Table of contents

- **1. Basic Concepts of Measurement Methods** (p. 1)
- **1.1 Introduction** (p. 1)
- **1.2 General Measurement System** (p. 2)
- **1.3 Experimental Test Plan** (p. 4)
- **Variables** (p. 5)
- **Parameters** (p. 6)
- **Noise and Interference** (p. 6)
- **Random Tests** (p. 8)
- **Replication and Repetition** (p. 12)
- **Concomitant Methods** (p. 13)
- **1.4 Calibration** (p. 13)
- **Static Calibration** (p. 13)
- **Dynamic Calibration** (p. 14)
- **Static Sensitivity** (p. 14)
- **Range** (p. 15)
- **Accuracy** (p. 15)
- **Precision and Bias Errors** (p. 15)
- **Sequential Test** (p. 18)
- **Random Test** (p. 18)
- **1.5 Standards** (p. 21)
- **Basic Dimensions and Their Units** (p. 22)
- **Derived Units** (p. 24)
- **Force** (p. 24)
- **Other Units** (p. 24)
- **Electrical Dimensions** (p. 25)
- **Hierarchy of Standards** (p. 26)
- **Test Standards** (p. 27)
- **1.6 Presenting Data** (p. 27)
- **Rectangular Coordinate Format** (p. 27)
- **Semilog Coordinate Format** (p. 27)
- **Full-Log Coordinate Format** (p. 28)
- **1.7 Summary** (p. 28)
- **References** (p. 28)
- **Nomenclature** (p. 28)
- **Problems** (p. 29)
- **2. Static and Dynamic Characteristics of Signals** (p. 35)
- **2.1 Introduction** (p. 35)
- **2.2 Input-Output Signal Concepts** (p. 35)
- **Classification of Waveforms** (p. 36)
- **Signal Waveforms** (p. 38)
- **2.3 Signal Analysis** (p. 39)
- **Effects of Signal-Averaging Period** (p. 41)
- **DC Offset** (p. 42)
- **2.4 Signal Amplitude and Frequency** (p. 44)

- **Periodic Signals** (p. 45)
- **Frequency Analysis** (p. 47)
- **Fourier Series and Coefficients** (p. 49)
- **Fourier Coefficients for Functions Having Arbitrary Periods** (p. 51)
- **2.5 Fourier Transform and the Frequency Spectrum** (p. 57)
- **Discrete Fourier Transform** (p. 59)
- **2.6 Summary** (p. 64)
- **References** (p. 64)
- **Nomenclature** (p. 64)
- **Problems** (p. 65)
- **3. Measurement System Behavior** (p. 70)
- **3.1 Introduction** (p. 70)
- **3.2 General Model for a Measurement System** (p. 70)
- **Dynamic Measurements** (p. 70)
- **Measurement System Model** (p. 72)
- **3.3 Special Cases of the General System Model** (p. 74)
- **Zero-Order Systems** (p. 74)
- **First-Order Systems** (p. 76)
- **Second-Order Systems** (p. 87)
- **3.4 Transfer Functions** (p. 96)
- **3.5 Phase Linearity** (p. 98)
- **3.6 Multiple-Function Inputs** (p. 99)
- **3.7 Coupled Systems** (p. 101)
- **3.8 Summary** (p. 104)
- **References** (p. 104)
- **Nomenclature** (p. 104)
- **Problems** (p. 105)
- **4. Probability and Statistics** (p. 109)
- **4.1 Introduction** (p. 109)
- **4.2 Statistical Measurement Theory** (p. 110)
- **Probability Density Functions** (p. 110)
- **4.3 Infinite Statistics** (p. 116)
- **4.4 Finite Statistics** (p. 121)
- **Standard Deviation of the Means** (p. 123)
- **Pooled Statistics** (p. 125)
- **4.5 Chi-Squared Distribution** (p. 126)
- **Precision Interval in a Sample Variance** (p. 127)
- **Goodness-of-Fit Test** (p. 129)
- **4.6 Regression Analysis** (p. 131)
- **Least-Squares Regression Analysis** (p. 132)
- **4.7 Data Outlier Detection** (p. 138)
- **4.8 Number of Measurements Required** (p. 140)
- **4.9 Summary** (p. 143)
- **References** (p. 143)
- **Nomenclature** (p. 143)
- **Problems** (p. 144)

- **5. Uncertainty Analysis** (p. 149)
- **5.1 Introduction** (p. 149)
- **5.2 Measurement Errors** (p. 149)
- **5.3 Design-Stage Uncertainty Analysis** (p. 151)
- **Combining Elemental Errors: RSS method** (p. 152)
- **Design-Stage Uncertainty** (p. 152)
- **5.4 Error Sources** (p. 155)
- **Calibration Errors** (p. 156)
- **Data-Acquisition Errors** (p. 156)
- **Data-Reduction Errors** (p. 157)
- **5.5 Bias and Precision Errors** (p. 157)
- **Bias Error** (p. 157)
- **Precision Error** (p. 158)
- **5.6 Uncertainty Analysis: Error Propagation** (p. 159)
- **Propagation of Error** (p. 159)
- **5.7 Advanced-Stage and Single-Measurement Uncertainty Analysis** (p. 163)
- **Zero-Order Uncertainty** (p. 164)
- **Higher-Order Uncertainty** (p. 164)
- **Nth-Order Uncertainty** (p. 165)
- **5.8 Multiple-Measurement Uncertainty Analysis** (p. 170)
- **Propagation of Elemental Errors** (p. 170)
- **Propagation of Uncertainty to a Result** (p. 176)
- **5.9 Summary** (p. 183)
- **References** (p. 183)
- **Nomenclature** (p. 184)
- **Problems** (p. 184)
- **6. Analog Electrical Devices and Measurements** (p. 192)
- **6.1 Introduction** (p. 192)
- **6.2 Analog Devices: Current Measurements** (p. 192)
- **Direct Current** (p. 192)
- **Alternating Current** (p. 195)
- **6.3 Analog Devices: Voltage Measurements** (p. 196)
- **Analog Meters** (p. 197)
- **Oscilloscope** (p. 197)
- **Potentiometer** (p. 199)
- **6.4 Analog Devices: Resistance Measurements** (p. 201)
- **Ohmmeter Circuits** (p. 201)
- **Bridge Circuits** (p. 203)
- **6.5 Loading Errors and Impedance Matching** (p. 208)
- **Loading Errors for A Voltage Dividing Circuit** (p. 209)
- **Interstage Loading Errors** (p. 210)
- **6.6 Analog Signal Conditioning: Amplifiers** (p. 213)
- **6.7 Analog Signal Conditioning: Special Purpose Circuits** (p. 216)
- **Analog Voltage Comparator** (p. 216)
- **Sample and Hold Circuit** (p. 217)
- **Charge Amplifier** (p. 217)

- **Current Loop: 4-20 mA** (p. 219)
- **Multivibrator and Flip-Flop Circuits** (p. 219)
- **6.8 Analog Signal Conditioning: Filters** (p. 221)
- **Butterworth Filter Design** (p. 222)
- **Bessel Filter Design** (p. 225)
- **Active Filters** (p. 226)
- **6.9 Grounds, Shielding, and Connecting Wires** (p. 226)
- **Ground and Ground Loops** (p. 227)
- **Shields** (p. 228)
- **Connecting Wires** (p. 229)
- **6.10 Summary** (p. 229)
- **References** (p. 230)
- **Nomenclature** (p. 230)
- **Problems** (p. 230)
- **7. Sampling, Digital Devices, and Data Acquisition** (p. 235)
- **7.1 Introduction** (p. 235)
- **7.2 Sampling Concepts** (p. 235)
- **Sample Rate** (p. 236)
- **Alias Frequencies** (p. 238)
- **Amplitude Ambiguity** (p. 241)
- **Selecting Sample Rate and Data Number** (p. 243)
- **7.3 Digital Devices: Bits and Words** (p. 244)
- **7.4 Transmitting Digital Numbers: High and Low Signals** (p. 246)
- **7.5 Voltage Measurements** (p. 246)
- **Digital-to-Analog Converter** (p. 247)
- **Analog-to-Digital Converter** (p. 248)
- **Digital Voltmeters** (p. 257)
- **7.6 Data-Acquisition Systems** (p. 258)
- **7.7 Data-Acquisition System Components** (p. 259)
- **Signal Conditioning: Filters and Amplification** (p. 259)
- **Analog Multiplexers** (p. 262)
- **A/D Converters** (p. 262)
- **D/A Converters** (p. 262)
- **Digital Input-Output** (p. 262)
- **Central Processing Unit: Microprocessor** (p. 263)
- **Memory** (p. 263)
- **Central Bus** (p. 264)
- **Buffers** (p. 265)
- **7.8 Analog Input-Output Communication** (p. 265)
- **Data-Acquisition Boards** (p. 265)
- **Single- and Differential-Ended Connections** (p. 267)
- **Special Signal Conditioning Modules** (p. 269)
- **Data-Acquisition Triggering** (p. 269)
- **Data Transfer** (p. 270)
- **7.9 Digital Input-Output Communication** (p. 270)
- **Serial Communications** (p. 271)

- **Universal Serial Bus** (p. 273)
- **Parallel Communications** (p. 274)
- **7.10 Summary** (p. 278)
- **References** (p. 278)
- **Nomenclature** (p. 279)
- **Problems** (p. 279)
- **8. Temperature Measurements** (p. 283)
- **8.1 Introduction** (p. 283)
- **Historical Background** (p. 283)
- **8.2 Temperature Standards and Definition** (p. 284)
- **Fixed-Point Temperatures and Interpolation** (p. 284)
- **Temperature Scales and Standards** (p. 285)
- **8.3 Thermometry Based on Thermal Expansion** (p. 287)
- **Liquid-in-Glass Thermometers** (p. 287)
- **Bimetallic Thermometers** (p. 288)
- **8.4 Electrical Resistance Thermometry** (p. 289)
- **Resistance Temperature Detectors** (p. 289)
- **Thermistors** (p. 297)
- **8.5 Thermoelectric Temperature Measurement** (p. 302)
- **Seebeck Effect** (p. 303)
- **Peltier Effect** (p. 304)
- **Thomson Effect** (p. 304)
- **Fundamental Thermocouple Laws** (p. 305)
- **Basic Temperature Measurement with Thermocouples** (p. 306)
- **Thermocouple Standards** (p. 307)
- **Thermocouple Voltage Measurement** (p. 310)
- **Multiple-Junction Thermocouple Circuits** (p. 316)
- **Data Acquisition Considerations** (p. 318)
- **8.6 Radiative Temperature Measurements** (p. 322)
- **Radiation Fundamentals** (p. 322)
- **Radiation Detectors** (p. 323)
- **Radiative Temperature Measurements** (p. 325)
- **Optical Fiber Thermometers** (p. 326)
- **8.7 Physical Errors in Temperature Measurement** (p. 327)
- **Insertion Errors** (p. 327)
- **Recovery Errors in Temperature Measurement** (p. 335)
- **8.8 Summary** (p. 337)
- **References** (p. 337)
- **Nomenclature** (p. 338)
- **Problems** (p. 339)
- **9. Pressure and Velocity Measurements** (p. 345)
- **9.1 Introduction** (p. 345)
- **9.2 Pressure Concepts** (p. 345)
- **9.3 Pressure Reference Instruments** (p. 348)
- **McLeod Gauge** (p. 348)
- **Barometer** (p. 349)

- **Manometers** (p. 350)
- **Deadweight Testers** (p. 354)
- **9.4 Pressure Transducers** (p. 356)
- **Bourdon Tube** (p. 357)
- **Bellows and Capsule** (p. 358)
- **Diaphragms** (p. 360)
- **9.5 Pressure Transducer Calibration** (p. 364)
- **Static Calibration** (p. 364)
- **Dynamic Calibration** (p. 364)
- **9.6 Pressure Measurements in Moving Fluids** (p. 366)
- **Total Pressure Measurement** (p. 367)
- **Static Pressure Measurement** (p. 368)
- **9.7 Design and Installation: Transmission Effects** (p. 369)
- **Gases** (p. 370)
- **Liquids** (p. 372)
- **Heavily Damped Systems** (p. 373)
- **9.8 Fluid Velocity Measuring Systems** (p. 374)
- **Pitot-Static Pressure Probe** (p. 375)
- **Thermal Anemometry** (p. 377)
- **Doppler Anemometry** (p. 379)
- **Selection of Velocity Measuring Methods** (p. 382)
- **Laser Doppler Anemometers** (p. 383)
- **9.9 Summary** (p. 383)
- **References** (p. 383)
- **Nomenclature** (p. 384)
- **Problems** (p. 384)
- **10. Flow Measurements** (p. 389)
- **10.1 Introduction** (p. 389)
- **10.2 Historical Comments** (p. 389)
- **10.3 Flow Rate Concepts** (p. 390)
- **10.4 Volume Flow Rate Through Velocity Determination** (p. 392)
- **10.5 Pressure Differential Meters** (p. 394)
- **Obstruction Meters** (p. 394)
- **Orifice Meter** (p. 397)
- **Venturi Meter** (p. 399)
- **Flow Nozzles** (p. 401)
- **Sonic Nozzles** (p. 405)
- **Obstruction Meter Selection** (p. 407)
- **Laminar Flow Elements** (p. 411)
- **10.6 Insertion Volume Flow Meters** (p. 412)
- **Electromagnetic Flow Meters** (p. 413)
- **Vortex Shedding Meters** (p. 414)
- **Rotameters** (p. 416)
- **Turbine Meters** (p. 418)
- **Positive-Displacement Meters** (p. 418)
- **10.7 Mass Flow Meters** (p. 419)

- **Thermal Flow Meter** (p. 419)
- **Coriolis Flow Meter** (p. 420)
- **10.8 Flow Meter Calibration and Standards** (p. 423)
- **10.9 Summary** (p. 425)
- **References** (p. 425)
- **Nomenclature** (p. 425)
- **Problems** (p. 426)
- **11. Strain Measurement** (p. 429)
- **11.1 Introduction** (p. 429)
- **11.2 Stress and Strain** (p. 429)
- **11.3 Resistance Strain Gauges** (p. 432)
- **Metallic Gauges** (p. 432)
- **Semiconductor Strain Gauges** (p. 436)
- **11.4 Strain Gauge Electrical Circuits** (p. 438)
- **11.5 Practical Considerations for Strain Measurement** (p. 442)
- **The Multiple Gauge Bridge** (p. 442)
- **Bridge Constant** (p. 443)
- **Apparent Strain and Temperature Compensation** (p. 445)
- **Construction and Installation** (p. 450)
- **Analysis of Strain Gauge Data** (p. 450)
- **Signal Conditioning** (p. 451)
- **Uncertainties in Multichannel Measurements** (p. 453)
- **11.6 Optical Strain Measuring Techniques** (p. 454)
- **Basic Characteristics of Light** (p. 455)
- **Photoelastic Measurement** (p. 456)
- **Moire Methods** (p. 457)
- **11.7 Summary** (p. 460)
- **References** (p. 460)
- **Nomenclature** (p. 461)
- **Problems** (p. 461)
- **12. Metrology, Motion, Force, and Power Measurements** (p. 466)
- **12.1 Introduction** (p. 466)
- **12.2 Dimensional Measurements: Metrology** (p. 466)
- **Historical Perspective** (p. 466)
- **Principles of Linear Measurement** (p. 467)
- **Optical Methods** (p. 473)
- **12.3 Displacement Measurements** (p. 474)
- **Potentiometers** (p. 474)
- **Linear Variable Differential Transformers** (p. 474)
- **12.4 Measurement of Mass** (p. 477)
- **12.5 Measurement of Acceleration and Vibration** (p. 482)
- **Seismic Transducer** (p. 482)
- **Transducers for Shock and Vibration Measurement** (p. 488)
- **12.6 Velocity Measurements** (p. 489)
- **Linear Velocity Measurements** (p. 489)
- **Velocity from Displacement or Acceleration** (p. 489)

- **Moving Coil Transducers** (p. 492)
- **Angular Velocity Measurements** (p. 492)
- **12.7 Force Measurement** (p. 496)
- **Load Cells** (p. 496)
- **12.8 Torque Measurements** (p. 500)
- **Measurement of Torque on Rotating Shafts** (p. 501)
- **12.9 Mechanical Power Measurements** (p. 502)
- **Rotational Speed, Torque, and Shaft Power** (p. 502)
- **Cradled Dynamometers** (p. 503)
- **12.10 Summary** (p. 504)
- **References** (p. 506)
- **Nomenclature** (p. 506)
- **Problems** (p. 506)
- **Appendix A A Guide for Technical Writing** (p. 509)
- **Appendix B Property Data and Conversion Factors** (p. 516)
- **Glossary** (p. 523)
- **Index** (p. 531)