

LINEAR CONTROL SYSTEM ANALYSIS AND DESIGN WITH MATLAB

Fifth Edition, Revised and Expanded

John J. D'Azzo and Constantine H. Houpis

*Air Force Institute of Technology
Wright-Patterson Air Force Base, Ohio, U.S.A.*

Stuart N. Sheldon

*U.S. Nuclear Regulatory Commission
Lisle, Illinois, U.S.A.*



MARCEL DEKKER, INC.

NEW YORK • BASEL

The fourth edition was published as *Linear Control System Analysis and Design: Conventional and Modern*, by John J. D'Azzo and Constantine H. Houpis (McGraw-Hill, 1995).

Although great care has been taken to provide accurate and current information, neither the author(s) nor the publisher, nor anyone else associated with this publication, shall be liable for any loss, damage, or liability directly or indirectly caused or alleged to be caused by this book. The material contained herein is not intended to provide specific advice or recommendations for any specific situation.

Trademark notice: Product or corporate names may be trademarks or registered trademarks and are used only for identification and explanation without intent to infringe.

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress.

ISBN: 0-8247-4038-6

This book is printed on acid-free paper.

Headquarters

Marcel Dekker, Inc., 270 Madison Avenue, New York, NY 10016, U.S.A.
tel: 212-696-9000; fax: 212-685-4540

Distribution and Customer Service

Marcel Dekker, Inc., Cimarron Road, Monticello, New York 12701, U.S.A.
tel: 800-228-1160; fax: 845-796-1772

Eastern Hemisphere Distribution

Marcel Dekker AG, Hutgasse 4, Postfach 812, CH-4001 Basel, Switzerland
tel: 41-61-260-6300; fax: 41-61-260-6333

World Wide Web

<http://www.dekker.com>

The publisher offers discounts on this book when ordered in bulk quantities. For more information, write to Special Sales/Professional Marketing at the headquarters address above.

Copyright © 2003 by Marcel Dekker, Inc. All Rights Reserved.

Neither this book nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming, and recording, or by any information storage and retrieval system, without permission in writing from the publisher.

Current printing (last digit):

10 9 8 7 6 5 4 3 2 1

PRINTED IN UNITED STATES OF AMERICA

Contents

Series Introduction

Preface

- 1 Introduction
 - 1.1 Introduction
 - 1.2 Introduction to Control Systems
 - 1.3 Definitions
 - 1.4 Historical Background
 - 1.5 Digital Control Development
 - 1.6 Mathematical Background
 - 1.7 The Engineering Control Problem
 - 1.8 Computer Literacy
 - 1.9 Outline of Text

- 2 Writing System Equations
 - 2.1 Introduction
 - 2.2 Electric Circuits and Components
 - 2.3 State Concepts
 - 2.4 Transfer Function and Block Diagram
 - 2.5 Mechanical Translation Systems
 - 2.6 Analogous Circuits
 - 2.7 Mechanical Rotational Systems

- 2.8 Effective Moment of Inertia and Damping of a Gear Train
 - 2.9 Thermal Systems
 - 2.10 Hydraulic Linear Actuator
 - 2.11 Liquid-Level System
 - 2.12 Rotating Power Amplifiers
 - 2.13 DC Servomotor
 - 2.14 AC Servomotor
 - 2.15 Lagrange's Equation
 - 2.16 Summary
- 3 Solution of Differential Equations
- 3.1 Introduction
 - 3.2 Standard Inputs to Control Systems
 - 3.3 Steady-State Response: Sinusoidal Input
 - 3.4 Steady-State Response: Polynomial Input
 - 3.5 Transient Response: Classical Method
 - 3.6 Definition of Time Constant
 - 3.7 Example: Second-Order System—Mechanical
 - 3.8 Example: Second-Order System—Electrical
 - 3.9 Second-Order Transients
 - 3.10 Time-Response Specifications
 - 3.11 CAD Accuracy Checks (CADAC)
 - 3.12 State-Variable Equations
 - 3.13 Characteristic Values
 - 3.14 Evaluating the State Transition Matrix
 - 3.15 Complete Solution of the State Equation
 - 3.16 Summary
- 4 Laplace Transform
- 4.1 Introduction
 - 4.2 Definition of the Laplace Transform
 - 4.3 Derivation of Laplace Transforms of Simple Functions
 - 4.4 Laplace Transform Theorems
 - 4.5 CAD Accuracy Checks: CADAC
 - 4.6 Application of the Laplace Transform to Differential Equations
 - 4.7 Inverse Transformation
 - 4.8 Heaviside Partial-Fraction Expansion Theorems
 - 4.9 MATLAB Partial-Fraction Example
 - 4.10 Partial-Fraction Shortcuts
 - 4.11 Graphical Interpretation of Partial-Fraction Coefficients

- 4.12 Frequency Response from the Pole-Zero Diagram
- 4.13 Location of Poles and Stability
- 4.14 Laplace Transform of the Impulse Function
- 4.15 Second-Order System with Impulse Excitation
- 4.16 Solution of State Equation
- 4.17 Evaluation of the Transfer-Function Matrix
- 4.18 MATLAB m-File for MIMO Systems
- 4.19 Summary

- 5 System Representation
 - 5.1 Introduction
 - 5.2 Block Diagrams
 - 5.3 Determination of the Overall Transfer Function
 - 5.4 Standard Block Diagram Terminology
 - 5.5 Position Control System
 - 5.6 Simulation Diagrams
 - 5.7 Signal Flow Graphs
 - 5.8 State Transition Signal Flow Graph
 - 5.9 Parallel State Diagrams from Transfer Functions
 - 5.10 Diagonalizing the A Matrix
 - 5.11 Use of State Transformation for the State Equation Solution
 - 5.12 Transforming a Matrix with Complex Eigenvalues
 - 5.13 Transforming an A Matrix into Companion Form
 - 5.14 Using MATLAB to Obtain the Companion A Matrix
 - 5.15 Summary

- 6 Control-System Characteristics
 - 6.1 Introduction
 - 6.2 Routh's Stability Criterion
 - 6.3 Mathematical and Physical Forms
 - 6.4 Feedback System Types
 - 6.5 Analysis of System Types
 - 6.6 Example: Type 2 System
 - 6.7 Steady-State Error Coefficients
 - 6.8 CAD Accuracy Checks: CADAC
 - 6.9 Use of Steady-State Error Coefficients
 - 6.10 Nonunity-Feedback System
 - 6.11 Summary

- 7 Root Locus
 - 7.1 Introduction
 - 7.2 Plotting Roots of a Characteristic Equation
 - 7.3 Qualitative Analysis of the Root Locus
 - 7.4 Procedure Outline
 - 7.5 Open-Loop Transfer Function
 - 7.6 Poles of the Control Ration $C(s)/R(s)$
 - 7.7 Application of the Magnitude and Angle Conditions
 - 7.8 Geometrical Properties (Construction Rules)
 - 7.9 CAD Accuracy Checks (CADAC)
 - 7.10 Root Locus Example
 - 7.11 Example of Section 7.10: MATLAB Root Locus
 - 7.12 Root Locus Example with an RH Plane Zero
 - 7.13 Performance Characteristics
 - 7.14 Transport Lag
 - 7.15 Synthesis
 - 7.16 Summary of Root-Locus Construction Rules for Negative Feedback
 - 7.17 Summary

- 8 Frequency Response
 - 8.1 Introduction
 - 8.2 Correlation of the Sinusoidal and Time Response
 - 8.3 Frequency-Response Curves
 - 8.4 Bode Plots (Logarithmic Plots)
 - 8.5 General Frequency-Transfer-Function Relationships
 - 8.6 Drawing the Bode Plots
 - 8.7 Example of Drawing a Bode Plot
 - 8.8 Generation of MATLAB Bode Plots
 - 8.9 System Type and Gain as Related to Log Magnitude Curves
 - 8.10 CAD Accuracy Checks (CADAC)
 - 8.11 Experimental Determination of Transfer Function
 - 8.12 Direct Polar Plots
 - 8.13 Summary: Direct Polar Plots
 - 8.14 Nyquist's Stability Criterion
 - 8.15 Examples of Nyquist's Criterion Using Direct Polar Plot
 - 8.16 Nyquist's Stability Criterion Applied to System Having Dead Time
 - 8.17 Definitions of Phase Margin and Gain Margin and Their Relation to Stability

- 8.18 Stability Characteristics of the Log Magnitude and Phase Diagram
 - 8.19 Stability from the Nichols Plot (Log Magnitude–Angle Diagram)
 - 8.20 Summary
- 9 Closed-Loop Tracking Performance Based on the Frequency Response
- 9.1 Introduction
 - 9.2 Direct Polar Plot
 - 9.3 Determination of M_m and ω_m for a Simple Second-Order System
 - 9.4 Correlation of Sinusoidal and Time Responses
 - 9.5 Constant $M(\omega)$ and $\alpha(\omega)$ Contours of $C(j\omega)/R(j\omega)$ on the Complex Plane (Direct Plot)
 - 9.6 Constant $1/M$ and α Contours (Unity Feedback) in the Inverse Polar Plane
 - 9.7 Gain Adjustment of a Unity-Feedback System for a Desired M_m : Direct Polar Plot
 - 9.8 Constant M and α Curves on the Log Magnitude–Angle Diagram (Nichols Chart)
 - 9.9 Generation of MATLAB Bode and Nyquist Plots
 - 9.10 Adjustment of Gain by Use of the Log Magnitude–Angle Diagram (Nichols Chart)
 - 9.11 Correlation of Pole-Zero Diagram with Frequency and Time Responses
 - 9.12 Summary
- 10 Root-Locus Compensation: Design
- 10.1 Introduction to Design
 - 10.2 Transient Response: Dominant Complex Poles
 - 10.3 Additional Significant Poles
 - 10.4 Root-Locus Design Considerations
 - 10.5 Reshaping the Root Locus
 - 10.6 CAD Accuracy Checks (CADAC)
 - 10.7 Ideal Integral Cascade Compensation (PI Controller)
 - 10.8 Cascade Lag Compensation Design Using Passive Elements
 - 10.9 Ideal Derivative Cascade Compensation (PD Controller)
 - 10.10 Lead Compensation Design Using Passive Elements

- 10.11 General Lead-Compensator Design
 - 10.12 Lag-Lead Cascade Compensation Design
 - 10.13 Comparison of Cascade Compensators
 - 10.14 PID Controller
 - 10.15 Introduction to Feedback Compensation
 - 10.16 Feedback Compensation: Design Procedures
 - 10.17 Simplified Rate Feedback Compensation:
A Design Approach
 - 10.18 Design of Rate Feedback
 - 10.19 Design: Feedback of Second Derivative of Output
 - 10.20 Results of Feedback Compensation Design
 - 10.21 Rate Feedback: Plants with Dominant
Complex Poles
 - 10.22 Summary
- 11 Frequency-Response Compensation Design
 - 11.1 Introduction to Feedback Compensation Design
 - 11.2 Selection of a Cascade Compensator
 - 11.3 Cascade Lag Compensator
 - 11.4 Design Example: Cascade Lag Compensation
 - 11.5 Cascade Lead Compensator
 - 11.6 Design Example: Cascade Lead Compensation
 - 11.7 Cascade Lag-Lead Compensator
 - 11.8 Design Example: Cascade Lag-Lead Compensation
 - 11.9 Feedback Compensation Design Using Log Plots
 - 11.10 Design Example: Feedback Compensation (Log Plots)
 - 11.11 Application Guidelines: Basic Minor-Loop
Feedback Compensators
 - 11.12 Summary
- 12 Control-Ratio Modeling
 - 12.1 Introduction
 - 12.2 Modeling a Desired Tracking Control Ratio
 - 12.3 Guillemin-Truxal Design Procedure
 - 12.4 Introduction to Disturbance Rejection
 - 12.5 A Second-Order Disturbance-Rejection Model
 - 12.6 Disturbance-Rejection Design Principles
for SISO Systems
 - 12.7 Disturbance-Rejection Design Example
 - 12.8 Disturbance-Rejection Models
 - 12.9 Summary

- 13 Design: Closed-Loop Pole-Zero Assignment (State-Variable Feedback)
 - 13.1 Introduction
 - 13.2 Controllability and Observability
 - 13.3 State Feedback for SISO Systems
 - 13.4 State-Feedback Design for SISO Systems Using the Control Canonical (Phase-Variable) Form
 - 13.5 State-Variable Feedback (Physical Variables)
 - 13.6 General Properties of State Feedback (Using Phase Variables)
 - 13.7 State-Variable Feedback: Steady-State Error Analysis
 - 13.8 Use of Steady-State Error Coefficients
 - 13.9 State-Variable Feedback: All-Pole Plant
 - 13.10 Plants with Complex Poles
 - 13.11 Compensator Containing a Zero
 - 13.12 State-Variable Feedback: Pole-Zero Plant
 - 13.13 Observers
 - 13.14 Control Systems Containing Observers
 - 13.15 Summary

- 14 Parameter Sensitivity and State-Space Trajectories
 - 14.1 Introduction
 - 14.2 Sensitivity
 - 14.3 Sensitivity Analysis
 - 14.4 Sensitivity Analysis Examples
 - 14.5 Parameter Sensitivity Examples
 - 14.6 Inaccessible States
 - 14.7 State-Space Trajectories
 - 14.8 Linearization (Jacobian Matrix)
 - 14.9 Summary

- 15 Sampled-Data Control Systems
 - 15.1 Introduction
 - 15.2 Sampling
 - 15.3 Ideal Sampling
 - 15.4 z -Transform Theorems
 - 15.5 Differentiation Process
 - 15.6 Synthesis in the z Domain (Direct Method)
 - 15.7 The Inverse z Transform
 - 15.8 Zero-Order Hold
 - 15.9 Limitations

- 15.10 Steady-State Error Analysis for Stable Systems
- 15.11 Root-Locus Analysis for Sampled-Data Control Systems
- 15.12 Summary

- 16 Digital Control Systems
 - 16.1 Introduction
 - 16.2 Complementary Spectra
 - 16.3 Tustin Transformation: s to z Plane Transformation
 - 16.4 z -Domain to the w - and w' -Domain Transformations
 - 16.5 Digitization (DIG) Technique
 - 16.6 Digitization (DIG) Design Technique
 - 16.7 The Pseudo-Continuous-Time (PCT) Control System
 - 16.8 Design of Digital Control System
 - 16.9 Direct (DIR) Compensator
 - 16.10 PCT Lead Cascade Compensation
 - 16.11 PCT Lag Compensation
 - 16.12 PCT Lag-Lead Compensation
 - 16.13 Feedback Compensation: Tracking
 - 16.14 Controlling Unwanted Disturbances
 - 16.15 Extensive Digital Feedback Compensator Example
 - 16.16 Controller Implementation
 - 16.17 Summary

Appendix A Table of Laplace Transform Pairs

Appendix B Matrix Linear Algebra

Appendix C Introduction to MATLAB and Simulink

Appendix D TOTAL-PC CAD Package

Problems

Answers to Selected Problems