

Devendra K. Chaturvedi

Modeling
and Simulation
of Systems Using
MATLAB[®]
and Simulink[®]



CRC Press
Taylor & Francis Group

Modeling and Simulation of Systems Using MATLAB[®] and Simulink[®]

Devendra K. Chaturvedi



CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

MATLAB[®] and Simulink[®] are trademarks of the MathWorks, Inc. and are used with permission. The MathWorks does not warrant the accuracy of the text or exercises in this book. This book's use or discussion of MATLAB[®] and Simulink[®] software or related products does not constitute endorsement or sponsorship by the MathWorks of a particular pedagogical approach or particular use of the MATLAB[®] and Simulink[®] software.

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2010 by Taylor and Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number: 978-1-4398-0672-2 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

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

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>

and the CRC Press Web site at
<http://www.crcpress.com>

**Modeling
and Simulation
of Systems Using
MATLAB[®]
and Simulink[®]**

Dedicated to
The cherished memories of my guru and guide
Most Revered Dr. Makund Behari Lal Sahab
DSc (Lucknow), DSc (Edinburgh)
(1907–2002)
August Founder of Dayalbagh Educational Institute

Preface

Systems engineering has great potential for solving problems related to physical, conceptual, and esoteric systems. The power of systems engineering lies in the three R's of science, namely, reductionism, repeatability, and refutation. Reductionism recognizes the fact that any system can be decomposed into a set of components that follow the fundamental laws of physics. The diversity of the real world can be reduced into laboratory experiments, which can be validated by their repeatability, and one can make intellectual progress by the refutation of hypotheses. Due to advancements in systems engineering for handling complex systems, modeling and simulation have, of late, become popular.

Modeling and simulation are very important tools of systems engineering that have now become a central activity in all disciplines of engineering and science. Not only do they help us gain a better understanding of the functioning of the real world, they are also important for the design of new systems as they enable us to predict the system behavior before the system is actually built. Modeling and simulation also allow us to analyze systems accurately under varying operating conditions.

This book aims to provide a comprehensive, state-of-the-art coverage of all important aspects of modeling and simulation of physical as well as conceptual systems. It strives to motivate beginners in this area through the modeling of real-life examples and their simulation to gain better insights into real-world systems. The extensive references and related literature at the end of every chapter can also be referred to for further studies in the area of modeling and simulation.

This book aims to

- Provide a basic understanding of systems and their modeling and simulation
- Explain the step-by-step procedure for modeling using top-down, bottom-up, and middle-out approaches
- Develop models for complex systems and reduce their order so as to use them effectively for online applications
- Present the simulation code in MATLAB®/Simulink® for gaining quick and useful insights into real-world systems
- Apply soft computing techniques for modeling nonlinear, ill-defined, and complex systems

The book will serve as a primary text for a variety of courses. It can be used as a first course in modeling and simulation at the junior, the senior, or the graduate levels in engineering, manufacturing, business, or computer science (Chapters 1 through 3, 5, and 8), providing a broad idea about modeling and simulation. At the end of such a course, the student would be prepared to carry out complete and effective simulation studies, and to take advanced modeling and simulation courses.

This book will also serve as a second course for more advanced studies in modeling and simulation for graduate students (Chapters 6 through 11) in any of the above disciplines. After completing this course, the student should be able to comprehend and conduct simulation research.

Finally, this book will serve as an introduction to simulation as part of a general course in operations research or management science (Chapters 1 through 3 and 6 through 8, Chapter 12).

Organization of the Book

Early chapters deal with the introduction of systems and includes concepts and their underlying philosophy; step-by-step procedures for the modeling of different types of systems using appropriate modeling techniques such as the graph-theoretic approach, interpretive structural modeling, and system dynamics modeling, are also discussed.

Focus then moves to the state of the art of simulation and how simulation evolved from the pre-computer days into the modern science of today. In this part, MATLAB/Simulink programs are developed for system simulation.

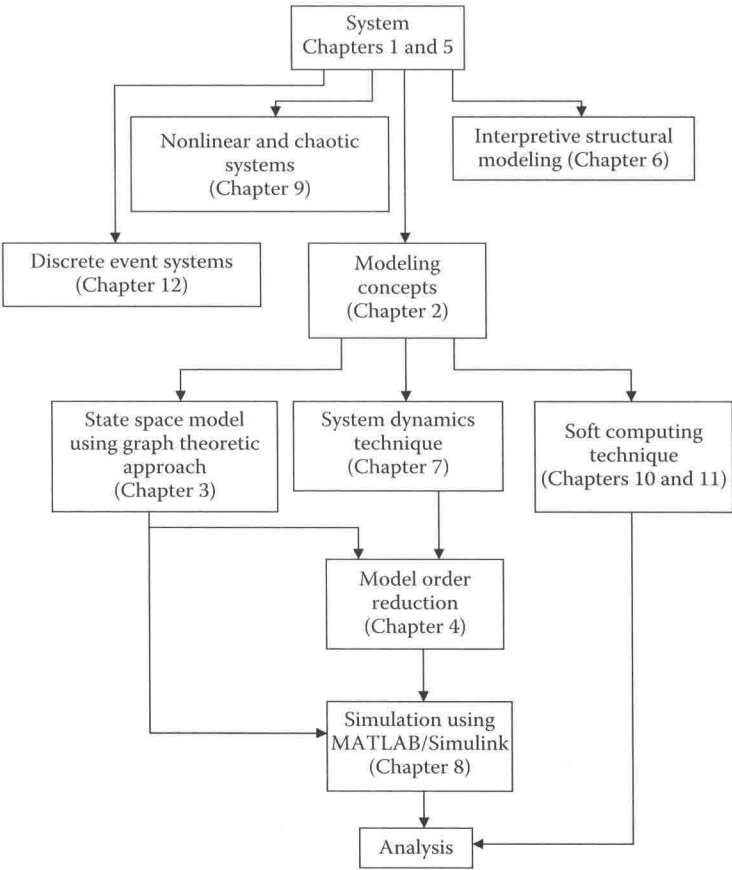


FIGURE P1
Schematic outline of the book.

We then take a fresh look at modern soft computing techniques (such as artificial neural networks [ANN], fuzzy systems, and genetic algorithms, or their combinations) for the modeling and simulation of complex and nonlinear systems.

Finally, chapters address the discrete systems modeling. The schematic outline of this book is shown in Figure P1.

Software Background

The key to the successful application of modeling and simulation techniques depends on the effective use of their software. For this, it is necessary that the student be familiar with their fundamentals. In this book, MATLAB/Simulink programming software are used. Appendix B provides some background information on MATLAB/Simulink. The MATLAB programs included in this book are easier to understand than the programs written in other programming languages such as C/C++.

MATLAB® is a registered trademark of The MathWorks, Inc. For product information, please contact:

The MathWorks, Inc.

3 Apple Hill Drive

Natick, MA 01760-2098 USA

Tel: 508 647 7000

Fax: 508-647-7001

E-mail: info@mathworks.com

Web: www.mathworks.com

Acknowledgments

I express my profound and grateful veneration to Prof. P. S. Satsangi, chairman, advisory committee on education in the Dayalbagh Educational Institute, Agra, Uttar Pradesh, India. Prof. Satsangi taught me modeling and simulation methodologies, and software engineering at the postgraduate (MTech) level and guided me during my MTech and PhD in the area of modeling and simulation. He is the fountain source of my inspiration and intuition in this area. I thank him with due reverence. I am also thankful to Prof. P. K. Kalra, Indian Institute of Technology, Kanpur, India, for the encouragement, support, and visionary ideas he provided during my research. I am very deeply indebted to Prof. O. P. Malik, University of Calgary, Alberta, Canada, for providing all the facilities in his laboratory to pursue my experimental work on modeling and control during my BOYSCAST (Better Opportunities for Young Scientists in Chosen Areas of Science and Technology) fellowship, offered by the Department of Science and Technology, Government of India, during 2001–2002, and, later, in the summer of 2005 and 2007.

I wish to express my deep gratitude to Prof. Helmut Röck and Prof. Anand Srivastava, Universitäre Zu Kiel, Kiel, Germany, and to Prof. Chaudhary, Imperial College London, United Kingdom, for providing all the facilities and help during my visit to these institutions in the summer of 2007.

I would also like to thank Prof. Westwick and Garwin Hancock, University of Calgary, Alberta, Canada; Prof. P.H. Roe, system design engineering, and Prof. Shesha Jayaram, High Voltage Lab, University of Waterloo, Ontario, Canada; and S. Krishnananda at the Dayalbagh Educational Institute, Agra, Uttar Pradesh, India, for their good wishes and help extended during the preparation of this book. Thanks are also due to my colleagues Anand Sinha, Gaurav Rana, Himanshu Vijay, and Ashish Chandiok for all their help.

I am thankful to Jessica Vakili and Amber Donley, project coordinators; Nora Konopka, publisher of engineering and environmental science books; and other team members from Taylor & Francis who directly or indirectly helped in realizing this book.

Finally, I am grateful to my wife, Dr. Lajwanti, and my daughters, Jyoti and Swati, who had to endure many inconveniences during the course of writing this book.

I also express my deepest gratitude to many, not mentioned here, for their support in countless ways when this book was written.

Devendra K. Chaturvedi

*Dayalbagh Educational Institute (Deemed University)
Agra, Uttar Pradesh, India*

Author



Devendra K. Chaturvedi was born in Madhya Pradesh, India, on August 3, 1967. He graduated in electrical engineering from the Government Engineering College, Ujjain, Madhya Pradesh, India in 1988, and did his MTech in engineering systems and management in 1993. He then pursued his PhD in electrical power systems in 1998 from the Dayalbagh Educational Institute (Deemed University), Agra, India. Currently, he is working as a professor in the Department of Electrical Engineering, Dayalbagh Educational Institute (Deemed University). He has won several awards and recognition including the President's

Gold Medal and the Director's Medal of the Dayalbagh Educational Institute (Deemed University) in 1993, the Tata Rao Medal in 1994, the Dr. P. S. Nigam U.P. State Power Sector Award in 2005 and 2007, the Musaddi Lal Memorial Award in 2007, and the institutional prize award in 2005 from the Institution of Engineers, India. He was awarded a BOYSCAST fellowship of the Department of Science and Technology, Government of India, in 2001.

He is a regular visiting fellow at the University of Calgary, Alberta, Canada. He has many national and international research collaborations in the area of modeling and simulations, soft computing, intelligent adaptive control systems, and optimization. He has also organized many short-term courses in the area of modeling and simulation of systems, and fuzzy systems and its applications. He serves as a consultant at the Aerial Delivery Research and Development Establishment, Agra, and at the Defense Research and Development Organisation (DRDO) lab, Government of India. He has organized many national seminars and workshops on theology; ethics, values, and social service; professional ethics; ethics, agriculture, and religion; the relationship between religion and the future of mankind; and the teachings of the *Bhagavad Gita* and the religions of saints.

He has authored a book, *Soft Computing and Its Applications to Electrical Engineering*, published by Springer, Germany (2008). He has also edited a book, *Theology, Science, and Technology: Ethics and Moral Values*, published by Vikas Publishing House, Delhi (2005).

His name is included in the *Marquis Who's Who in Engineering and Science in Asia* (2006–2007), the *Marquis Who's Who in Engineering and Science in America* (2006–2007), and the *Marquis Who's Who in World* (2006–2007). He is a fellow of the Institution of Engineers, India, and a member of many professional bodies such as the IEEE, the IEE, the Indian Society for Technical Education (ISTE), the Indian Society of Continuing Engineering Education (ISCEE), the Aeronautical Society of India, and the System Society of India.

Contents

Preface..... xvii

Acknowledgments xxi

Author..... xxiii

1. Introduction to Systems 1

 1.1 System 1

 1.1.1 System Boundary 3

 1.1.2 System Components and Their Interactions..... 3

 1.1.3 Environment..... 4

 1.2 Classification of Systems 5

 1.2.1 According to the Time Frame 5

 1.2.2 According to the Complexity of the System 6

 1.2.3 According to the Interactions..... 6

 1.2.4 According to the Nature and Type of Components..... 7

 1.2.5 According to the Uncertainties Involved 7

 1.2.5.1 Static vs. Dynamic Systems 8

 1.2.5.2 Linear vs. Nonlinear Systems 8

 1.3 Linear Systems..... 9

 1.3.1 Superposition Theorem..... 9

 1.3.2 Homogeneity 10

 1.3.3 Mathematical Viewpoint of a Linear System..... 10

 1.3.3.1 Linear Differential Equation..... 10

 1.3.3.2 Nonlinear Differential Equations 11

 1.4 Time-Varying vs. Time-Invariant Systems 12

 1.5 Lumped vs. Distributed Parameter Systems..... 13

 1.6 Continuous-Time and Discrete-Time Systems..... 13

 1.7 Deterministic vs. Stochastic Systems 15

 1.7.1 Complexity of Systems..... 15

 1.8 Hard and Soft Systems 16

 1.9 Analysis of Systems 18

 1.10 Synthesis of Systems..... 18

 1.11 Introduction to System Philosophy 18

 1.11.1 Method of Science..... 20

 1.11.1.1 Reductionism 20

 1.11.1.2 Repeatability 20

 1.11.1.3 Refutation 20

 1.11.2 Problems of Science and Emergence of System..... 20

 1.12 System Thinking 21

 1.13 Large and Complex Applied System Engineering:
 A Generic Modeling 24

 1.14 Review Questions 29

 1.15 Bibliographical Notes 30

- 2. Systems Modeling 31
 - 2.1 Introduction 31
 - 2.2 Need of System Modeling..... 33
 - 2.3 Modeling Methods for Complex Systems 34
 - 2.4 Classification of Models 35
 - 2.4.1 Physical vs. Abstract Model 35
 - 2.4.2 Mathematical vs. Descriptive Model 36
 - 2.4.3 Static vs. Dynamic Model 37
 - 2.4.4 Steady State vs. Transient Model 37
 - 2.4.5 Open vs. Feedback Model..... 37
 - 2.4.6 Deterministic vs. Stochastic Models 37
 - 2.4.7 Continuous vs. Discrete Models..... 37
 - 2.5 Characteristics of Models..... 38
 - 2.6 Modeling 38
 - 2.6.1 Fundamental Axiom (Modeling Hypothesis) 40
 - 2.6.2 Component Postulate (First Postulate) 40
 - 2.6.3 Model Evaluation 41
 - 2.6.4 Generic Description of Two-Terminal Components..... 41
 - 2.6.4.1 Dissipater Type Components 41
 - 2.6.4.2 Delay Type Elements 42
 - 2.6.4.3 Accumulator Type..... 42
 - 2.6.4.4 Sources or Drivers..... 43
 - 2.7 Mathematical Modeling of Physical Systems 43
 - 2.7.1 Modeling of Mechanical Systems..... 46
 - 2.7.1.1 Translational Mechanical Systems..... 47
 - 2.7.1.2 Rotational Mechanical Systems 64
 - 2.7.2 Modeling of Electrical Systems..... 78
 - 2.7.3 Modeling of Electromechanical Systems 84
 - 2.7.4 Modeling of Fluid Systems 87
 - 2.7.4.1 Hydraulic Systems 87
 - 2.7.5 Modeling of Thermal Systems 92
 - 2.8 Review Questions 99
 - 2.9 Bibliographical Notes 102
- 3. Formulation of State Space Model of Systems 103
 - 3.1 Physical Systems Theory 103
 - 3.2 System Components and Interconnections..... 103
 - 3.3 Computation of Parameters of a Component 105
 - 3.4 Single Port and Multiport Systems 109
 - 3.4.1 Linear Perfect Couplers..... 110
 - 3.4.2 Summary of Two-Terminal and Multiterminal Components..... 113
 - 3.4.3 Multiterminal Components..... 113
 - 3.5 Techniques of System Analysis..... 114
 - 3.5.1 Lagrangian Technique 115
 - 3.5.2 Free Body Diagram Method..... 115
 - 3.5.3 Linear Graph Theoretic Approach 115
 - 3.6 Basics of Linear Graph Theoretic Approach 116

3.7	Formulation of System Model for Conceptual System	119
3.7.1	Fundamental Axioms.....	121
3.7.2	Component Postulate	121
3.7.3	System Postulate	121
3.7.3.1	Cutset Postulate	122
3.7.3.2	Circuit Postulate	124
3.8	Formulation of System Model for Physical Systems	127
3.9	Topological Restrictions	131
3.9.1	Perfect Coupler	131
3.9.2	Gyrator.....	131
3.9.3	Short Circuit Element ("A" Type)	132
3.9.4	Open Circuit Element ("B" Type)	132
3.9.5	Dissipater Type Elements	132
3.9.6	Delay Type Elements	132
3.9.7	Accumulator Type Elements	132
3.9.8	Across Drivers	133
3.9.9	Through Drivers	133
3.10	Development of State Model of Degenerative System	144
3.10.1	Development of State Model for Degenerate System.....	146
3.10.2	Symbolic Formulation of State Model for Nondegenerative Systems	151
3.10.3	State Model of System with Multiterminal Components.....	157
3.10.4	State Model for Systems with Time Varying and Nonlinear Components.....	162
3.11	Solution of State Equations	166
3.12	Controllability	180
3.13	Observability	181
3.14	Sensitivity	182
3.15	Liapunov Stability	184
3.16	Performance Characteristics of Linear Time Invariant Systems.....	186
3.17	Formulation of State Space Model Using Computer Program (SYSMO)	187
3.17.1	Preparation of the Input Data	187
3.17.2	Algorithm for the Formulation of State Equations	187
3.18	Review Questions	208
3.19	Bibliographical Notes	217
4.	Model Order Reduction.....	219
4.1	Introduction	219
4.2	Difference between Model Simplification and Model Order Reduction	220
4.3	Need for Model Order Reduction.....	221
4.4	Principle of Model Order Reduction	221
4.5	Methods of Model Order Reduction	223
4.5.1	Time Domain Simplification Techniques	223
4.5.1.1	Dominant Eigenvalue Approach	223
4.5.1.2	Aggregation Method.....	228
4.5.1.3	Subspace Projection Method	232
4.5.1.4	Optimal Order Reduction.....	233
4.5.1.5	Hankel Matrix Approach.....	233
4.5.1.6	Hankel-Norm Model Order Reduction.....	234

4.5.2	Model Order Reduction in Frequency Domain	234
4.5.2.1	Pade Approximation Method	234
4.5.2.2	Continued Fraction Expansion.....	235
4.5.2.3	Moment-Matching Method.....	235
4.5.2.4	Balanced Realization-Based Reduction Method	236
4.5.2.5	Balanced Truncation	238
4.5.2.6	Frequency-Weighted Balanced Model Reduction	244
4.5.2.7	Time Moment Matching.....	249
4.5.2.8	Continued Fraction Expansion.....	252
4.5.2.9	Model Order Reduction Based on the Routh Stability Criterion.....	259
4.5.2.10	Differentiation Method for Model Order Reduction.....	263
4.6	Applications of Reduced-Order Models	273
4.7	Review Questions	273
4.8	Bibliographical Notes	275
5.	Analogous of Linear Systems	277
5.1	Introduction	277
5.1.1	D'Alembert's Principle	277
5.2	Force–Voltage (f – v) Analogy	278
5.2.1	Rule for Drawing f – v Analogous Electrical Circuits.....	278
5.3	Force–Current (f – i) Analogy.....	279
5.3.1	Rule for Drawing f – i Analogous Electrical Circuits.....	279
5.4	Review Questions	298
6.	Interpretive Structural Modeling	301
6.1	Introduction	301
6.2	Graph Theory.....	301
6.2.1	Net.....	305
6.2.2	Loop	305
6.2.3	Cycle.....	305
6.2.4	Parallel Lines	306
6.2.5	Properties of Relations	306
6.3	Interpretive Structural Modeling	307
6.4	Review Questions	323
6.5	Bibliographical Notes	325
7.	System Dynamics Techniques	327
7.1	Introduction	327
7.2	System Dynamics of Managerial and Socioeconomic System	327
7.2.1	Counterintuitive Nature of System Dynamics.....	327
7.2.2	Nonlinearity	328
7.2.3	Dynamics	328
7.2.4	Causality	328
7.2.5	Endogenous Behavior	328
7.3	Traditional Management.....	328
7.3.1	Strength of the Human Mind	328
7.3.2	Limitation of the Human Mind	328

7.4	Sources of Information.....	329
7.4.1	Mental Database.....	329
7.4.2	Written/Spoken Database	330
7.4.3	Numerical Database	330
7.5	Strength of System Dynamics	331
7.6	Experimental Approach to System Analysis	332
7.7	System Dynamics Technique	332
7.8	Structure of a System Dynamic Model.....	333
7.9	Basic Structure of System Dynamics Models	334
7.9.1	Level Variables	334
7.9.2	Flow-Rate Variables	334
7.9.3	Decision Function	335
7.10	Different Types of Equations Used in System Dynamics Techniques	342
7.10.1	Level Equation.....	342
7.10.2	Rate Equation (Decision Functions).....	343
7.10.3	Auxiliary Equations	343
7.11	Symbol Used in Flow Diagrams	344
7.11.1	Levels.....	344
7.11.2	Source and Sinks.....	345
7.11.3	Information Takeoff.....	345
7.11.4	Auxiliary Variables.....	345
7.11.5	Parameters (Constants)	345
7.12	Dynamo Equations	345
7.13	Modeling and Simulation of Parachute Deceleration Device.....	376
7.13.1	Parachute Inflation.....	377
7.13.2	Canopy Stress Distribution	378
7.13.3	Modeling and Simulation of Parachute Trajectory	378
7.14	Modeling of Heat Generated in a Parachute during Deployment.....	382
7.14.1	Dynamo Equations.....	384
7.15	Modeling of Stanchion System of Aircraft Arrestor Barrier System	385
7.15.1	Modeling and Simulation of Forces Acting on Stanchion System Using System Dynamic Technique.....	387
7.15.2	Dynamic Model	389
7.15.3	Results	390
7.16	Review Questions	395
7.17	Bibliographical Notes	399
8.	Simulation.....	401
8.1	Introduction	401
8.2	Advantages of Simulation.....	402
8.3	When to Use Simulations.....	403
8.4	Simulation Provides.....	403
8.5	How Simulations Improve Analysis and Decision Making?	404
8.6	Application of Simulation.....	404
8.7	Numerical Methods for Simulation.....	405
8.7.1	The Rectangle Rule.....	406
8.7.2	The Trapezoid and Tangent Formulae.....	406
8.7.3	Simpson’s Rule	407
8.7.4	One-Step Euler’s Method.....	410

- 8.7.5 Runge–Kutta Methods of Integration..... 410
 - 8.7.5.1 Physical Interpretation 411
 - 8.7.6 Runge–Kutta Fourth-Order Method..... 411
 - 8.7.7 Adams–Bashforth Predictor Method..... 412
 - 8.7.8 Adams–Moulton Corrector Method 413
- 8.8 The Characteristics of Numerical Methods 413
- 8.9 Comparison of Different Numerical Methods 413
- 8.10 Errors during Simulation with Numerical Methods 414
 - 8.10.1 Truncation Error..... 414
 - 8.10.2 Round Off Error 415
 - 8.10.3 Step Size vs. Error 418
 - 8.10.4 Discretization Error 418
- 8.11 Review Questions 430
- 9. Nonlinear and Chaotic System 433**
 - 9.1 Introduction 433
 - 9.2 Linear vs. Nonlinear System 434
 - 9.3 Types of Nonlinearities 434
 - 9.4 Nonlinearities in Flight Control of Aircraft..... 435
 - 9.4.1 Basic Control Surfaces Used in Aircraft Maneuvers 435
 - 9.4.2 Principle of Flight Controls 435
 - 9.4.3 Components Used in Pitch Control..... 437
 - 9.4.4 Modeling of Various Components of Pitch Control System..... 438
 - 9.4.5 Simulink Model of Pitch Control in Flight..... 440
 - 9.4.5.1 Simulink Model of Pitch Control in Flight Using Nonlinearities 440
 - 9.4.6 Study of Effects of Different Nonlinearities on Behavior of the Pitch Control Model 440
 - 9.4.6.1 Effects of Dead-Zone Nonlinearities 440
 - 9.4.6.2 Effects of Saturation Nonlinearities 441
 - 9.4.6.3 Effects of Backlash Nonlinearities 442
 - 9.4.6.4 Cumulative Effects of Backlash, Saturation, Dead-Zone Nonlinearities 443
 - 9.4.7 Designing a PID Controller for Pitch Control in Flight 445
 - 9.4.7.1 Designing a PID Controller for Pitch Control in Flight with the Help of Root Locus Method (Feedback Compensation)..... 445
 - 9.4.7.2 Designing a PID Controller (Connected in Cascade with the System) for Pitch Control in Flight..... 454
 - 9.4.7.3 Design of P, I, D, PD, PI, PID, and Fuzzy Controllers..... 456
 - 9.4.8 Design of Fuzzy Controller 461
 - 9.4.8.1 Basic Structure of a Fuzzy Controller 462
 - 9.4.8.2 The Components of a Fuzzy System 462
 - 9.4.9 Tuning Fuzzy Controller 469
 - 9.5 Conclusions..... 473
 - 9.6 Introduction to Chaotic System 478
 - 9.6.1 General Meaning 478
 - 9.6.2 Scientific Meaning 478
 - 9.6.3 Definition 479

9.7	Historical Prospective	481
9.8	First-Order Continuous-Time System	484
9.9	Bifurcations	487
9.9.1	Saddle Node Bifurcation.....	488
9.9.2	Transcritical Bifurcation	488
9.9.3	Pitchfork Bifurcation	490
9.9.3.1	Supercritical Pitchfork Bifurcation	490
9.9.4	Catastrophes	492
9.9.4.1	Globally Attracting Point for Stability	492
9.10	Second-Order System	493
9.11	Third-Order System.....	496
9.11.1	Lorenz Equation: A Chaotic Water Wheel	498
9.12	Review Questions	501
9.13	Bibliographical Notes	501
10.	Modeling with Artificial Neural Network	503
10.1	Introduction	503
10.1.1	Biological Neuron	503
10.1.2	Artificial Neuron.....	504
10.2	Artificial Neural Networks.....	505
10.2.1	Training Phase.....	505
10.2.1.1	Selection of Neuron Characteristics	505
10.2.1.2	Selection of Topology.....	505
10.2.1.3	Error Minimization Process	506
10.2.1.4	Selection of Training Pattern and Preprocessing	506
10.2.1.5	Stopping Criteria of Training	506
10.2.2	Testing Phase.....	506
10.2.2.1	ANN Model.....	506
10.2.2.2	Building ANN Model.....	508
10.2.2.3	Backpropagation.....	509
10.2.2.4	Training Algorithm.....	509
10.2.2.5	Applications of Neural Network Modeling	510
10.3	Review Questions	526
11.	Modeling Using Fuzzy Systems	527
11.1	Introduction	527
11.2	Fuzzy Sets	528
11.3	Features of Fuzzy Sets.....	531
11.4	Operations on Fuzzy Sets	532
11.4.1	Fuzzy Intersection	532
11.4.2	Fuzzy Union	532
11.4.3	Fuzzy Complement.....	532
11.4.4	Fuzzy Concentration	533
11.4.5	Fuzzy Dilation.....	534
11.4.6	Fuzzy Intensification	535
11.4.7	Bounded Sum	536
11.4.8	Strong α -Cut	537
11.4.9	Linguistic Hedges.....	538
11.5	Characteristics of Fuzzy Sets.....	540