

Table of contents

- **Preface** (p. vii)
- **Reader Background** (p. vii)
- **Rationale** (p. vii)
- **Description of the Chapters** (p. viii)
- **Features** (p. x)
- **1 Sources and Properties of Biomedical Signals** (p. 1)
- **1.1 Introduction** (p. 1)
- **1.2 Sources of Endogenous Bioelectric Signals** (p. 1)
- **1.3 Nerve Action Potentials** (p. 2)
- **1.4 Muscle Action Potentials** (p. 5)
- **1.4.1 Introduction** (p. 5)
- **1.4.2 The Origin of EMGs** (p. 6)
- **1.4.3 EMG Amplifiers** (p. 9)
- **1.5 The Electrocardiogram** (p. 9)
- **1.5.1 Introduction** (p. 9)
- **1.5.2 ECG Amplifiers** (p. 10)
- **1.6 Other Biopotentials** (p. 11)
- **1.6.1 Introduction** (p. 11)
- **1.6.2 EEGs** (p. 12)
- **1.6.3 Other Body Surface Potentials** (p. 13)
- **1.7 Discussion** (p. 13)
- **1.8 Electrical Properties of Bioelectrodes** (p. 13)
- **1.9 Exogenous Bioelectric Signals** (p. 17)
- **1.10 Chapter Summary** (p. 20)
- **2 Models for Semiconductor Devices Used in Analog Electronic Systems** (p. 23)
- **2.1 Introduction** (p. 23)
- **2.2 pn Junction Diodes** (p. 24)
- **2.2.1 Introduction** (p. 24)
- **2.2.2 The pn Diode's Volt-Ampere Curve** (p. 24)
- **2.2.3 High-Frequency Behavior of Diodes** (p. 28)
- **2.2.4 Schottky Diodes** (p. 30)
- **2.3 Mid-Frequency Models for BJT Behavior** (p. 33)
- **2.3.1 Introduction** (p. 33)
- **2.3.2 Mid-Frequency Small-Signal Models for BJTs** (p. 35)
- **2.3.3 Amplifiers Using One BJT** (p. 40)
- **2.3.4 Simple Amplifiers Using Two Transistors at Mid-Frequencies** (p. 44)
- **2.3.5 The Use of Transistor Dynamic Loads To Improve Amplifier Performance** (p. 53)
- **2.4 Mid-Frequency Models for Field-Effect Transistors** (p. 56)
- **2.4.1 Introduction** (p. 56)
- **2.4.2 JFETs at Mid-Frequencies** (p. 57)
- **2.4.3 MOSFET Behavior at Mid-Frequencies** (p. 60)
- **2.4.4 Basic Mid-Frequency Single FET Amplifiers** (p. 62)

- **2.4.5 Simple Amplifiers Using Two FETs at Mid-Frequencies** (p. 65)
- **2.5 High-Frequency Models for Transistors, and Simple Transistor Amplifiers** (p. 71)
 - **2.5.1 Introduction** (p. 71)
 - **2.5.2 High-Frequency SSMs for BJTs and FETs** (p. 74)
 - **2.5.3 Behavior of One-BJT and One-FET Amplifiers at High Frequencies** (p. 78)
 - **2.5.4 High-Frequency Behavior of Two-Transistor Amplifiers** (p. 89)
 - **2.5.5 Broadbanding Strategies** (p. 94)
- **2.6 Photons, Photodiodes, Photoconductors, LEDs, and Laser Diodes** (p. 97)
 - **2.6.1 Introduction** (p. 97)
 - **2.6.2 PIN Photodiodes** (p. 99)
 - **2.6.3 Avalanche Photodiodes** (p. 105)
 - **2.6.4 Signal Conditioning Circuits for Photodiodes** (p. 108)
 - **2.6.5 Photoconductors** (p. 113)
 - **2.6.6 LEDs** (p. 115)
 - **2.6.7 Laser Diodes** (p. 117)
- **2.7 Chapter Summary** (p. 126)
- **3 The Differential Amplifier** (p. 141)
 - **3.1 Introduction** (p. 141)
 - **3.2 DA Circuit Architecture** (p. 142)
 - **3.3 Common-Mode Rejection Ratio (CMRR)** (p. 145)
 - **3.4 CM and DM Gain of Simple DA Stages at High Frequencies** (p. 147)
 - **3.4.1 Introduction** (p. 147)
 - **3.4.2 High-Frequency Behavior of A_C and A_D for the JFET DA** (p. 147)
 - **3.4.3 High-Frequency Behavior of A_D and A_C for the BJT DA** (p. 152)
 - **3.5 Input Resistance of Simple Transistor DAs** (p. 153)
 - **3.6 How Signal Source Impedance Affects Low-Frequency CMRR** (p. 157)
 - **3.7 How Op Amps Can Be Used To Make DAs for Medical Applications** (p. 160)
 - **3.7.1 Introduction** (p. 160)
 - **3.7.2 Two-Op Amp DA Designs** (p. 161)
- **3.8 Chapter Summary** (p. 162)
- **4 General Properties of Electronic Single-Loop Feedback Systems** (p. 173)
 - **4.1 Introduction** (p. 173)
 - **4.2 Classification of Electronic Feedback Systems** (p. 173)
 - **4.3 Some Effects of Negative Voltage Feedback** (p. 175)
 - **4.3.1 Reduction of Output Resistance** (p. 175)
 - **4.3.2 Reduction of Total Harmonic Distortion** (p. 177)
 - **4.3.3 Increase of NFB Amplifier Bandwidth at the Cost of Gain** (p. 179)
 - **4.3.4 Decrease in Gain Sensitivity** (p. 181)
 - **4.4 Effects of Negative Current Feedback** (p. 183)
 - **4.5 Positive Voltage Feedback** (p. 187)
 - **4.5.1 Introduction** (p. 187)
 - **4.5.2 Amplifier with Capacitance Neutralization** (p. 188)
- **4.6 Chapter Summary** (p. 190)

- **5 Feedback, Frequency Response, and Amplifier Stability** (p. 199)
- **5.1 Introduction** (p. 199)
- **5.2 Review of Amplifier Frequency Response** (p. 199)
- **5.2.1 Introduction** (p. 199)
- **5.2.2 Bode Plots** (p. 200)
- **5.3 What Stability Means** (p. 205)
- **5.4 Use of Root Locus in Feedback Amplifier Design** (p. 214)
- **5.5 Use of Root-Locus in the Design of "Linear" Oscillators** (p. 223)
- **5.5.1 Introduction** (p. 223)
- **5.5.2 The Phase-Shift Oscillator** (p. 225)
- **5.5.3 The Wien Bridge Oscillator** (p. 228)
- **5.6 Chapter Summary** (p. 230)
- **6 Operational Amplifiers** (p. 239)
- **6.1 Ideal Op Amps** (p. 239)
- **6.1.1 Introduction** (p. 239)
- **6.1.2 Properties of Ideal OP Amps** (p. 240)
- **6.1.3 Some Examples of Op Amp Circuits Analyzed Using IOAs** (p. 240)
- **6.2 Practical Op Amps** (p. 245)
- **6.2.1 Introduction** (p. 245)
- **6.2.2 Functional Categories of Real Op Amps** (p. 245)
- **6.3 Gain-Bandwidth Relations for Voltage-Feedback OAs** (p. 248)
- **6.3.1 The GBWP of an Inverting Summer** (p. 248)
- **6.3.2 The GBWP of a Noninverting Voltage-Feedback OA** (p. 250)
- **6.4 Gain-Bandwidth Relations in Current Feedback Amplifiers** (p. 251)
- **6.4.1 The Noninverting Amplifier Using a CFOA** (p. 251)
- **6.4.2 The Inverting Amplifier Using a CFOA** (p. 252)
- **6.4.3 Limitations of CFOAs** (p. 253)
- **6.5 Voltage Comparators** (p. 256)
- **6.5.1 Introduction** (p. 256)
- **6.5.2 Applications of Voltage Comparators** (p. 259)
- **6.5.3 Discussion** (p. 261)
- **6.6 Some Applications of Op Amps in Biomedicine** (p. 263)
- **6.6.1 Introduction** (p. 263)
- **6.6.2 Analog Integrators and Differentiators** (p. 263)
- **6.6.3 Charge Amplifiers** (p. 267)
- **6.6.4 A Two-Op Amp ECG Amplifier** (p. 268)
- **6.7 Chapter Summary** (p. 270)
- **7 Analog Active Filters** (p. 281)
- **7.1 Introduction** (p. 281)
- **7.2 Types of Analog Active Filters** (p. 282)
- **7.2.1 Introduction** (p. 282)
- **7.2.2 Sallen and Key Controlled-Source AFs** (p. 283)
- **7.2.3 Biquad Active Filters** (p. 288)
- **7.2.4 Generalized Impedance Converter AFs** (p. 292)
- **7.3 Electronically Tunable AFs** (p. 297)
- **7.3.1 Introduction** (p. 297)

- **7.3.2 The Tunable Two-Loop Biquad LPF** (p. 299)
- **7.3.3 Use of Digitally Controlled Potentiometers To Tune a Sallen and Key LPF** (p. 301)
- **7.4 Filter Applications (Anti-Aliasing, SNR Improvement, etc.)** (p. 303)
- **7.5 Chapter Summary** (p. 304)
- **7.5.1 Active Filters** (p. 304)
- **7.5.2 Choice of AF Components** (p. 304)
- **8 Instrumentation and Medical Isolation Amplifiers** (p. 311)
- **8.1 Introduction** (p. 311)
- **8.2 Instrumentation Amps** (p. 312)
- **8.3 Medical Isolation Amps** (p. 314)
- **8.3.1 Introduction** (p. 314)
- **8.3.2 Common Types of Medical Isolation Amplifiers** (p. 316)
- **8.3.3 A Prototype Magnetic IsoA** (p. 319)
- **8.4 Safety Standards in Medical Electronic Amplifiers** (p. 322)
- **8.4.1 Introduction** (p. 322)
- **8.4.2 Certification Criteria for Medical Electronic Systems** (p. 324)
- **8.5 Medical-Grade Power Supplies** (p. 329)
- **8.6 Chapter Summary** (p. 329)
- **9 Noise and the Design of Low-Noise Amplifiers for Biomedical Applications** (p. 331)
- **9.1 Introduction** (p. 331)
- **9.2 Descriptors of Random Noise in Biomedical Measurement Systems** (p. 332)
- **9.2.1 Introduction** (p. 332)
- **9.2.2 The Probability Density Function** (p. 332)
- **9.2.3 The Power Density Spectrum** (p. 334)
- **9.2.4 Sources of Random Noise in Signal Conditioning Systems** (p. 338)
- **9.2.4.1 Noise from Resistors** (p. 338)
- **9.2.4.2 The Two-Source Noise Model for Active Devices** (p. 341)
- **9.2.4.3 Noise in JFETs** (p. 342)
- **9.2.4.4 Noise in BJTs** (p. 344)
- **9.3 Propagation of Noise through LTI Filters** (p. 346)
- **9.4 Noise Factor and Figure of Amplifiers** (p. 347)
- **9.4.1 Broadband Noise Factor and Noise Figure of Amplifiers** (p. 347)
- **9.4.2 Spot Noise Factor and Figure** (p. 349)
- **9.4.3 Transformer Optimization of Amplifier NF and Output SNR** (p. 351)
- **9.5 Cascaded Noisy Amplifiers** (p. 353)
- **9.5.1 Introduction** (p. 353)
- **9.5.2 The SNR of Cascaded Noisy Amplifiers** (p. 354)
- **9.6 Noise in Differential Amplifiers** (p. 355)
- **9.6.1 Introduction** (p. 355)
- **9.6.2 Calculation of the SNR_o of the DA** (p. 356)
- **9.7 Effect of Feedback on Noise** (p. 357)
- **9.7.1 Introduction** (p. 357)
- **9.7.2 Calculation of SNR_o of an Amplifier with NVFB** (p. 357)

- **9.8 Examples of Noise-Limited Resolution of Certain Signal Conditioning Systems** (p. 359)
- **9.8.1 Introduction** (p. 359)
- **9.8.2 Calculation of the Minimum Resolvable AC Input Voltage to a Noisy Op Amp** (p. 359)
- **9.8.3 Calculation of the Minimum Resolvable AC Input Signal to Obtain a Specified SNR_o in a Transformer-Coupled Amplifier** (p. 361)
- **9.8.4 The Effect of Capacitance Neutralization on the SNR_o of an Electrometer Amplifier Used for Glass Micropipette Intracellular Recording** (p. 363)
- **9.8.5 Calculation of the Smallest Resolvable DR/R in a Wheatstone Bridge Determined by Noise** (p. 365)
 - **9.8.5.1 Introduction** (p. 365)
 - **9.8.5.2 Bridge Sensitivity Calculations** (p. 366)
 - **9.8.5.3 Bridge SNR_o** (p. 367)
- **9.8.6 Calculation of the SNR Improvement Using a Lock-In Amplifier** (p. 367)
- **9.8.7 Signal Averaging of Evoked Signals for Signal-to-Noise Ratio Improvement** (p. 371)
 - **9.8.7.1 Introduction** (p. 371)
 - **9.8.7.2 Analysis of SNR Improvement by Averaging** (p. 373)
 - **9.8.7.3 Discussion** (p. 377)
- **9.9 Some Low-Noise Amplifiers** (p. 377)
- **9.10 The Art of Low-Noise Signal Conditioning System Design** (p. 378)
 - **9.10.1 Introduction** (p. 378)
- **9.11 Chapter Summary** (p. 381)
- **10 Digital Interfaces** (p. 391)
 - **10.1 Introduction** (p. 391)
 - **10.2 Aliasing and the Sampling Theorem** (p. 391)
 - **10.2.1 Introduction** (p. 391)
 - **10.2.2 The Sampling Theorem** (p. 392)
 - **10.3 Digital-to-Analog Converters (DACs)** (p. 397)
 - **10.3.1 Introduction** (p. 397)
 - **10.3.2 DAC Designs** (p. 397)
 - **10.3.3 Static and Dynamic Characteristics of DACs** (p. 402)
 - **10.4 Hold Circuits** (p. 405)
 - **10.5 Analog-to-Digital Converters (ADCs)** (p. 406)
 - **10.5.1 Introduction** (p. 406)
 - **10.5.2 The Tracking (Servo) ADC** (p. 407)
 - **10.5.3 The Successive Approximation ADC** (p. 408)
 - **10.5.4 Integrating Converters** (p. 410)
 - **10.5.5 Flash Converters** (p. 414)
 - **10.5.6 Delta-Sigma ADCs** (p. 418)
 - **10.6 Quantization Noise** (p. 422)
 - **10.7 Chapter Summary** (p. 427)
- **11 Modulation and Demodulation of Biomedical Signals** (p. 431)
 - **11.1 Introduction** (p. 431)

- **11.2 Modulation of a Sinusoidal Carrier Viewed in the Frequency Domain** (p. 432)
- **11.3 Implementation of AM** (p. 434)
 - **11.3.1 Introduction** (p. 434)
 - **11.3.2 Some Amplitude Modulation Circuits** (p. 435)
- **11.4 Generation of Phase and Frequency Modulation** (p. 441)
 - **11.4.1 Introduction** (p. 441)
 - **11.4.2 NBFM Generation by Phase-Locked Loop** (p. 442)
 - **11.4.3 Integral Pulse Frequency Modulation as a Means of Frequency Modulation** (p. 444)
- **11.5 Demodulation of Modulated Sinusoidal Carriers** (p. 447)
 - **11.5.1 Introduction** (p. 447)
 - **11.5.2 Detection of AM** (p. 447)
 - **11.5.3 Detection of FM Signals** (p. 451)
 - **11.5.4 Demodulation of DSBSCM Signals** (p. 453)
- **11.6 Modulation and Demodulation of Digital Carriers** (p. 457)
 - **11.6.1 Introduction** (p. 457)
 - **11.6.2 Delta Modulation** (p. 459)
- **11.7 Chapter Summary** (p. 461)
- **12 Examples of Special Analog Circuits and Systems in Biomedical Instrumentation** (p. 467)
 - **12.1 Introduction** (p. 467)
 - **12.2 The Phase-Sensitive Rectifier** (p. 467)
 - **12.2.1 Introduction** (p. 467)
 - **12.2.2 The Analog Multiplier/LPF PSR** (p. 468)
 - **12.2.3 The Switched Op Amp PSR** (p. 469)
 - **12.2.4 The Chopper PSR** (p. 469)
 - **12.2.5 The Balanced Diode Bridge PSR** (p. 470)
 - **12.3 Phase Detectors** (p. 472)
 - **12.3.1 Introduction** (p. 472)
 - **12.3.2 The Analog Multiplier Phase Detector** (p. 472)
 - **12.3.3 Digital Phase Detectors** (p. 475)
 - **12.4 Voltage and Current-Controlled Oscillators** (p. 482)
 - **12.4.1 Introduction** (p. 482)
 - **12.4.2 An Analog VCO** (p. 482)
 - **12.4.3 Switched Integrating Capacitor VCOs** (p. 484)
 - **12.4.4 The Voltage-Controlled, Emitter-Coupled Multivibrator** (p. 485)
 - **12.4.5 The Voltage-to-Period Converter and Applications** (p. 490)
 - **12.4.6 Summary** (p. 495)
 - **12.5 Phase-Locked Loops** (p. 495)
 - **12.5.1 Introduction** (p. 495)
 - **12.5.2 PLL Components** (p. 497)
 - **12.5.3 PLL Applications in Biomedicine** (p. 497)
 - **12.5.4 Discussion** (p. 502)
 - **12.6 True RMS Converters** (p. 502)
 - **12.6.1 Introduction** (p. 502)

- **12.6.2 True RMS Circuits** (p. 503)
- **12.7 IC Thermometers** (p. 508)
- **12.7.1 Introduction** (p. 508)
- **12.7.2 IC Temperature Transducers** (p. 509)
- **12.8 Instrumentation Systems** (p. 511)
- **12.8.1 Introduction** (p. 511)
- **12.8.2 A Self-Nulling Microdegree Polarimeter** (p. 511)
- **12.8.3 A Laser Velocimeter and Rangefinder** (p. 522)
- **12.8.4 Self-Balancing Impedance Plethysmographs** (p. 528)
- **12.8.5 Respiratory Acoustic Impedance Measurement System** (p. 533)
- **12.9 Chapter Summary** (p. 537)
- **References** (p. 539)
- **Index** (p. 543)