Introduction to

MECHATRONICS

and Measurement Systems

Michael B. Histand ▪ David G. Alciatore

INTRODUCTION TO MECHATRONICS AND MEASUREMENT SYSTEMS

Michael B. Histand
and
David G. Alciatore

Department of Mechanical Engineering
Colorado State University

WCB McGraw-Hill

Boston Burr Ridge, IL Dubuque, IA Madison, WI
New York San Francisco St. Louis
Bangkok Bogotá Caracas Lisbon London Madrid Mexico City
Milan New Delhi Seoul Singapore Sydney Taipei Toronto

WCB/McGraw-Hill

A Division of The ***McGraw·Hill*** *Companies*

INTRODUCTION TO MECHATRONICS AND MEASURMENT SYSTEMS

This book is printed on acid-free paper.

4 5 6 7 8 9 0 DOC / DOC 3 2 1

ISBN 0-07-029089-X

Vice president and editorial director: *Kevin T. Kane*
Publisher: *Tom Casson*
Senior sponsoring editor: *Debra Riegert*
Marketing manager: *John T. Wannemacher*
Project manager: *Jim Labeots*
Production supervisor: *Scott M. Hamilton*
Freelance design coordinator: *Laurie J. Entringer*
Cover design: *Z-Graphics*
Photo research coordinator: *Sharon Miller*
Supplement coordinator: *Linda Huenecke*
Compositor: *Lachina Publishing Services*
Typeface: *10/12 Times Roman*
Printer: *R.R. Donnelley & Sons Company*

Library of Congress Cataloging-in-publication Data

Histand, Michael B.
Introduction to mechatronics and measurement systems / Michael B. Histand, David G. Alciatore.
p. cm.
Includes index.
ISBN 0-07-029089-X
1. Mechatronics. 2. Measuring instruments. I. Alciatore, David G. II. Title.
TJ163.12.H57 1998
621--dc21 98-6438

http://www.mhhe.com

McGraw-Hill Series in Mechanical Engineering

Consulting Editors

Jack P. Holman, Southern Methodist University

John R. Lloyd, Michigan State University

Anderson: *Computational Fluid Dynamics: The Basics with Applications*
Anderson: *Modern Compressible Flow: With Historical Perspective*
Arora: *Introduction to Optimum Design*
Borman and Ragland: *Combustion Engineering*
Burton: *Introduction to Dynamic Systems Analysis*
Culp: *Principles of Energy Conversion*
Dieter: *Engineering Design: A Materials & Processing Approach*
Doebelin: *Engineering Experimentation: Planning, Execution, Reporting*
Driels: *Linear Control Systems Engineering*
Edwards and McKee: *Fundamentals of Mechanical Component Design*
Gebhart: *Heat Conduction and Mass Diffusion*
Gibson: *Principles of Composite Material Mechanics*
Hamrock: *Fundamentals of Fluid Film Lubrication*
Heywood: *Internal Combustion Engine Fundamentals*
Hinze: *Turbulence*
Histand and Alciatore: *Introduction to Mechatronics and Measurement Systems*
Holman: *Experimental Methods for Engineers*
Howell and Buckius: *Fundamentals of Engineering Thermodynamics*
Jaluria: *Design and Optimization of Thermal Systems*
Juvinall: *Engineering Considerations of Stress, Strain, and Strength*
Kays and Crawford: *Convective Heat and Mass Transfer*
Kelly: *Fundamentals of Mechanical Vibrations*
Kimbrell: *Kinematics Analysis and Synthesis*
Kreider and Rabl: *Heating and Cooling of Buildings*
Martin: *Kinematics and Dynamics of Machines*
Mattingly: *Elements of Gas Turbine Propulsion*
Modest: *Radiative Heat Transfer*
Norton: *Design of Machinery*
Oosthuizen and Carscallen: *Compressible Fluid Flow*
Oosthuizen and Naylor: *Introduction to Convective Heat Transfer Analysis*
Phelan: *Fundamentals of Mechanical Design*
Reddy: *An Introduction to Finite Element Method*
Rosenberg and Karnopp: *Introduction to Physical Systems Dynamics*
Schlichting: *Boundary-Layer Theory*
Shames: *Mechanics of Fluids*

Shigley: *Kinematic Analysis of Mechanisms*
Shigley and Mischke: *Mechanical Engineering Design*
Shigley and Uicker: *Theory of Machines and Mechanisms*
Stiffler: *Design with Microprocessors for Mechanical Engineers*
Stoecker and Jones: *Refrigeration and Air Conditioning*
Turns: *An Introduction to Combustion: Concepts and Applications*
Ullman: *The Mechanical Design Process*
Wark: *Advanced Thermodynamics for Engineers*
White: *Viscous Fluid Flow*
Zeid: *CAD/CAM Theory and Practice*

PREFACE

Approach

The formal boundaries of traditional engineering disciplines have become fuzzy following the advent of integrated circuits and computers. Nowhere is this more evident than in mechanical and electrical engineering, where products today include an assembly of interdependent electrical and mechanical components. The field of mechatronics has broadened the scope of the traditional field of electromechanics. Mechatronics is defined as the field of study involving the analysis, design, synthesis, and selection of systems which combine electronic and mechanical components with modern controls and microprocessors.

This book is designed to serve as a text for (1) a modern instrumentation and measurements course, (2) a hybrid electrical and mechanical engineering course replacing traditional circuits and instrumentation courses, (3) a mechatronics course, or (4) the first course in a mechatronics sequence. The second option, the hybrid course, provides an opportunity to reduce the number of credit hours in a typical mechanical engineering curriculum. Options three and four could involve the development of new interdisciplinary courses.

Currently, most curricula do not include a mechatronics course but include some of the elements in other, more traditional courses. The purpose of a course in mechatronics is to provide a focused interdisciplinary experience for undergraduates that encompasses important elements from traditional courses as well as contemporary developments in electronics and computer control. These elements include measurement theory, electronic circuits, computer interfacing, sensors, actuators, and the design, analysis, and synthesis of mechatronic systems. This approach is valuable to students since virtually every newly designed engineering product is a mechatronic system.

Content

Chapter 1 introduces mechatronics and measurement systems. Chapter 2 provides a review of basic electrical relations, circuit elements, and circuit analysis. Chapter 3 deals with semiconductor electronics. Chapter 4 presents approaches to analyzing and characterizing the response of mechatronic and measurement systems. Chapter 5 covers the basics of analog signal processing and the design and analysis of operational amplifier circuits. Chapter 6 presents the basics of digital logic and the use of integrated circuits. Chapter 6 also provides an introduction to the microprocessor and microcontroller. Chapter 7 deals with issues involved with coupling microprocessors and computers to measurement systems in order to automate data acquisition and analysis. Chapter 8 provides an overview of the many sensors common in mechatronic systems. Chapter 9 introduces a number of devices used for actuating mechatronic systems. Finally, Chapter 10 provides an overview of mechatronic system control architectures and presents some case studies. The Appendices review the fundamentals of unit systems, statistics, error analysis, and mechanics of materials to support and supplement measurement systems topics in the book. Two mechatronics topics this book does not cover directly are control theory and microprocessor programming. These topics are important and should be included in a curriculum that emphasizes mechatronics, but we decided it would be impractical to adequately cover these topics in this book.

Learning Tools

Class discussion items are included throughout the book to serve as thought-provoking exercises for the students as instructor-led cooperative learning activities in the classroom. They can also be used as out-of-class homework assignments to supplement the questions at the end of each chapter. Analysis and design examples are also provided throughout the book to improve a student's ability to apply the material. To enhance student learning, carefully designed laboratory exercises coordinated with the lectures should accompany a course using this text. The combination of class discussion items, design examples, and laboratory exercises exposes a student to a real-world practical approach and provides a useful framework for future design work.

Supplements

More information, including a recommended course outline, a typical laboratory syllabus, MathCAD files for examples from the book, and other supplemental material, is available on the Internet at:

http://www.engr.colostate.edu/~dga/mechatronics.html

An instructor guide is also available from the publisher. It includes complete solutions for all end-of-chapter problems.

ACKNOWLEDGMENTS

To ensure accuracy of this text, it has been class tested at Colorado State University for four years and at the University of Wyoming for two years. We'd like to thank all of the students at both institutions and Dave Walrath at the University of Wyoming, who have given us valuable feedback throughout this process. In addition, we'd like to thank our many manuscript reviewers for their valuable input. The reviewers included the following people in the field of mechatronics:

Ramendra P. Roy	*Arizona State University*
Charles Ume	*Georgia Institute of Technology*
Jawarharlal Mariappan	*GMI Engineering and Management Institute*
Melvin R. Corley	*Louisiana Tech University*
Donald G. Morin	*Rose-Hulman Institute of Technology*
J. Edward Carryer	*Stanford University*
Ahmad Smaili	*Tennessee Technological University*
Louis Everett	*Texas A&M University*
Gregory P. Starr	*University of New Mexico*
David E. Walrath	*University of Wyoming*

CONTENTS

1 Introduction to Mechatronics and Measurement Systems 1

1.1 Introduction to Mechatronics 1

1.2 Introduction to Measurement Systems 3

2 Electric Circuits and Components 6

2.1 Introduction 6

2.2 The Basic Electrical Elements 8

2.2.1 The Resistor / 2.2.2 The Capacitor / 2.2.3 The Inductor

2.3 Kirchoff's Laws 16

2.3.1 Series Resistance Circuit / 2.3.2 Parallel Resistance Circuit

2.4 Voltage and Current Sources and Meters 23

2.5 Thevenin and Norton Equivalent Circuits 29

2.6 Alternating Current Circuit Analysis 30

2.7 Power in Electrical Circuits 36

2.8 Transformer 38

2.9 Impedance Matching 39

2.10 Grounding and Electrical Interference 41

2.10.1 Electrical Safety

3 Semiconductor Electronics 52

3.1 Introduction 52

3.2 Semiconductor Physics as the Basis for Understanding Electronic Devices 53

3.3 Junction Diode 54

3.3.1 Zener Diode / 3.3.2 Voltage Regulators / 3.3.3 Optoelectronic Diodes / 3.3.4 Analysis of Diode Circuits

3.4 The Bipolar Junction Transistor 69

3.4.1 Understanding the Physics of a Bipolar Transistor / 3.4.2 The Common Emitter Transistor Circuit / 3.4.3 The Bipolar Transistor Switch / 3.4.4 Bipolar Transistor Packages / 3.4.5 Darlington Transistor / 3.4.6 The Phototransistor and Opto-Isolator

3.5 Field Effect Transistors 80

3.5.1 Symbols Representing Field Effect Transistors / 3.5.2 Behavior of Field Effect Transistors

4 System Response 91
4.1 Measurement System Response 91
4.2 Amplitude Linearity 92
4.3 Fourier Series Representation of Signals 94
4.4 Bandwidth and Frequency Response 98
4.5 Phase Linearity 102
4.6 Distortion of Signals 103
4.7 Dynamic Characteristics of Measurement Systems 105
4.8 Zero Order Measurement Systems 105
4.9 First Order Measurement Systems 107
4.10 Experimental Testing of First Order Measurement Systems 109
4.11 Second Order Measurement Systems 110
4.12 Step Response of Second Order Systems 114
4.13 Frequency Response of a System 116
4.14 System Modeling and Analogies 125

5 Analog Signal Processing Using Operational Amplifiers 136
5.1 Introduction 136
5.2 Amplifiers 137
5.3 Operational Amplifiers 138
5.4 Ideal Model for the Operational Amplifier 139
5.5 Inverting Amplifier 142
5.6 Noninverting Amplifier 144
5.7 Summer 146
5.8 Difference Amplifier 147
5.9 Instrumentation Amplifier 149
5.10 Integrator 151
5.11 Differentiator 153
5.12 Sample and Hold Circuit 154
5.13 Comparator 155
5.14 The Real Op Amp 156
5.14.1 Important Parameters from Op Amp Data Sheets

6 Digital Circuits and Systems 174
6.1 Introduction 174
6.2 Digital Representations 175
6.3 Combinational Logic 178
6.4 Timing Diagrams 183
6.5 Boolean Identities 184
6.6 Design of Logic Networks 186
6.6.1 Define the Problem in Words / 6.6.2 Write Quasi-Logic Statements / 6.6.3 Write the Boolean Expression / 6.6.4 AND Realization / 6.6.5 Draw the Circuit Diagram
6.7 Finding a Boolean Expression Given a Truth Table 189
6.8 Sequential Logic 192

6.9 Flip-Flops 192
6.10 Triggering of Flip-Flops 194
6.11 D Flip-Flop 197
6.12 JK Flip-Flop 198
6.13 Master-Slave Flip-Flops 201
6.14 Applications of Flip-Flops 202
6.14.1 Switch Debouncing / 6.14.2 Data Register / 6.14.3 Binary Counter / 6.14.4 Serial and Parallel Interfaces
6.15 Decade Counter 206
6.16 Schmitt Trigger 210
6.17 The 555 Timer 211
6.18 Integrated Circuit System Design 214
6.19 Microprocessors and Microcomputers 218
6.19.1 Microcontrollers

7 Data Acquisition 232
7.1 Introduction 232
7.2 Quantizing Theory 236
7.3 Hardware for Analog to Digital Conversion 238
7.4 Analog to Digital (A/D) Conversion 240
7.5 Digital to Analog (D/A) Converters 244

8 Sensors 249
8.1 Introduction 249
8.2 Position and Speed Measurement 250
8.2.1 Proximity Sensors and Switches / 8.2.2 Potentiometer / 8.2.3 Linear Variable Differential Transformer / 8.2.4 Digital Optical Encoder
8.3 Stress and Strain Measurement 264
8.3.1 Electrical Resistance Strain Gage / 8.3.2 Measuring Resistance Changes with a Wheatstone Bridge / 8.3.3 Measuring Different States of Stress with Strain Gages / 8.3.4 Force Measurement with Load Cells
8.4 Temperature Measurement 281
8.4.1 Liquid-in-Glass Thermometer / 8.4.2 Bimetallic Strip / 8.4.3 Electrical Resistance Thermometer / 8.4.4 Thermocouple
8.5 Vibration and Acceleration Measurement 291
8.5.1 Piezoelectric Accelerometers
8.6 Pressure and Flow Measurement 301
8.7 Semiconductor Sensors and Micro-Electromechanical Devices 301

9 Actuators 306
9.1 Introduction 306
9.2 Electromagnetic Principles 307
9.3 Solenoids and Relays 308
9.4 Electric Motors 309

9.5 dc Motors 316
9.5.1 dc Motor Electrical Equations / 9.5.2 PM dc Motor Dynamic Equations / 9.5.3 Electronic Control of a PM dc Motor
9.6 Stepper Motors 326
9.7 Stepper Motor Drive Circuits 332
9.8 Selecting a Motor 333
9.9 Hydraulics 337
9.9.1 Hydraulic Valves / 9.9.2 Hydraulic Actuators
9.10 Pneumatics 345

10 Mechatronic Systems—Control Architectures and Case Studies 349
10.1 Introduction 349
10.2 Control Architectures 350
10.2.1 Analog Circuits Alone / 10.2.2 Digital Circuits Alone / 10.2.3 Programmable Logic Controller / 10.2.4 Microcontroller / 10.2.5 Single Board Computer / 10.2.6 Personal Computer
10.3 Case Study 1—Mechatronic Design of a Coin Counter 352
10.4 Case Study 2—Mechatronic Design of a Robotic Walking Machine 356
10.5 List of Various Mechatronic Systems 368

Appendices
1 Measurement Fundamentals 369
2 Physical Principles 384
3 Mechanics of Materials 389

Index 395

LIST OF FIGURES

1.1	Elements of a Measurement System	4
2.1	Electrical Circuits	7
2.2	Electric Circuits Terminology	8
2.3	Basic Electrical Elements	9
2.4	Voltage-Current Relation for an Ideal Resistor	9
2.5	Wire Resistance	10
2.6	Resistor Packaging	11
2.7	Wire-Lead Resistor Color Bands	11
2.8	Potentiometer Schematic Symbols	13
2.9	Parallel Plate Capacitor	13
2.10	Inductor Flux Linkage	15
2.11	Kirchoff's Voltage Law	16
2.12	Kirchoff's Current Law	18
2.13	Series Resistance Circuit	18
2.14	Parallel Resistance Circuit	20
2.15	Real Voltage Source with Output Impedance	23
2.16	Example of a Commercially Available Power Supply	24
2.17	Real Current Source with Output Impedance	24
2.18	Real Ammeter with Input Impedance	25
2.19	Real Voltmeter with Input Impedance	25
2.20	Examples of Commercially Available Digital Multimeters	26
2.21	Example of a Commercially Available Oscilloscope	26
2.22	Example Illustrating Thevenin's Theorem	29
2.23	Thevenin Equivalent Circuit	30
2.24	Norton Equivalent Circuit	30
2.25	Sinusoidal Waveform	31
2.26	Phasor Representation of a Sinusoidal Signal	33
2.27	Power in a Circuit Element	37
2.28	Transformer	38
2.29	Signal Termination	39

2.30 Impedance Matching—String Analogy 40
2.31 Impedance Matching 41
2.32 Common Ground 42
2.33 Inductive Coupling 43
2.34 Three-Prong ac Power Plug 44

3.1 Valence and Conduction Bands of Materials 53
3.2 pn Junction Characteristics 55
3.3 Silicon Diode 55
3.4 Diode Check Valve Analogy 56
3.5 Ideal, Approximate, and Real Diode Curves 56
3.6 Zener Diode Symbol and Current-Voltage Relationship 59
3.7 Zener Diode Voltage Regulator 60
3.8 Zener Diode Voltage Regulator Circuit 62
3.9 15 V Regulated dc Supply 64
3.10 1.2 to 37 V Adjustable Regulator 64
3.11 Light-Emitting Diode (LED) 65
3.12 Photodiode Light Detector Circuit 66
3.13 npn Bipolar Junction Transistor 70
3.14 pnp Bipolar Junction Transistor 71
3.15 Common Emitter Circuit 72
3.16 Common Emitter Characteristics for a Transistor 73
3.17 Transistor Switch Circuit 74
3.18 Models for Transistor Switch States 75
3.19 Bipolar Transistor Packages 77
3.20 Darlington Pair 77
3.21 Opto-Isolator 78
3.22 Field Effect Transistor Cross Section (n-channel MOSFET) 80
3.23 Comparison of BJT and FET Switches 81
3.24 FET Analog Switch Circuit 82
3.25 Field Effect Transistor Schematic Symbols 83
3.26 Common Source Curves for an FET 84

4.1 Measurement System Input-Output 92
4.2 Amplitude Linearity and Nonlinearity 93
4.3 Square Wave 95
4.4 Harmonic Decomposition of a Square Wave 96
4.5 Spectrum of a Square Wave 97
4.6 Frequency Response and Bandwidth 99
4.7 Effect of Measurement System Bandwidth on Signal Spectrum 100
4.8 Relationship Between Phase and Time Displacement 103
4.9 Amplitude Distortion of a Square Wave 104
4.10 Phase Distortion of a Square Wave 105
4.11 Displacement Potentiometer 106
4.12 First Order Response 108
4.13 Experimental Determination of τ 110

4.14 Second Order Mechanical System and Free-Body Diagram 111
4.15 Strip Chart Recorder as an Example of a Second Order System 112
4.16 Transient Response of Second Order Systems 114
4.17 Second Order Step Responses 115
4.18 Features of an Underdamped Step Response 116
4.19 Second Order System Amplitude Response 119
4.20 Second Order Phase Response 120
4.21 Example of System Analogies 127
4.22 Mechanical System Analogy Example 128
4.23 Beginning the Analog Schematic 130
4.24 Electrical System Analogy Example 130

5.1 Amplifier Model 138
5.2 Op Amp Terminology and Schematic Representation 139
5.3 Op Amp Feedback 139
5.4 Op Amp Equivalent Circuit 140
5.5 741 Op Amp Pin-Out 141
5.6 741 Internal Design 141
5.7 Inverting Amplifier 142
5.8 Equivalent Circuit for Inverting Amplifier 143
5.9 Illustration of Inversion 143
5.10 Noninverting Amplifier 144
5.11 Equivalent Circuit for Noninverting Amplifier 145
5.12 Buffer or Follower 146
5.13 Summer Circuit 146
5.14 Difference Amplifier Circuit 147
5.15 Difference Amplifier with V_2 Shorted 148
5.16 Difference Amplifier with V_1 Shorted 148
5.17 Instrumentation Amplifier 150
5.18 Ideal Integrator 152
5.19 Improved Integrator 153
5.20 Differentiator 154
5.21 Sample and Hold Circuit 155
5.22 Comparator 156
5.23 Effect of Slew Rate on a Square Wave 157
5.24 Typical Op Amp Open and Closed Loop Response 158
5.25 Example Op Amp Data Sheet 160
5.26 TL071 FET Input Op Amp 162

6.1 Analog and Digital Signals 175
6.2 NAND Gate Internal Design 181
6.3 QUAD NAND Gate IC Pin-Out 181
6.4 DM74LS00 NAND Gate IC Data Sheet 182
6.5 Open Collector Output with Pull-Up Resistor 183
6.6 AND Gate Timing Diagram 183
6.7 OR Gate Timing Diagram 184

6.8 AND Realization Schematic of the Security System 189
6.9 Clock Pulse Edges 192
6.10 RS Flip-Flop 193
6.11 RS Flip-Flop Internal Design and Timing 194
6.12 Edge-Triggered RS Flip-Flops 195
6.13 Positive Edge-Triggered RS Flip-Flop Timing Diagram 196
6.14 Latch 196
6.15 Latch Timing Diagram 197
6.16 Preset and Clear Flip-Flop Functions 197
6.17 Positive Edge-Triggered D Flip-Flop 198
6.18 Negative Edge-Triggered JK Flip-Flop 199
6.19 Positive Edge-Triggered T Flip-Flop 200
6.20 Master-Slave JK Flip-Flop 202
6.21 Switch Bounce 203
6.22 Switch Debouncer Circuit 203
6.23 4-Bit Data Register 204
6.24 4-Bit Binary Counter 205
6.25 Serial-to-Parallel Converter 206
6.26 Parallel-to-Serial Converter 206
6.27 Decade Counter Timing 207
6.28 Cascaded Decade Counters 208
6.29 7-Segment LED Display 208
6.30 7447 Internal Design 209
6.31 7447 Output Circuit 210
6.32 Input and Output of Schmitt Trigger 211
6.33 Block Diagram of the 555 IC 211
6.34 555 Pin-Out 212
6.35 Monostable Multivibrator (One-Shot) 213
6.36 One-Shot Timing 213
6.37 IEEE Standard Symbols for Digital ICs 218
6.38 Microcomputer Architecture 219
6.39 Motorola 68HC11 222

7.1 Analog Signal and Sampled Equivalent 233
7.2 Aliasing 234
7.3 Analog to Digital Conversion 237
7.4 Components Used in A/D Conversion 239
7.5 Example DAC Card 239
7.6 Example DAC Card Architecture 240
7.7 A/D Conversion Aperture Time 241
7.8 Successive Approximation A/D Converter 242
7.9 4-Bit Successive Approximation A/D Conversion 243
7.10 A/D Flash Converter 244
7.11 4-Bit Resistor Ladder D/A Converter 245
7.12 4-Bit Resistor Ladder D/A with Digital Input 0001 246
7.13 Computer Control Hardware 247

8.1 Various Configurations for Photoemitter-Detector Pairs 251
8.2 Example of a Photoemitter-Detector Pair in a Single Housing 251
8.3 Switches 252
8.4 Potentiometer 252
8.5 Linear Variable Differential Transformer 253
8.6 LVDT Linear Range 253
8.7 LVDT Demodulation 254
8.8 LVDT Output Filter 255
8.9 Commercial LVDT 255
8.10 Components of an Optical Encoder 257
8.11 4-Bit Gray Code Absolute Encoder Disk Track Patterns 258
8.12 4-Bit Natural Binary Absolute Encoder Disk Track Patterns 259
8.13 Gray Code to Binary Code Conversion 260
8.14 Incremental Encoder Disk Track Patterns 261
8.15 Quadrature Direction Sensing and Resolution Enhancement 262
8.16 1X Quadrature Decoder Circuit 263
8.17 Metal Foil Strain Gage Construction 265
8.18 Strain Gage Application 266
8.19 Rectangular Conductor 266
8.20 Static Balanced Bridge Circuit 269
8.21 Dynamic Unbalanced Bridge Circuit 270
8.22 Leadwire Effects in 1/4 Bridge Circuits 271
8.23 Temperature Compensation with Dummy Gage in 1/2 Bridge 272
8.24 Bar under Uniaxial Stress 273
8.25 Biaxial Stress in a Long Thin-Walled Pressure Vessel 274
8.26 General State of Planar Stress on the Surface of a Component 275
8.27 Assortment of Different Strain Gage and Rosette Configurations 275
8.28 Most Common Strain Gage Rosette Configurations 276
8.29 Rectangular Strain Gage Rosette 276
8.30 Various 3-Gage Commercial Rosettes 277
8.31 Typical Axial Load Cells 279
8.32 Bimetallic Strip 282
8.33 Thermoelectric Junction 283
8.34 Thermocouple Circuit 284
8.35 Law of Leadwire Temperatures 284
8.36 Law of Intermediate Leadwire Metals 285
8.37 Law of Intermediate Junction Metals 285
8.38 Law of Intermediate Temperatures 286
8.39 Law of Intermediate Metals 286
8.40 Standard Thermocouple Configuration 287
8.41 Attaching Leadwires of Selected Metal 287
8.42 Thermopile 288
8.43 Thermocouple Types and Characteristics 291
8.44 Accelerometer Displacement References and Free-Body Diagram 292
8.45 Ideal Accelerometer Amplitude Response 295
8.46 Ideal Accelerometer Phase Response 295