SECTION 1-4 EXPERIMENTS

1-4-1 Safety Precautions 26
1-4-2 General Procedures and Test Equipment to Use 28
EXPERIMENT 1-1 Output Polarity 29
EXPERIMENT 1-2 Closed-Loop DC Voltage Gain (Inverting) 30
EXPERIMENT 1-3 Closed-Loop DC Voltage Gain (Noninverting) 32
EXPERIMENT 1-4 Maximum DC Output-Voltage Range 33
EXPERIMENT 1-5 Maximum DC Input-Voltage Range 35
EXPERIMENT 1-6 Input Impedance 36
EXPERIMENT 1-7 Output Impedance 37
EXPERIMENT 1-8 Input-Offset Current 38
EXPERIMENT 1-9 Input-Offset Voltage 39
EXPERIMENT 1-10 Output-Offset Voltage 40
EXPERIMENT 1-11 Offset Null Adjustment 41
EXPERIMENT 1-12 Slew Rate 42
EXPERIMENT 1-13 Open-Loop Frequency Response 44
EXPERIMENT 1-14 Unity-Gain Frequency 45
EXPERIMENT 1-15 Common-Mode Rejection 46

SECTION 1-5 SUMMARY POINTS 47

SECTION 1-6 SELF-CHECKING QUIZ 48

CHAPTER 2 Basic Op-Amp Circuits 50

2-1-1 VOLTAGE COMPARATOR 50
2-1-1-1 Sensing a Sine Wave on the Inverting Input 50
2-1-1-2 Sensing a Sine Wave on the Noninverting Input 51
2-1-1-3 Detecting Phase Difference 51
2-1-1-4 Positive-Voltage-Level Detector 52
2-1-1-5 Negative-Voltage-Level Detector 53
2-1-1-6 Determining Resistive Voltage Divider 54

2-1-2 INVERTING AMPLIFIER 55
2-1-2-1 Virtual Ground 59
2-1-2-2 Input Impedance 60

2-1-3 NONINVERTING AMPLIFIER 60

2-1-4 VOLTAGE FOLLOWERS 62

2-1-5 VOLTAGE SUMMING AMPLIFIER 63
2-1-5-1 Summing Amplifier with Gain 64
2-1-5-2 Scaling Adder Amplifier 66
2-1-6 VOLTAGE DIFFERENCE AMPLIFIER
2-1-6-1 Voltage Difference Amplifier with Gain 69

SECTION 2-2 TERMINOLOGY EXERCISE 69

SECTION 2-3 PROBLEMS AND EXERCISES 70

SECTION 2-4 EXPERIMENTS 74
EXPERIMENT 2-1 Basic Op-Amp Comparator Operation 74
EXPERIMENT 2-2 Sensing Sine Waves With an Op Amp 75
EXPERIMENT 2-3 Op-Amp Voltage-Level Detectors 77
EXPERIMENT 2-4 Op-Amp Inverting Amplifier 78
EXPERIMENT 2-5 Op-Amp Noninverting Amplifier 80
EXPERIMENT 2-6 Two-Stage Op-Amp Amplifier 82
EXPERIMENT 2-7 Op-Amp Voltage Followers 84
EXPERIMENT 2-8 Summing Currents 85
EXPERIMENT 2-9 Op-Amp Summing Amplifiers 87
EXPERIMENT 2-10 Op-Amp Difference Amplifier 88

SECTION 2-5 SUMMARY POINTS 89

SECTION 2-6 SELF-CHECKING QUIZ 91

CHAPTER 3 Signal Processing with Op Amps 95

3-1-1 INTEGRATOR CIRCUIT 95

3-1-2 DIFFERENTIATOR CIRCUIT 97

3-1-3 ACTIVE LOW-PASS FILTER 99

3-1-4 ACTIVE HIGH-PASS FILTER 102

3-1-5 ACTIVE BANDPASS FILTER 102

3-1-6 ACTIVE NOTCH (BAND-REJECT) FILTER 108

SECTION 3-2 TERMINOLOGY EXERCISE 110

SECTION 3-3 PROBLEMS AND EXERCISES 110

SECTION 3-4 EXPERIMENTS 112
EXPERIMENT 3-1 Practical Integrator Circuit 112
EXPERIMENT 3-2 Practical Differentiator Circuit 113
EXPERIMENT 3-3 Op-Amp Low-Pass Filter 115
EXPERIMENT 3-4 Op-Amp High-Pass Filter 115
EXPERIMENT 3-5 Op-Amp Bandpass Filter 117
EXPERIMENT 3-6 Op-Amp Notch Filter 118

SECTION 3-5 SUMMARY POINTS 120
SELF-CHECKING QUIZ 121

CHAPTER 4 Op-Amp Oscillators 124

4-1-1 SQUARE-WAVE GENERATOR 124
4-1-2 SAWTOOTH-WAVE GENERATOR 126
4-1-3 TRIANGLE-WAVE GENERATOR 129
4-1-3-1 Positive Feedback 129
4-1-4 SINE-WAVE OSCILLATOR 133
4-1-5 QUADRATURE OSCILLATOR 134
4-1-6 FUNCTION GENERATOR 135

SECTION 4-2 TERMINOLOGY EXERCISE 136
SECTION 4-3 PROBLEMS AND EXERCISES 137
SECTION 4-4 EXPERIMENTS 137
EXPERIMENT 4-1 Op-Amp Square-Wave Generator 137
EXPERIMENT 4-2 Square/Triangle Wave Generator 138
EXPERIMENT 4-3 Two Op-Amp Sine-Wave Oscillator 140
EXPERIMENT 4-4 Basic Quadrature Oscillator 142
EXPERIMENT 4-5 Tri-Function Generator 143

SECTION 4-5 SUMMARY POINTS 145
SECTION 4-6 SELF-CHECKING QUIZ 146
CHAPTER 5  Op-Amp Applications to Audio Circuits 148

5-1-1 THE INVERTING AMPLIFIER 150
5-1-2 THE NONINVERTING AMPLIFIER 151
5-1-3 SIMPLE AUDIO-VOLTAGE-AMPLIFIER APPLICATIONS 152
5-1-4 EQUALIZATION PREAMPLIFIER 154
  5-1-4-1 RIAA Equalization Preamplifier 154
  5-1-4-2 NAB Equalization Preamplifier 156
5-1-5 ACTIVE-TONE-CONTROL CIRCUITS 157
5-1-6 AUDIO MIXERS 159
5-1-7 MISCELLANEOUS AUDIO CIRCUITS 161
  5-1-7-1 Scratch Filter 161
  5-1-7-2 Rumble Filter 162
  5-1-7-3 Speech Filter 162
  5-1-7-4 Octave Equalizer 162
  5-1-7-5 Active Crossover Network 164
  5-1-7-6 Two-Channel Panning Circuit 165
5-1-8 SIMPLE MEDIUM-POWER AMPLIFIERS 166

SECTION 5-2 TERMINOLOGY EXERCISE 166
SECTION 5-3 PROBLEMS AND EXERCISES 168
SECTION 5-4 EXPERIMENTS 169
  EXPERIMENT 5-1 General Audio Circuits 169
SECTION 5-5 SUMMARY POINTS 171
SECTION 5-6 SELF-CHECKING QUIZ 171

CHAPTER 6  Op-Amp Protection, Stability, and Testing 174

6-1-1 INPUT PROTECTION 174
6-1-2 OUTPUT PROTECTION AND LATCH-UP 174
<table>
<thead>
<tr>
<th>Section</th>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-1-3</td>
<td>POWER SUPPLY PROTECTION</td>
<td>175</td>
</tr>
<tr>
<td>6-1-4</td>
<td>BASIC CIRCUIT STABILITY APPLICATIONS</td>
<td>176</td>
</tr>
<tr>
<td>6-1-5</td>
<td>TESTING THE OP AMP</td>
<td>178</td>
</tr>
<tr>
<td>6-1-6</td>
<td>IN-CIRCUIT TESTING WITH A VOLTMETER</td>
<td>180</td>
</tr>
<tr>
<td>6-1-7</td>
<td>IN-CIRCUIT TESTING WITH AN OSCILLOSCOPE</td>
<td>183</td>
</tr>
<tr>
<td></td>
<td>6-1-7-1 Noise Problems</td>
<td>184</td>
</tr>
<tr>
<td>SECTION 6-2</td>
<td>TERMINOLOGY EXERCISE</td>
<td>185</td>
</tr>
<tr>
<td>SECTION 6-3</td>
<td>PROBLEMS AND EXERCISES</td>
<td>185</td>
</tr>
<tr>
<td>SECTION 6-4</td>
<td>EXPERIMENTS</td>
<td>185</td>
</tr>
<tr>
<td></td>
<td>EXPERIMENT 6-1 Op Amp Basic Troubleshooting</td>
<td>186</td>
</tr>
<tr>
<td>SECTION 6-5</td>
<td>SUMMARY POINTS</td>
<td>186</td>
</tr>
<tr>
<td>SECTION 6-6</td>
<td>SELF-CHECKING QUIZ</td>
<td>188</td>
</tr>
<tr>
<td>CHAPTER 7</td>
<td>Special Type Op Amps</td>
<td>190</td>
</tr>
<tr>
<td>7-1-1</td>
<td>JFET-INPUT OP AMP</td>
<td>190</td>
</tr>
<tr>
<td>7-1-2</td>
<td>OPERATIONAL TRANSCONDUCTANCE AMPLIFIER</td>
<td>190</td>
</tr>
<tr>
<td></td>
<td>7-1-2-1 Calculating $R_{bias}$</td>
<td>194</td>
</tr>
<tr>
<td></td>
<td>7-1-2-2 OTA Schmitt Trigger Circuit</td>
<td>195</td>
</tr>
<tr>
<td></td>
<td>7-1-2-3 OTA Micropower Amplifier</td>
<td>196</td>
</tr>
<tr>
<td>7-1-3</td>
<td>CURRENT-DIFFERENCING AMPLIFIER</td>
<td>197</td>
</tr>
<tr>
<td></td>
<td>7-1-3-1 Biasing the Norton Op Amp</td>
<td>199</td>
</tr>
<tr>
<td></td>
<td>7-1-3-2 The CDA as a Comparator</td>
<td>201</td>
</tr>
<tr>
<td>SECTION 7-2</td>
<td>TERMINOLOGY EXERCISE</td>
<td>201</td>
</tr>
<tr>
<td>SECTION 7-3</td>
<td>PROBLEMS AND EXERCISES</td>
<td>202</td>
</tr>
<tr>
<td>SECTION 7-4</td>
<td>EXPERIMENTS</td>
<td>202</td>
</tr>
<tr>
<td></td>
<td>EXPERIMENT 7.1 CDA AC Inverting Amplifier</td>
<td>202</td>
</tr>
<tr>
<td></td>
<td>EXPERIMENT 7-2 CDAs Used as Comparators</td>
<td>203</td>
</tr>
</tbody>
</table>
CHAPTER 8  Basic Op-Amp Circuit Design 207

DESIGN 8-1  COMPARATOR CIRCUITS  208
  8-1-1 Basic Positive-Clamped Comparator  208
  8-1-2 Basic Negative-Clamped Comparator  209
  8-1-3 Output Clamping to a Specific Level  209

DESIGN 8-2  INVERTING AMPLIFIER CIRCUITS  210
  8-2-1 Inverting DC Amplifier  212
  8-2-2 Inverting AC Amplifier  213
  8-2-3 Basic Two-Stage Cascaded Amplifier  215

DESIGN 8-3  NONINVERTING AMPLIFIER CIRCUITS  215
  8-3-1 Noninverting DC Amplifier  215
  8-3-2 Noninverting AC Amplifier  216
  8-3-3 Basic Two-Stage Cascaded Noninverting Amplifier  217

DESIGN 8-4  VOLTAGE-FOLLOWER CIRCUITS  218
  8-4-1 Noninverting DC Voltage Follower  218
  8-4-2 Noninverting AC Voltage Follower  219
  8-4-3 Inverting DC Voltage Follower  219
  8-4-4 Inverting AC Voltage Follower  220

DESIGN 8-5  VOLTAGE-SUMMING-AMPLIFIER CIRCUITS  221
  8-5-1 Inverting DC Summing Amplifier  221
  8-5-2 Inverting AC Summing Amplifier  223

DESIGN 8-6  DIFFERENTIAL AMPLIFIER CIRCUITS  224
  8-6-1 Differential DC Amplifier  224
  8-6-2 Differential AC Amplifier  226

DESIGN 8-7  SQUARE-WAVE-GENERATOR CIRCUIT  226

CHAPTER 9  Collection of Practical Op-Amp Circuits 228

SECTION 9-1  POWER-SUPPLY APPLICATIONS  228
9-1-1 Voltage Regulator 228
9-1-2 Dual-Tracking Op-Amp Power Supply 228
9-1-3 Crowbar Overvoltage Protection 229
9-1-4 Crowbar Undervoltage Protection 229

SECTION 9-2 AMPLIFIERS 230
9-2-1 Bridge Amplifier 230
9-2-2 Buffer Amplifier 231
9-2-3 Current Amplifier 232
9-2-4 Lamp Driver 232
9-2-5 LED Driver 232
9-2-6 Photodiode/Phototransistor Amplifier 233
9-2-7 Photoresistor Amplifier 233
9-2-8 Solar-Cell Amplifier 233
9-2-9 Power-Booster Amplifier 234
9-2-10 Phono Amplifier 235
9-2-11 Squaring Amplifier 235
9-2-12 Instrumentation Amplifier 236
9-2-13 Audio Bridge Amplifier 236
9-2-14 DC Servo Amplifier 236
9-2-15 AC Servo Amplifier 236
9-2-16 Absolute-Value Amplifier 237

SECTION 9-3 OSCILLATORS AND WAVEFORM GENERATORS 239
9-3-1 Phase-Shift Oscillator 239
9-3-2 Easily Tuned Sine-Wave Oscillator 239
9-3-3 Crystal Oscillator 240
9-3-4 Simple Staircase Generator 240
9-3-5 Free-Running Staircase Generator/Pulse Counter 240
9-3-6 Digital-to-Analog Staircase Generator 241
9-3-7 Monostable (One-Shot) Multivibrator 241
9-3-8 Schmitt Trigger 242
9-3-9 Programmable Unijunction Oscillator 244
9-3-10 Frequency Doubler 244
9-3-11 Pulse Generator 245
9-3-12 Two-Tone Alarm Circuit 245

SECTION 9-4 SIMPLE TEST INSTRUMENTS 246
9-4-1 Sensitive Low-Cost DC Voltmeter 246
9-4-2 Wide-Band AC Voltmeter 246
9-4-3 Triple-Range Ohmmeter 247
9-4-4 Audio Circuit Tester 248

SECTION 9-5 LOGIC CIRCUITS 250
9-5-1 AND Gate 250
9-5-2 OR Gate 250
9-5-3 NAND Gate 250
9-5-4 NOR Gate 252
9-5-5 RS Flip-Flop 253

SECTION 9-6 MISCELLANEOUS CIRCUITS 253

9-6-1 Feedforward Frequency Compensation 253
9-6-2 One-IC Intercom 254
9-6-3 Simulated Inductor (Gyrator) 254
9-6-4 Op-Amp Tachometer 254
9-6-5 Low-Frequency Mixer 255
9-6-6 Window Voltage Detector 256
9-6-7 Sample-and-Hold Circuit 256
9-6-8 Bi-Quad Active Bandpass Filter 257
9-6-9 Compressor/Expander Amplifiers 258
9-6-10 Log Generator 259
9-6-11 Antilog Generator 259
9-6-12 Multiplier/Divider 259
9-6-13 Cube Generator 260
9-6-14 Root Extractor 260
9-6-15 High-Speed Warning Device 260
9-6-16 Pulse-Width Modulator 265
9-6-17 Capacitance Multiplier 265
9-6-18 Precision Rectifiers 265
9-6-19 Phase Shifter 266
9-6-20 Phase-Locked Loop 266
9-6-21 Voltage-Level Detector 267

Appendix A Voltage Waveform Photographs for Selected Experiments 269

Appendix B Review Of Test Equipment Operation And Use 274

B-1-1 UNDERSTANDING MULTIMETERS 274
B-1-2 READING MULTIMETERS 275
B-1-3 UNDERSTANDING THE OSCILLOSCOPE 276
B-1-4 READING THE OSCILLOSCOPE 279
B-1-5 USING THE BASIC SIGNAL GENERATOR 280
B-1-6 USE OF A POWER SUPPLY 282
B-1-7 PROCEDURE FOR EXPERIMENTING WITH TESTING A DISCRETE CIRCUIT

Appendix C Selected Manufacturers’ Op-Amp Specification Sheets 285

Answers to Self-Checking Quizzes 312

Op Amp Final Examination 313