedback Control Systems 225	
	Example Problems and Solutions 231	
	Problems 263	

iv Contents

Chap	ter 6 Control Systems Analysis and Design by the Root-Locus Method	269
6–1	Introduction 269	
6–2	Root-Locus Plots 270	
6–3	Plotting Root Loci with MATLAB 290	
6–4	Root-Locus Plots of Positive Feedback Systems 303	
6–5	Root-Locus Approach to Control-Systems Design 308	
6–6	Lead Compensation 311	
6–7	Lag Compensation 321	
6-8	Lag-Lead Compensation 330	
6–9	Parallel Compensation 342	
	Example Problems and Solutions 347	
	Problems 394	
Chap	ter 7 Control Systems Analysis and Design by the Frequency-Response Method	398
7–1	Introduction 398	
7–2	Bode Diagrams 403	
7–3	Polar Plots 427	
7–4	Log-Magnitude-versus-Phase Plots 443	
7–5	Nyquist Stability Criterion 445	
7–6	Stability Analysis 454	
7–7	Relative Stability Analysis 462	
7–8	Closed-Loop Frequency Response of Unity-Feedback Systems 477	
7–9	Experimental Determination of Transfer Functions 486	
7–10	Control Systems Design by Frequency-Response Approach 491	
7–11	Lead Compensation 493	
7–12	Lag Compensation 502	
7–13	Lag-Lead Compensation 511	
	Example Problems and Solutions 521	
	Problems 561	
Chap	ter 8 PID Controllers and Modified PID Controllers	567
8–1	Introduction 567	
8–2	Ziegler–Nichols Rules for Tuning PID Controllers 568	
Conter	nts	v

8–3	Design of PID Controllers with Frequency-Response Approach 577				
8–4	Design of PID Controllers with Computational Optimization Approach 583				
8–5	Modifications of PID Control Schemes 590				
8–6	Two-Degrees-of-Freedom Control 592				
8–7	Zero-Placement Approach to Improve Response Characteristics 595				
	Example Problems and Solutions 614				
	Problems 641				
Chap	oter 9 Control Systems Analysis in State Space	648			
9–1	Introduction 648				
9–2	State-Space Representations of Transfer-Function Systems 649				
9–3	Transformation of System Models with MATLAB 656				
9–4	Solving the Time-Invariant State Equation 660				
9–5	Some Useful Results in Vector-Matrix Analysis 668				
9–6	Controllability 675				
9–7	Observability 682				
	Example Problems and Solutions 688				
	Problems 720				
Chap	oter 10 Control Systems Design in State Space	722			
10-1	Introduction 722				
10-2	Pole Placement 723				
10-3	Solving Pole-Placement Problems with MATLAB 735				
10–4	Design of Servo Systems 739				
10-5	State Observers 751				
10-6	Design of Regulator Systems with Observers 778				
10-7	Design of Control Systems with Observers 786				
10-8	Quadratic Optimal Regulator Systems 793				
10–9	Robust Control Systems 806				
	Example Problems and Solutions 817				
	Problems 855				

vi Contents

Appendix A	Laplace Transform Tables	859
Appendix B	Partial-Fraction Expansion	867
Appendix C	Vector-Matrix Algebra	874
References		882
Index		886

Contents