

OPERATIONAL AMPLIFIERS: INTEGRATED AND HYBRID CIRCUITS

GEORGE B. RUTKOWSKI, P.E.

Computek



A Wiley-Interscience Publication

JOHN WILEY & SONS, INC.

New York • Chichester • Brisbane • Toronto • Singapore

CONTENTS

Preface	xi
1 Differential and Operational Amplifiers	1
1.1 Transistor Review, 1	
1.2 The Differential Circuit, 5	
1.3 A BJT Current Source, 9	
1.4 Current-Sourced Biased Differential Amplifier, 13	
1.5 Multistage Differential Circuits, 14	
1.6 Level Shifting with Intermediate Stage, 16	
1.7 Output Stage and Complete Operational Amplifier, 17	
Review Questions 1, 18	
Problems 1, 19	
2 Characteristics of Op Amps and Their Power Supply Requirements	22
2.1 Open-Loop Voltage Gain A_{VOL} , 22	
2.2 Output Offset Voltage V_{oo} , 25	
2.3 Input Resistance R_i , 25	
2.4 Output Resistance R_o , 26	
2.5 Bandwidth BW, 26	
2.6 Response Time, 27	
2.7 Power Supply Requirements, 28	
Review Questions 2, 28	

3	The Op Amp With and Without Feedback	30
3.1	Open-Loop Considerations, 30	
3.2	Feedback and the Inverting Amplifier, 34	
3.3	Feedback and the Noninverting Amplifier, 41	
3.4	The Voltage Follower, 45	
	Review Questions 3, 47	
	Problems 3, 48	
4	Offset Considerations	55
4.1	Input Offset Voltage V_{io} , 55	
4.2	Input Bias Current I_B , 59	
4.3	Input Offset Current I_{io} , 63	
4.4	Combined Effects of V_{io} and I_{io} , 65	
	Review Questions 4, 66	
	Problems 4, 66	
5	Common-Mode Voltages and Differential Amplifiers	72
5.1	Differential-Mode Op Amp Circuit, 73	
5.2	Common-Mode Rejection Ratio, CMRR, 75	
5.3	Maximum Common-Mode Input Voltages, 79	
5.4	Op Amp Instrumentation Circuits, 80	
	Review Questions 5, 85	
	Problems 5, 85	
6	The Op Amp's Behavior at Higher Frequencies	92
6.1	Gain and Phase Shift vs. Frequency, 92	
6.2	Bode Diagrams, 94	
6.3	External Frequency Compensation, 96	
6.4	Compensated Op Amps, 99	
6.5	Slew Rate, 101	
6.6	Output Swing Capability vs. Frequency, 103	
6.7	Harmonics in Nonsinusoidal Waveforms, 105	
6.8	Noise, 110	
6.9	Equivalent Input Noise Model, 111	
	Review Questions 6, 113	
	Problems 6, 114	
7	Practical Considerations	123
7.1	Offset Voltage vs. Power Supply Voltage, 123	
7.2	Bias and Offset Currents vs. Temperature, 127	
7.3	Input Offset Voltage vs. Temperature, 132	
7.4	Other Temperature-Sensitive Parameters, 133	

7.5	Channel Separation, 135	
7.6	Cleaning PC Boards and Guarding Input Terminals, 136	
7.7	Protecting Techniques, 137	
	Review Questions 7, 139	
	Problems 7, 139	
8	Analog Applications of Op Amps	142
8.1	Op Amps as ac Amplifiers, 142	
8.2	Summing and Averaging Circuits, 146	
8.3	The Op Amp as an Integrator, 151	
8.4	Three-Terminal Regulators, 155	
8.5	Regulator Power Dissipation, 157	
8.6	Heat Sinks, 158	
8.7	Variable Regulated Power Supply, 159	
	Review Questions 8, 163	
	Problems 8, 164	
9	Active Filters	169
9.1	Basic RC Filters, 169	
9.2	First-Order Active Filters, 173	
9.3	<i>N</i> th-Order Active Filters, 175	
9.4	Typical Second-Order Low-Pass Active Filter, 180	
9.5	Equal-Component Low-Pass Active Filter, 185	
9.6	Typical Second-Order High-Pass Active Filter, 188	
9.7	Active Bandpass Filters, 190	
9.8	Active Bandstop (Notch) Filters, 193	
	Review Questions 9, 196	
	Problems 9, 198	
10	Nonlinear and Digital Applications of Op Amps	201
10.1	Voltage Limiters, 201	
10.2	The Zero-Crossing Detector, 206	
10.3	Op Amps as Comparators, 207	
10.4	Digital-to-Analog (D/A) Converters, 214	
10.5	Analog-to-Digital (A/D) Converters, 220	
10.6	Absolute Value Circuits, 223	
10.7	The Op Amp as a Sample-and-Hold Circuit, 226	
	Problems 10, 227	
11	Op Amp Signal Generators	232
11.1	A Square-Wave Generator, 232	
11.2	A Triangular-Wave Generator, 235	
11.3	A Sawtooth Generator, 235	

11.4	Variable-Frequency Signal Generators,	237
11.5	The Wien Bridge Oscillator,	238
11.6	The Twin-T Oscillator,	239
	Problems 11,	241
12	Power Operational Amplifiers	242
12.1	Boosting Output Power,	242
12.2	Safe Operating Area (SOA),	248
12.3	Current Limiting on Power Amplifiers,	249
12.4	External Current Limiting/ Internal Transient Protection,	251
12.5	Stability,	252
12.6	Input Compensation,	253
12.7	Isolating a Capacitive Load,	254
12.8	An Output Snubber,	256
12.9	Sleep Mode,	256
12.10	Selecting a Heat Sink,	258
12.11	Mounting Considerations,	260
12.12	Motor Drives,	261
	Review Questions 12,	265
	Problems 12,	266
	Glossary	268
	Appendix A Derivation of Eq. (1-6)	273
	Appendix B Derivation of Eqs. (1-12a) and (1-12b)	275
	Appendix C Derivation of Eqs. (1-13) and (1-18)	278
	Appendix D Derivation of Eq. (1-19)	279
	Appendix E Table of Op Amps and Specifications	282
	Appendix F Specifications of the 741 Op Amp	286
	Appendix G Derivation of Eq. (4-4)	289
	Appendix H Derivation of Eq. (4-7)	291
	Appendix I Derivation of Eq. (6-1)	293
	Appendix J Specification of the 709 Op Amp	297
	Appendix K Selection of Coupling Capacitors	301

Appendix L	Op Amp as an Integrator	302
Appendix M	Op Amp as a Differentiator	305
Appendix N	Phase Shift in Second-Order Active Filters	309
Appendix O	Programs that Display Tables of Gain vs. Frequency of Second-Order Low-Pass and High-Pass Active Filters	310
Appendix P	Program for Analyzing Multiple-Feedback Bandpass Filters	312
Appendix Q	Program for Analyzing Multiple-Feedback Bandstop Filters	314
Appendix R	Fixed Voltage Regulators	317
Appendix S	Electronics Packages	319
Appendix T	Power Op Amp Specs	322
Appendix U	Derivation of Eqs. (12-3) and (12-4)	325
Appendix V	Op Amp Applications	328
	Answers to Selected Odd-Numbered Problems	346
	Index	353