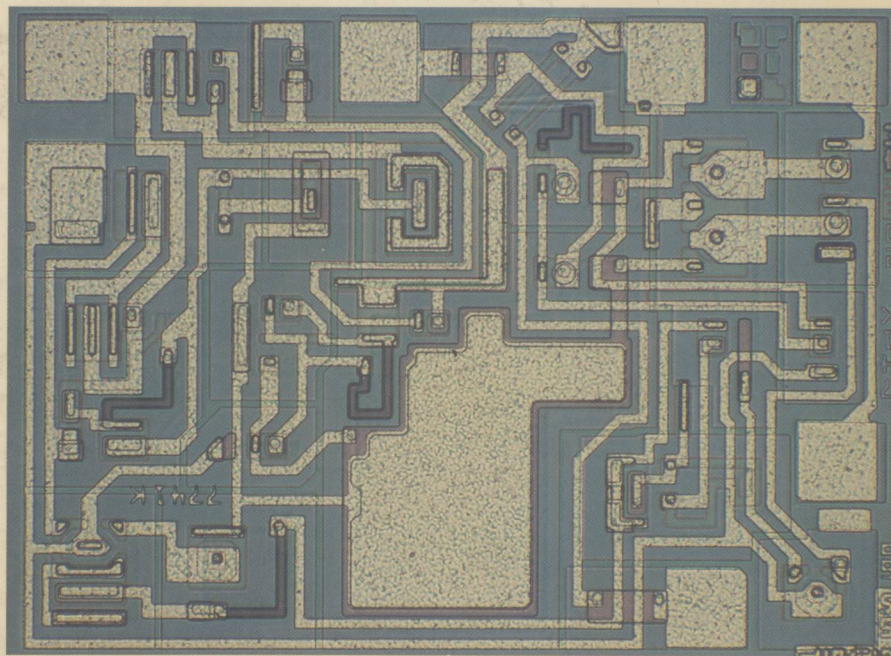




Robert F. Coughlin **Frederick F. Driscoll**

Operational Amplifiers AND Linear Integrated Circuits

THIRD EDITION



THIRD EDITION

OPERATIONAL AMPLIFIERS AND LINEAR INTEGRATED CIRCUITS

Robert F. Coughlin

Frederick F. Driscoll

Wentworth Institute of Technology

PRENTICE-HALL, INC., *Englewood Cliffs, New Jersey 07632*

Library of Congress Cataloging-in-Publication Data

Coughlin, Robert F.

Operational amplifiers and linear integrated circuits.

Bibliography

Includes index

1. Operational amplifiers. 2. Linear integrated circuits. I. Driscoll, Frederick, F. II. Title.

TK7871 .58.06C68 1987

621.3815'35

86-4945

ISBN 0-13-637901-X

Editorial/production supervision: *Ellen Denning*

Interior design: *Jayne Conte*

Cover design: *Photo Plus Art*

Manufacturing buyer: *Carol Bystrom*

Cover photo courtesy of Fairchild Semiconductor

©1987, 1982, 1977 by Prentice-Hall, Inc.

A Division of Simon & Schuster

Englewood Cliffs, New Jersey 07632

All rights reserved. No part of this book may be reproduced, in any form or by any means, without permission in writing from the publisher.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-637901-X 025

PRENTICE-HALL INTERNATIONAL (UK) LIMITED, *London*

PRENTICE-HALL OF AUSTRALIA PTY. LIMITED, *Sydney*

PRENTICE-HALL CANADA INC., *Toronto*

PRENTICE-HALL HISPANOMERICANA, S. A., *Mexico*

PRENTICE-HALL OF INDIA PRIVATE LIMITED, *New Delhi*

PRENTICE-HALL OF JAPAN, INC., *Tokyo*

PRENTICE-HALL OF SOUTHEAST ASIA PTE. LTD., *Singapore*

EDITORIA PRENTICE-HALL DO BRASIL, LTDA., *Rio de Janeiro*

To Our Partners
in Ballroom Dancing
and
Our Lifetime Partners
Barbara and Jean

Preface

Operational amplifiers and other linear integrated circuits are both fun and easy to use, especially if the application does not require the devices to operate near their design limits. It is the purpose of this book to show just how easy they are to use in a variety of applications involving instrumentation, signal generation, filter, and control circuits.

When first learning how to use an op amp, one should *not* be presented with a myriad of op amps and asked to make an informed selection. For this reason, our introduction begins with an inexpensive, reliable op amp that forgives most mistakes in wiring, ignores long lead capacitance, and does not burn out easily. Such an op amp is the 741, whose characteristics are documented in Appendix 1 and whose applications are sprinkled throughout the text.

If a slightly faster op amp is needed for a wider bandwidth, another inexpensive and widely used op amp is the 301. See Appendix 2 for its electrical characteristics and Chapter 10 to learn when one might prefer the 301 over the 741.

Where appropriate, we have added specialized op amps: the LM339 single supply comparator in Chapter 2 and the LM311 high-performance comparator in Chapter 4. Where better dc performance is required, we have added BiFET op amps in Chapter 7.

The third edition is organized into a set of core chapters that should be read first. They are Chapters 1 through 6 and proceed in a logical teaching sequence to show how the op amp can be used to solve a variety of application problems.

The limitations of op amps are not discussed in Chapters 1 to 6 because it is very important to gain confidence in using op amps before pushing performance to its limits. When studying transistors or other devices, we do not begin with their limitations. Regrettably, much of the early literature on integrated circuits begins with their limitations and thus obscures the inherent simplicity and overwhelming advantages of basic integrated circuits over basic transistor circuits. For these reasons, op amp limitations are not presented until Chapters 9 and 10 for those readers who need to understand some of their limitations with respect to dc and ac performance. Furthermore, not all op amp limitations apply to every op amp circuit. For example, dc op amp limitations such as offset voltages are usually not important if the op amp is used in an ac amplifier circuit. Thus dc limitations (Chapter 9) are treated separately from ac limitations (Chapter 10).

The remaining chapters have been written to stand alone. They can be studied in any order after completion of Chapters 1 through 6.

Chapter 7 deals with the specialized applications that can best be accomplished by op amps combined with diodes.

Chapter 8 is concerned with problems of measuring physical variables such as force, pressure weight, and temperature. Bridge and instrumentation amplifiers are ideal for these measurements.

Chapter 11 simplifies the design of active filters. The four basic types of active filters are shown: low-pass, high-pass, band-pass, and band-reject filters. Butterworth filters were selected because they are often used and easy to design. If you want to design a three-pole (60-dB/decade) Butterworth low- or high-pass filter, Chapter 11 tells you how to do it in four steps with a pencil and paper. No calculator or computer program is required. Basic algebra is the only mathematics that is required throughout the text.

A fascinating integrated circuit, the multiplier, is presented in Chapter 12 because it makes analysis and design of communication circuits very easy. Modulators, demodulators, frequency shifters, a universal AM radio receiver, and a host of other applications are performed by the multiplier, an op amp, and a few resistors.

Chapter 13 is included for those who need to use the ubiquitous 555 IC timer and also the XR2240 counter timer.

Since almost all linear integrated circuits require a regulated power supply, we have, because of requests from readers, rewritten Chapter 14. The latest IC regulators are used to show how you can make excellent linear regulated supplies at low cost for (a) 5-V digital logic ICs, (b) ± 15 -V linear ICs, (c) combined (a) and (b) for μP supplies, and (d) either positive or negative adjustable supplies.

This third edition has been extensively rewritten. Every chapter has been either fully or partially revised to substitute better circuits that have been found and to add more circuits that solve problems. We have incorporated suggestions from students, instructors,

and practicing engineers from all parts of the United States and from Indonesia, Poland, Japan, and the USSR.

This edition contains more than enough material for a single-semester course. All circuits have been personally lab tested by the authors and their recommendations for laboratory work have been added to the end of each chapter. The material is suitable for both nonelectronic specialists who just want to learn something about linear ICs and for electronic majors who wish to use linear ICs.

We thank Mrs. Phyllis Wolff for the preparation of the revised manuscript. Our colleagues Robert S. Villanucci, William F. Megow, John Marchand, Richard Bean, Dominic Giampietro, and Alexander Avtgis have been particularly helpful with their suggestions, and testing of ideas.

We also thank two highly respected analog engineers, Dan Sheingold of Analog Devices and Bob Pease of National Semiconductors, for their constructive criticism, technical corrections, and guidance in areas we found difficult.

Finally, we thank our students for their insistence on relevant instruction that is immediately useful, and our readers for both their enthusiastic reception of this text and their perceptive comments.

ROBERT F. COUGHLIN
FREDERICK F. DRISCOLL

Boston, Mass.

Contents

PREFACE

xxi

1

INTRODUCTION TO OP AMPS

1

1-0 Introduction 1

1-1 A Short History 2

1-1.1 *The Early Days, 2*

1-1.2 *Birth and Growth of the IC Op Amp, 2*

1-1.3 *Further Progress in Op Amp Development, 2*

1-1.4 *Op Amps Become Specialized, 3*

1-1.5 *Speculation on the Op Amp's Future, 4*

1-2 Schematic-Symbol-Package 4

1-2.1 *Schematic, 4*

1-2.2 *Op Amp Symbol, 4*

1-2.3 *Op Amp Package, 4*

v

- 1-3 Common Packages and Typical Pinouts 6
 - 1-3.1 *Metal Can and Dual-in-Line, 6*
 - 1-3.2 *Combining Symbol and Pinout, 6*
- 1-4 How to Identify or Order an Op Amp, 6
 - 1-4.1 *The Identification Code, 6*
 - 1-4.2 *Order Number Example, 9*
- 1-5 Second Sources 9
- 1-6 Breadboarding Op Amp Circuits 9
 - 1-6.1 *The Power Supply, 9*
 - 1-6.2 *Breadboarding Suggestions, 10*

2 FIRST EXPERIENCES WITH AN OP AMP

12

- 2-0 Introduction 12
- 2-1 Op Amp Terminals 14
 - 2-1.1 *Power Supply Terminals, 14*
 - 2-1.2 *Output Terminal, 16*
 - 2-1.3 *Input Terminals, 16*
- 2-2 Open-Loop Voltage Gain 18
 - 2-2.1 *Definition, 18*
 - 2-2.2 *Differential Input Voltage, E_d , 18*
 - 2-2.3 *Conclusions, 18*
- 2-3 Zero-Crossing Detectors 20
 - 2-3.1 *Noninverting Zero-Crossing Detector, 20*
 - 2-3.2 *Inverting Zero-Crossing Detector, 21*
- 2-4 Positive- and Negative-Voltage-Level Detectors 21
 - 2-4.1 *Positive-Level Detectors, 21*
 - 2-4.2 *Negative-Level Detectors, 22*
- 2-5 Typical Applications of Voltage-Level Detectors 23
 - 2-5.1 *Sound-Activated Switch, 23*
 - 2-5.2 *Light Column Voltmeter, 24*
 - 2-5.3 *Smoke Detector, 26*
- 2-6 Signal Processing with Voltage-Level Detectors 26
 - 2-6.1 *Introduction, 26*
 - 2-6.2 *Sine-to-Square Wave Converter, 27*
- 2-7 Computer Interfacing with Voltage-Level Detectors 27
 - 2-7.1 *Introduction, 27*
 - 2-7.2 *Quad Voltage Comparator, LM339, 28*

- 2-7.3 *Pulse-Width Modulator, Noninverting, 31*
- 2-7.4 *Inverting and Noninverting Pulse-Width Modulators, 32*
- 2-8 **Analog-to-Digital Conversion with a Microcomputer and a Pulse-Width Modulator 32**
 - Laboratory Exercises 34
 - Problems 35

3 INVERTING AND NONINVERTING AMPLIFIERS

38

- 3-0 **Introduction 38**
- 3-1 **The Inverting Amplifier 39**
 - 3-1.1 *Introduction, 39*
 - 3-1.2 *Positive Voltage Applied to the Inverting Input, 39*
 - 3-1.3 *Load and Output Currents, 40*
 - 3-1.4 *Negative Voltage Applied to the Inverting Input, 42*
 - 3-1.5 *AC Voltage Applied to the Inverting Input, 43*
 - 3-1.6 *Design Procedure, 44*
 - 3-1.7 *Analysis Procedure, 45*
- 3-2 **Inverting Adder and Audio Mixer 45**
 - 3-2.1 *Inverting Adder, 45*
 - 3-2.2 *Audio Mixer, 47*
 - 3-2.3 *DC Offsetting an AC Signal, 47*
- 3-3 **Multichannel Amplifier 49**
 - 3-3.1 *The Need for a Multichannel Amplifier, 49*
 - 3-3.2 *Circuit Analysis, 49*
 - 3-3.3 *Design Procedure, 50*
- 3-4 **Inverting Averaging Amplifier 51**
- 3-5 **Voltage Follower 51**
 - 3-5.1 *Introduction, 51*
 - 3-5.2 *Using the Voltage Follower, 53*
- 3-6 **Noninverting Amplifier 54**
 - 3-6.1 *Circuit Analysis, 54*
 - 3-6.2 *Design Procedure, 58*
- 3-7 **The "Ideal" Voltage Source 58**
 - 3-7.1 *Definition and Awareness, 58*
 - 3-7.2 *The Unrecognized Ideal Voltage Source, 58*
 - 3-7.3 *The Practical Ideal Voltage Source, 59*
- 3-8 **Noninverting Adder 60**
- 3-9 **Single-Supply Operation 60**

- 3-10 Combined Inverting–Noninverting Amplifiers 62
 - 3-10.1 Circuit Analysis, 62
 - 3-10.2 Practical Precautions, 62
 - Laboratory Exercises 64
 - Problems 66

4 COMPARATORS AND CONTROLS

69

- 4-0 Introduction 69
- 4-1 Effect of Noise on Comparator Circuits 70
- 4-2 Positive Feedback 70
 - 4-2.1 Introduction, 70
 - 4-2.2 Upper-Threshold Voltage, 71
 - 4-2.3 Lower-Threshold Voltage, 72
- 4-3 Zero-Crossing Detector with Hysteresis 74
 - 4-3.1 Defining Hysteresis, 74
 - 4-3.2 Zero-Crossing Detector with Hysteresis as a Memory Element, 75
- 4-4 Voltage-Level Detectors with Hysteresis 75
 - 4-4.1 Introduction, 75
 - 4-4.2 Noninverting Voltage-Level Detector with Hysteresis, 76
 - 4-4.3 Inverting Voltage-Level Detector with Hysteresis, 79
- 4-5 Voltage-Level Detector with Independent Adjustment of Hysteresis and Center Voltage 80
 - 4-5.1 Introduction, 80
 - 4-5.2 Battery-Charger Control Circuit, 82
- 4-6 On–Off Control Principles 84
 - 4-6.1 Comparators in Process Control, 84
 - 4-6.2 The Room Thermostat as a Comparator, 84
 - 4-6.3 Selection/Design Guideline, 84
- 4-7 An Independently Adjustable Setpoint Controller 84
 - 4-7.1 Principle of Operation, 84
 - 4-7.2 Output–Input Characteristics of an Independently Adjustable Setpoint Controller, 86
 - 4-7.3 Choice of Setpoint Voltages, 86
 - 4-7.4 Circuit for Independently Adjustable Setpoint Voltage, 86
 - 4-7.5 Precautions, 88
- 4-8 IC Precision Comparator, 111/311 88
 - 4-8.1 Introduction, 88
 - 4-8.2 Output Terminal Operation, 89
 - 4-8.3 Strobe Terminal Operation, 90

- 4-9 Window Detector 91
 - 4-9.1 Introduction, 91
 - 4-9.2 Circuit Operation, 92
- 4-10 Propagation Delay 93
 - 4-10.1 Definition, 93
 - 4-10.2 Measurement of Propagation Delay, 94
- Laboratory Exercises 94
- Problems 95

5 SELECTED APPLICATIONS OF OP AMPS

97

- 5-0 Introduction 97
- 5-1 High-Resistance DC Voltmeter 98
 - 5-1.1 Basic Voltage-Measuring Circuit, 98
 - 5-1.2 Voltmeter Scale Changing, 99
- 5-2 Universal High-Resistance Voltmeter 99
 - 5-2.1 Circuit Operation, 99
 - 5-2.2 Design Procedure, 100
- 5-3 Voltage-to-Current Converters: Floating Loads 101
 - 5-3.1 Voltage Control of Load Current, 101
 - 5-3.2 Zener Diode Tester, 101
 - 5-3.3 Diode Tester, 103
- 5-4 Light-Emitting-Diode Tester 104
- 5-5 Furnishing a Constant Current to a Grounded Load 104
 - 5-5.1 Differential Voltage-to-Current Converter, 104
 - 5-5.2 Constant-High-Current Source, Grounded Load, 106
 - 5-5.3 Interfacing a Microcomputer to a Teleprinter, 107
 - 5-5.4 Digitally Controlled 4- to 20-mA Current Source, 107
- 5-6 Short-Circuit Current Measurement and Current-to-Voltage Conversion 109
 - 5-6.1 Introduction, 109
 - 5-6.2 Using the Op Amp to Measure Short-Circuit Current, 110
- 5-7 Measuring Current from Photodetectors 110
 - 5-7.1 Photoconductive Cell, 110
 - 5-7.2 Photodiode, 111
- 5-8 Current Amplifier 112
- 5-9 Solar Cell Energy Measurements 113
 - 5-9.1 Introduction to the Problems, 113

5-9.2	<i>Converting Solar Cell Short-Circuit Current to a Voltage, 113</i>
5-9.3	<i>Current-Divider Circuit (Current-to-Current Converter), 114</i>
5-10	Phase Shifter 115
5-10.1	<i>Introduction, 115</i>
5-10.2	<i>Phase-Shifter Circuit, 116</i>
5-11	The Constant-Velocity Recording Process 117
5-11.1	<i>Introduction to Record-Cutting Problems, 117</i>
5-11.2	<i>Groove Modulation with Constant-Velocity Recording, 118</i>
5-11.3	<i>Record Cutover and Noise, 119</i>
5-11.4	<i>Solution to Record Cutover and Noise Problems, 119</i>
5-12	Record Playback 121
5-12.1	<i>Need for Playback Equalization, 121</i>
5-12.2	<i>Preamplifier Gain and Signal Voltage Levels, 122</i>
5-12.3	<i>Playback Preamplifier Circuit Operation, 122</i>
5-13	Tone Control 124
5-13.1	<i>Introduction, 124</i>
5-13.2	<i>Tone-Control Circuit, 124</i>
	Laboratory Exercises 125
	Problems 126

6

SIGNAL GENERATORS

129

6-0	Introduction 129
6-1	Free-Running Multivibrator 130
6-1.1	<i>Multivibrator Action, 130</i>
6-1.2	<i>Frequency of Oscillation, 131</i>
6-2	One-Shot Multivibrator 134
6-2.1	<i>Introduction, 134</i>
6-2.2	<i>Stable State, 134</i>
6-2.3	<i>Transition to the Timing State, 136</i>
6-2.4	<i>Timing State, 136</i>
6-2.5	<i>Duration of Output Pulse, 136</i>
6-2.6	<i>Recovery Time, 137</i>
6-3	Generating Triangle and Sawtooth Waves with a Multivibrator 138
6-3.1	<i>Introduction, 138</i>
6-3.2	<i>Triangular-Wave Generator, 138</i>
6-4	Multivibrator Triangular-Wave Generator with Independently Adjustable Slopes 141

- 6-5 Multivibrator Sawtooth-Wave Generator 141
- 6-6 Timers and Triangular-Wave Generators with the Integrator 143
 - 6-6.1 *The Integrator, 143*
 - 6-6.2 *Ramp-Generator Theory, 143*
 - 6-6.3 *Ramp-Generator Circuit, 144*
- 6-7 Adjustable Timer 145
 - 6-7.1 *Circuit Description, 145*
 - 6-7.2 *Circuit Analysis, 147*
- 6-8 Triangular-Wave Generator with an Integrator 148
 - 6-8.1 *Introduction, 148*
 - 6-8.2 *Basic Operation, 148*
 - 6-8.3 *Design Procedure, 151*
- 6-9 Single-Polarity Triangular-Wave Generators with an Integrator 152
 - 6-9.1 *Positive-Voltage Single-Polarity Triangular-Wave Generator, 152*
 - 6-9.2 *Negative-Voltage Single-Polarity Triangular-Wave Generator with an Integrator, 154*
- 6-10 Sawtooth-Wave Generator with an Integrator 154
 - 6-10.1 *Introduction, 154*
 - 6-10.2 *Circuit Analysis, 154*
 - 6-10.3 *Sawtooth Wave-Shape Analysis, 154*
 - 6-10.4 *Design Procedure, 156*
 - 6-10.5 *Voltage-to-Frequency Converters, 157*
 - 6-10.6 *Frequency Modulation and Frequency Shift Keying, 158*
- 6-11 Sine-Wave Oscillator 158
 - 6-11.1 *Oscillator Theory, 158*
 - 6-11.2 *Setting Up an Oscillator, 160*
 - 6-11.3 *Wein Bridge Oscillator, 161*
- Laboratory Exercises 161
- Problems 163

7 OP AMPS WITH DIODES

165

- 7-0 Introduction to Precision Rectifiers 165
- 7-1 Linear Half-Wave Rectifiers 167
 - 7-1.1 *Introduction, 167*
 - 7-1.2 *Inverting Linear Half-Wave Rectifier, Positive Output, 167*

7-1.3	<i>Inverting Linear Half-Wave Rectifier, Negative Output, 169</i>	
7-1.4	<i>Signal Polarity Separator, 170</i>	
7-2	Precision Rectifiers: The Absolute-Value Circuit	172
7-2.1	<i>Introduction, 172</i>	
7-2.2	<i>Types of Precision Full-Wave Rectifiers, 172</i>	
7-3	Peak Detectors	176
7-3.1	<i>Positive Peak Follower and Hold, 176</i>	
7-3.2	<i>Negative Peak Follower and Hold, 176</i>	
7-4	AC-to-DC Converter	178
7-4.1	<i>AC-to-DC Conversion or MAV Circuit, 178</i>	
7-4.2	<i>Precision Rectifier with Grounded Summing Inputs, 178</i>	
7-4.3	<i>AC-to-DC Converter, 179</i>	
7-5	Dead-Zone Circuits	181
7-5.1	<i>Introduction, 181</i>	
7-5.2	<i>Dead-Zone Circuit with Negative Output, 181</i>	
7-5.3	<i>Dead-Zone Circuit with Positive Output, 183</i>	
7-5.4	<i>Bipolar-Output Dead-Zone Circuit, 184</i>	
7-6	Precision Clipper	186
7-7	Triangular-to-Sine Wave Converter	186
	Laboratory Exercises	187
	Problems	188

8 DIFFERENTIAL, INSTRUMENTATION, AND BRIDGE AMPLIFIERS

189

8-0	Introduction	189
8-1	Basic Differential Amplifier	190
8-1.1	<i>Introduction, 190</i>	
8-1.2	<i>Common-Mode Voltage, 191</i>	
8-2	Differential versus Single-Input Amplifiers	192
8-2.1	<i>Measurement with a Single-Input Amplifier, 192</i>	
8-2.2	<i>Measurement with a Differential Amplifier, 194</i>	
8-3	Improving the Basic Differential Amplifier	194
8-3.1	<i>Increasing Input Resistance, 194</i>	
8-3.2	<i>Adjustable Gain, 194</i>	
8-4	Instrumentation Amplifier	196
8-4.1	<i>Circuit Operation, 196</i>	
8-4.2	<i>Referencing Output Voltage, 198</i>	

- 8-5 Sensing and Measuring with the Instrumentation Amplifier 200
 - 8-5.1 *Sense Terminal*, 200
 - 8-5.2 *Differential Voltage Measurements*, 201
 - 8-5.3 *Differential Voltage-to-Current Converter*, 203
- 8-6 Basic Bridge Amplifier 204
 - 8-6.1 *Introduction*, 204
 - 8-6.2 *Basic Bridge Circuit Operation*, 205
 - 8-6.3 *Temperature Measurement with a Bridge Circuit*, 206
 - 8-6.4 *Bridge Amplifiers and Computers*, 209
- 8-7 Adding Versatility to the Bridge Amplifier 209
 - 8-7.1 *Grounded Transducers*, 209
 - 8-7.2 *High-Current Transducers*, 209
- 8-8 The Strain Gage and Measurement of Small Resistance Changes 209
 - 8-8.1 *Introduction to the Strain Gage*, 209
 - 8-8.2 *Strain-Gage Material*, 211
 - 8-8.3 *Using Strain-Gage Data*, 211
 - 8-8.4 *Strain-Gage Mounting*, 212
 - 8-8.5 *Strain-Gage Resistance Changes*, 212
- 8-9 Measurement of Small Resistance Changes 213
 - 8-9.1 *Need for a Resistance Bridge*, 213
 - 8-9.2 *Basic Resistance Bridge*, 213
 - 8-9.3 *Thermal Effects on Bridge Balance*, 214
- 8-10 Balancing a Strain-Gage Bridge 215
 - 8-10.1 *The Obvious Technique*, 215
 - 8-10.2 *The Better Technique*, 216
- 8-11 Increasing Strain-Gage Bridge Output 217
- 8-12 A Practical Strain-Gage Application 219
- 8-13 Measurement of Pressure, Force, and Weight 221
 - Laboratory Exercises 221
 - Problems 222

9 DC PERFORMANCE: BIAS, OFFSETS, AND DRIFT

224

- 9-0 Introduction 224
- 9-1 Input Bias Currents 226
- 9-2 Input Offset Current 227

- 9-3 Effect of Bias Currents on Output Voltage 227
 - 9-3.1 *Simplification*, 227
 - 9-3.2 *Effect of (-) Input Bias Current*, 228
 - 9-3.3 *Effect of (+) Input Bias Current*, 228
- 9-4 Effect of Offset Current on Output Voltage 230
 - 9-4.1 *Current-Compensating the Voltage Follower*, 230
 - 9-4.2 *Current-Compensating Other Amplifiers*, 231
 - 9-4.3 *Summary on Bias-Current Compensation*, 232
- 9-5 Input Offset Voltage 232
 - 9-5.1 *Definition and Model*, 232
 - 9-5.2 *Effect of Input Offset Voltage on Output Voltage*, 234
 - 9-5.3 *Measurement of Input Offset Voltage*, 235
- 9-6 Input Offset Voltage for the Adder Circuit 235
 - 9-6.1 *Comparison of Signal Gain and Offset Voltage Gain*, 235
 - 9-6.2 *How Not to Eliminate the Effects of Offset Voltage*, 237
- 9-7 Nulling-Out Effect of Offset Voltage and Bias Currents 237
 - 9-7.1 *Design or Analysis Sequence*, 237
 - 9-7.2 *Null Circuits for Offset Voltage*, 237
 - 9-7.3 *Nulling Procedure for Output Voltage*, 239
- 9-8 Drift 239
- 9-9 Measurement of Offset Voltage and Bias Currents 241
 - Laboratory Exercises 242
 - Problems 243

10 AC PERFORMANCE: BANDWIDTH, SLEW RATE, NOISE, AND FREQUENCY COMPENSATION

245

- 10-0 Introduction 245
- 10-1 Frequency Response of the Op Amp 246
 - 10-1.1 *Internal Frequency Compensation*, 246
 - 10-1.2 *Frequency-Response Curve*, 246
 - 10-1.3 *Unity-Gain Bandwidth*, 246
 - 10-1.4 *Rise Time*, 249
- 10-2 Amplifier Gain and Frequency Response 249
 - 10-2.1 *Effect of Open-Loop Gain on Closed-Loop Gain of an Amplifier, DC Operation*, 249
 - 10-2.2 *Small-Signal Bandwidth, Low- and High-Frequency Limits*, 251