

EXPERIMENTAL METHODS FOR ENGINEERS

SEVENTH EDITION

J. P. Holman

*Professor of Mechanical Engineering
Southern Methodist University*



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The cover shows three-dimensional views of response of second-order system to step input. Adapted from Figure 2.9 of the text.

Physical constants

Avogadro's number	$N_0 = 6.022045 \times 10^{26}$ molecules/kg mol
Universal gas constant	$R = 1545.35 \text{ ft} \cdot \text{lb}/\text{lbm} \cdot \text{mol} \cdot ^\circ\text{R}$ $= 8314.41 \text{ J}/\text{kg mol} \cdot \text{K}$ $= 1.986 \text{ Btu}/\text{lbm} \cdot \text{mol} \cdot ^\circ\text{R}$ $= 1.986 \text{ kcal}/\text{kg mol} \cdot \text{K}$
Planck's constant	$h = 6.626176 \times 10^{-34}$ J-sec
Boltzmann's constant	$k = 1.380662 \times 10^{-23}$ J/molecule \cdot K $= 8.6173 \times 10^{-5}$ eV/molecule \cdot K
Speed of light in vacuum	$c = 2.997925 \times 10^8$ m/s
Standard gravitational acceleration	$g = 32.174 \text{ ft}/\text{s}^2$ $= 9.80665 \text{ m}/\text{s}^2$
Electron mass	$m_e = 9.1095 \times 10^{-31}$ kg
Charge on the electron	$e = 1.602189 \times 10^{-19}$ C
Stefan-Boltzmann constant	$\sigma = 0.1714 \times 10^{-8}$ Btu/hr \cdot ft ² \cdot R ⁴ $= 5.669 \times 10^{-8}$ W/m ² \cdot K ⁴

Conversion factors

Length 12 in = 1 ft 2.54 cm = 1 in 1 $\mu\text{m} = 10^{-6}$ m = 10^{-4} cm Mass 1 kg = 2.205 lbm 1 slug = 32.17 lbm 454 g = 1 lbm Force 1 dyn = 2.248×10^{-6} lbf 1 lbf = 4.448 N 10 ⁵ dyn = 1 N Energy 1 ft \cdot lbf = 1.356 J 1 kW \cdot h = 3413 Btu 1 hp \cdot h = 2545 Btu 1 Btu = 252 cal 1 Btu = 778 ft \cdot lbf Pressure 1 atm = 14.696 psia = 2116 lbf/ft ² $= 1.01325 \times 10^5$ Pa = 760 mmHg 1 bar = 10 ⁵ Pa 1 $\mu\text{bar} = 1 \text{ dyn}/\text{cm}^2 = 2.089 \text{ lbf}/\text{ft}^2 = 0.1 \text{ Pa}$ 1 mmHg = 1333.22 bar = 133.3 Pa 1 μmHg (micron) = 10^{-3} mmHg = 0.133 Pa 1 Torr = 1 mmHg 1 in Hg = 70.73 lbf/ft ² 1 in H ₂ O = 5.203 lbf/ft ² = 249.1 Pa 1 psia = 6.89476 kPa $= 0.070307 \text{ kgf}/\text{cm}^2$ (kp/cm ²)	Dynamic viscosity 1 lbf-s/ft ² = 47.8803 N-s/m ² = 478.803 P $= 1.158 \times 10^5$ lbm/h-ft $= 47.8803 \text{ kg}/\text{m-s}$ 1 N-s/m ² = 2.08854 $\times 10^{-2}$ lbf-s/ft ² $= 10 \text{ P} = 1000 \text{ cP}$ $= 2419 \text{ lbm}/\text{h-ft} = 1 \text{ kg}/\text{m-s}$ 1 Poise(P) = 100 cP = 1 dyn-s/cm ² $= 0.1 \text{ N-s}/\text{m}^2 = 0.1 \text{ kg}/\text{m-s}$ $= 2.08854 \times 10^{-3} \text{ lbf-s}/\text{ft}^2$ $= 241.9 \text{ lbm}/\text{h-ft}$ Kinematic viscosity 1 ft ² /s = 9.2903×10^{-2} m ² /s $= 929.03 \text{ St} = 929.03 \text{ cm}^2/\text{s}$ 1 m ² /s = 10.7639 ft ² /s = 10 ⁴ St 1 Stoke(St) = 1 cm ² /s = 100 cSt $= 10^{-4} \text{ m}^2/\text{s} = 10.7639 \times 10^{-4} \text{ ft}^2/\text{s}$ Volume flow rates 1 gpm = 231 in ³ /min = 63.09 cm ³ /s 1 liter = 0.26417 gal 1 ft ³ /min (cfm) = 0.028317 m ³ /min $= 471.95 \text{ cm}^3/\text{s}$ 1 std cfm of air at 1 atm, 20°C = 0.07513 lbm/min $= 0.54579 \text{ g/s}$ Thermal conductivity 1 cal/s \cdot cm \cdot °C = 242 Btu/h \cdot ft \cdot F 1 W/cm \cdot °C = 57.79 Btu/h \cdot ft \cdot F
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BASIC DATA ANALYSIS RELATIONS

PROPAGATION OF UNCERTAINTY

General

$$R = f(x_1, x_2, \dots, x_n); \quad w_R = \left[\left(\frac{\partial R}{\partial x_1} \right)^2 w_{x_1}^2 + \dots + \left(\frac{\partial R}{\partial x_n} \right)^2 w_{x_n}^2 \right]^{1/2}$$

Product Function

$$R = x_1^{a_1} \cdot x_2^{a_2} \cdot \dots \cdot x_n^{a_n} = \prod_{i=1}^n x_i^{a_i}; \quad \frac{w_R}{R} = \left[\sum_{i=1}^n \left(a_i \frac{w_{x_i}}{x_i} \right)^2 \right]^{1/2}$$

Arithmetic Function

$$R = a_1 x_1 + a_2 x_2 + \dots + a_n x_n = \sum_{i=1}^n a_i x_i; \quad w_R = \left[\sum_{i=1}^n (a_i w_{x_i})^2 \right]^{1/2}$$

POPULATION STANDARD DEVIATION

$$\sigma = \left[\frac{\sum_{i=1}^n (x_i - x_m)^2}{n} \right]^{1/2}, \quad \text{where } x_m = \frac{\sum x_i}{n}$$

SAMPLE STANDARD DEVIATION

$$\sigma = \left[\frac{\sum_{i=1}^n (x_i - x_m)^2}{n-1} \right]^{1/2}$$

STANDARD DEVIATION OF MEAN

$$\sigma_m = \frac{\sigma}{n^{1/2}}$$

COEFFICIENT OF DETERMINATION r^2 (square of correlation coefficient)

$$r^2 = 1 - \sigma_{y,x}^2 / \sigma_y^2; \quad \sigma = \left[\frac{\sum (y_i - y_{ic})^2}{n-1} \right]^{1/2}; \quad \sigma_{y,x} = \left[\frac{\sum (y_i - y_{ic})^2}{n-2} \right]^{1/2}$$

Computer Equation for r^2

$$r^2 = \frac{[n \sum x_i y_i - (\sum x_i)(\sum y_i)]^2}{[n \sum x_i^2 - (\sum x_i)^2] [n \sum y_i^2 - (\sum y_i)^2]}$$

NORMAL DISTRIBUTION

x	Fraction of Data within Range of $\pm x$
0.6745σ	0.5
1.0σ	0.6827
2.0σ	0.9545
3.0σ	0.9973
4.0σ	0.999937

POWER FUNCTION CORRELATION

$$y = ax^b; \quad \ln y = \ln a + b \ln x; \quad \text{plots as straight line on loglog chart}$$

EXPONENTIAL CORRELATION

$$y = ae^{bx}; \quad \ln y = \ln a + bx; \quad \text{plots as straight line on semilog chart}$$

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ABOUT THE AUTHOR

J. P. Holman received his Ph.D. in mechanical engineering from Oklahoma State University. After two years active duty as a research scientist in the Air Force Aerospace Research Laboratory, he joined the faculty of Southern Methodist University, where he is presently Brown Foundation Professor of Mechanical Engineering. He has held administrative positions as Director of the Thermal and Fluid Sciences Center, Head of Civil and Mechanical Engineering Department, Assistant Provost for Instructional Media, and has been the recipient of fifteen outstanding teacher awards.

Dr. Holman published over 30 papers in several areas of heat transfer and his three widely used textbooks, *Heat Transfer*, 1963 (8th ed. 1998), *Experimental Methods for Engineers*, 1966 (6th ed. 1994), and *Thermodynamics*, 1969 (4th ed. 1988), all published by McGraw-Hill, Inc., have been translated into Spanish, Chinese, Japanese, Korean, Indonesian, and Portuguese and are distributed worldwide.

A member of the American Society of Engineering Education, Dr. Holman is past Chairman of the National Mechanical Engineering Division and past Chairman of the ASME Region X Mechanical Engineering Department Heads. Dr. Holman is a registered professional engineer in the state of Texas and received the *Mechanical Engineer of the Year* award from the North Texas Section of the American Society of Mechanical Engineers in 1971.

Dr. Holman is also the recipient of the *George Washington Award* from the American Society of Engineering Education for distinguished contributions to Engineering Education (1972), the *James Harry Potter Gold Medal* for contributions to thermodynamics from ASME (1986), and the *Worcester Reed Warner Gold Medal* for outstanding contributions to the permanent literature of engineering from ASME (1987). He is a Life Fellow of ASME. In 1993 he was the recipient of the *Lohmann Medal* from Oklahoma State University, awarded annually to a distinguished alumnus of that institution. In 1995, Dr. Holman received the *Ralph Coats Roe Award* from ASEE for excellence in mechanical engineering education.

PREFACE

Experimental measurements can be vexatious, and a textbook about experimental methods cannot alleviate all the problems that are perplexing to the experimental engineer. Engineering education has placed an increased emphasis on the ability of an individual to perform a theoretical analysis of a problem. Experimental methods are not unimportant, but analytical studies have, at times, seemed to deserve more emphasis, particularly with the enormous computing power that is available. Laboratory work has also become more sophisticated in the modern engineering curricula. Conventional laboratory courses have consistently been changed to include experiments with rather elaborate electronic instrumentation and microprocessor- or computer-based data acquisition systems. Surprisingly enough, however, many engineering graduates do not seem capable of performing simple engineering measurements with acceptable precision. Furthermore, they are amazingly inept when asked the question: How *good* is the measurement? They automatically assume the results are accurate to the number of digits displayed in the computer printout.

This book represents a first survey of experimental methods for undergraduate students. As such, it covers a broad range of topics and may be lacking in depth on certain topics. In these instances, the reader is referred to more detailed treatments in specialized monographs.

It is important that engineers be able to perform successful experiments, and it is equally important that they know or be able to estimate the accuracy of their measurements. This book discusses a rather broad range of instruments and experimental measurement techniques. Strong emphasis is placed on problem-solving, and the importance of accuracy, error, and uncertainty in experimental measurements is stressed throughout all the discussions. The book is generally suitable as an accompaniment to laboratory sessions oriented around the specific experiments available at a particular institution. Portions of the text material may be covered in a lecture session. The lectures would be concerned with the principles of instrumentation, whereas the laboratory periods would afford the student an opportunity to use some of the devices discussed in this text and laboratory manuals that may be available to faculty planning the course. The particular experiments, or the instruments used in the laboratory periods, will depend on the facilities available and the objectives set by each curriculum. A mathematical background through ordinary differential equations is assumed for the text developments, and it is expected that basic courses in thermodynamics, engineering mechanics, and electric-circuit theory will precede a course based on this text.

Whatever the course arrangement for which this text is applied, it is strongly recommended that the problems at the end of each chapter receive careful attention. These problems force the student to examine several instruments to determine their accuracy and the uncertainties that might result from faulty measurement techniques. In many instances the problems are very similar to numerical examples in the text. Other problems require the student to extend the text material through derivations.

design of experiments, and so on. The selection of problems for a typical course will depend, naturally, on the types of experiments and laboratory facilities available for use with the course.

A few remarks concerning the arrangement of the text material are in order. A brief presentation of all topics was desired so that a rather broad range of experimental methods could be discussed within the framework of a book of modest length. Chapters 1 and 2 provide initial motivation remarks and some brief definitions of important terms common to all measurement systems. This discussion includes basic concepts of dynamic response in zeroth-, first-, and second-order systems. Next, a simple presentation of some of the principles of statistical data analysis is given in Chapter 3. Some of the concepts in Chapter 3 are used in almost every subsequent chapter in the book, particularly the concept of experimental uncertainty.

Chapter 4 presents several simple electrical-measurement and amplifier circuits and the principles of operation of typical electric transducers. Many of these transducers are applicable to measurement problems described in later chapters. Chapters 5 and 6, concerning dimensional and pressure measurements, offer fairly conventional presentations of their subject matter, except that numerical examples and problems are included to emphasize the importance of experimental uncertainty in the various devices. Flow measurement is discussed in Chapter 7 in a rather conventional manner. A notable feature of this chapter is the section on flow-visualization techniques. Again, the examples and problems illustrate some of the advantages and shortcomings of the various experimental techniques. Chapter 8 is quite specific in its discussion of temperature-measurement devices. Strong emphasis is placed on the errors that may arise from conduction, convection, and heat transfer between the temperature-sensing device and its thermal environment. Methods are presented for correcting these errors. Chapter 9 is brief but gives the reader an insight into the problems associated with transport-property measurements. The material in this chapter is dependent on the measurement techniques discussed in Chapters 6, 7, and 8. The material in Chapter 9 could be dispersed through the three previous chapters and still achieve a balanced presentation; however, it was believed best to bring transport properties and thermal measurements into sharper focus by grouping them in one chapter.

Static force, torque, and strain measurements are discussed in Chapter 10. The strain measurements are related to some elementary principles of experimental stress analysis, and the operation of the electrical strain gage is emphasized.

Some of the elementary principles of motion- and vibration-measurement devices are discussed in Chapter 11. Included in this presentation is a discussion of sound waves, sound-pressure level, and acoustic measurements. The inclusion of the acoustics material in Chapter 11 is somewhat arbitrary since this material would be equally pertinent in Chapter 6.

Chapter 12 discusses thermal- and nuclear-radiation measurements. The presentation is brief, but some of the more important detection techniques are examined, and examples are given to illustrate the important principles. A short presentation of the statistics of counting illustrates the importance of background activity in nuclear-radiation detection. The thermal-radiation measurements are properly related to the temperature measurement material in Chapter 8.

Chapter 13 presents some of the measurement techniques that are used in air-pollution-control applications. Such measurements make use of the basic pressure, flow, and temperature measurement techniques discussed in Chapters 6, 7, and 8. The importance of electronic data processing and its relation to the basic electrical measuring devices of Chapter 4 are discussed in a general way in Chapter 14. Because the fields of electronic microprocessors and data acquisition systems change so rapidly, the discussion follows a fairly general pattern. A glossary of terms is given that is applicable to a number of acquisition systems.

Since all experimental work must be reported in some form, Chapter 15, on reports and presentations, has been given in a general format that will apply to several applications. This material includes information on graphical and oral presentations as well.

Some remarks concerning units are in order. There is no question regarding the desirability to move toward the adoption of SI (metric) units wherever possible. Accordingly, the educational system must anticipate this movement and teach students to operate in SI. Courses in analysis (fluid mechanics, heat transfer, mechanics, and so on) can adopt SI as the primary system with appropriate conversions to the old English system. The experimental engineer may have a more cumbersome task. One does not buy new instruments, gages, or meters just to change to SI units. Unhappily, a common practice is to operate in a mixed system of units that combines SI and non-SI metric with English units, which are coupled to empirical design relationships at hand. This means that the experimental engineer will be operating in a "bilingual" mode for many years. In addition, many field engineers do not *want* to change to SI and will not change until they are forced to do so. Of course, companies heavily involved with export markets, like the auto industry, are already heavily into SI units. It is in recognition of these facts that I have chosen to mix SI and English units throughout the book, even though my personal desire is to change over to SI completely as soon as possible. There is another problem that the engineer must deal with. Some work is performed in metric units that are not in the SI system. Examples are the calorie unit for energy and the kilogram *force* per square centimeter for pressure. Alas, these are hazards to be encountered, and one must adapt as best as one can.

In this edition, pruning of comments and topics has been applied throughout. Recognition is made of the fact that electronic instrumentation and computer-based data acquisition systems change so rapidly that the experimental engineer is best served by timely consultation with well-disposed manufacturers of the necessary instrumentation for their particular application. There are some things that do not change so rapidly though. Uncertainty analysis and data correlations are still important. Increased computer power just makes the tasks easier to perform. The discussions in Chapter 3 concerning data correlations, regression analysis, and graphical presentations have been expanded considerably, with emphasis on computer generation of trendlines and least-squares analysis for a number of functional relationships. Particular attention is devoted to the type of graphical displays that should be used for different data presentations. This emphasis on adaptation of computer-generated graphs is carried through to the report writing discussions of Chapter 15 in which specific examples of graph constructions are displayed that will be applicable to reports and oral presentations.

Chapter 16 on Design of Experiments is new. It presents, in brief tabular and checklist forms, a protocol for design of experiments to accomplish various objectives. Five diverse examples (or case studies) are offered as applications of the protocol. The information in this chapter is built on both the data and uncertainty analysis sections of previous chapters as well as information contained in the chapters concerned with specific measurement techniques.

In consonance with the pruning and updating here and there, some problems have been deleted and 115 new problems added. New examples have been added and all examples now carry a title. A list of all examples is found on page x.

With a book at this stage of development, the list of persons who have been generous with their comments and suggestions has grown very long indeed. The author hopes that a blanket note of thanks for all these people's contributions will suffice. As in the past, all comments from users will be appreciated and acknowledged. The McGraw-Hill editorial staff appreciates the comments and suggestions of the following people who reviewed the prospectus for the new edition:

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J. P. Holman

CONTENTS

Chapter 1

INTRODUCTION 1

Chapter 2

BASIC CONCEPTS 5

- 2.1 Introduction 5
- 2.2 Definition of Terms 5
- 2.3 Calibration 6
- 2.4 Standards 7
- 2.5 Dimensions and Units 11
- 2.6 The Generalized Measurement System 14
- 2.7 Basic Concepts in Dynamic Measurements 18
- 2.8 System Response 31
- 2.9 Distortion 32
- 2.10 Impedance Matching 32
- 2.11 Experiment Planning 35
- 2.12 Review Questions 39
- 2.13 Problems 41
- 2.14 References 46

Chapter 3

ANALYSIS OF EXPERIMENTAL DATA 48

- 3.1 Introduction 48
- 3.2 Causes and Types of Experimental Errors 49
- 3.3 Error Analysis on a Commonsense Basis 50
- 3.4 Uncertainty Analysis 51
- 3.5 Evaluation of Uncertainties for Complicated Data Reduction 60
- 3.6 Statistical Analysis of Experimental Data 62
- 3.7 Probability Distributions 67
- 3.8 The Gaussian or Normal Error Distribution 71
- 3.9 Comparison of Data with Normal Distribution 80

- 3.10 The Chi-Square Test of Goodness of Fit 84
- 3.11 Method of Least Squares 91
- 3.12 The Correlation Coefficient 95
- 3.13 Multivariable Regression 96
- 3.14 Standard Deviation of the Mean 98
- 3.15 Student's *t*-Distribution 99
- 3.16 Graphical Analysis and Curve Fitting 106
- 3.17 Choice of Graph Formats 107
- 3.18 General Considerations in Data Analysis 123
- 3.19 Summary 124
- 3.20 Review Questions 125
- 3.21 Problems 125
- 3.22 References 141

Chapter 4

BASIC ELECTRICAL MEASUREMENTS AND SENSING DEVICES 144

- 4.1 Introduction 144
- 4.2 Forces of Electromagnetic Origin 144
- 4.3 Waveform Measures 148
- 4.4 Basic Analog Meters 151
- 4.5 Basic Digital Meters 157
- 4.6 Basic Input Circuits 158
- 4.7 Amplifiers 172
- 4.8 Differential Amplifiers 176
- 4.9 Operational Amplifiers 176
- 4.10 Transformers 180
- 4.11 Power Supplies 182
- 4.12 Signal Conditioning 183
- 4.13 The Electronic Voltmeter (EVM) 194
- 4.14 Digital Voltmeters 195
- 4.15 The Oscilloscope 197
- 4.16 Oscilloscope Selection 201
- 4.17 Output Recorders 203
- 4.18 Counters—Time and Frequency Measurements 204
- 4.19 Transducers 204
- 4.20 The Variable-Resistance Transducer 205

- 4.21 The Differential Transformer (LVDT) 205
- 4.22 Capacitive Transducers 209
- 4.23 Piezoelectric Transducers 211
- 4.24 Photoelectric Effects 213
- 4.25 Photoconductive Transducers 214
- 4.26 Photovoltaic Cells 217
- 4.27 Ionization Transducers 217
- 4.28 Magnetometer Search Coil 218
- 4.29 Hall-Effect Transducers 220
- 4.30 Digital Displacement Transducers 221
- 4.31 Comparison of Analog and Digital Instruments 222
- 4.32 Summary 222
- 4.33 Review Questions 223
- 4.34 Problems 224
- 4.35 References 231

Chapter 5

DISPLACEMENT AND AREA MEASUREMENTS 233

- 5.1 Introduction 233
- 5.2 Dimensional Measurements 233
- 5.3 Gage Blocks 235
- 5.4 Optical Methods 236
- 5.5 Pneumatic Displacement Gage 239
- 5.6 Area Measurements 241
- 5.7 The Planimeter, a Device of Historical Interest 242
- 5.8 Graphical and Numerical Methods for Area Measurement 243
- 5.9 Surface Areas 248
- 5.10 Problems 249
- 5.11 References 253

Chapter 6

PRESSURE MEASUREMENT 255

- 6.1 Introduction 255
- 6.2 Dynamic Response Considerations 258
- 6.3 Mechanical Pressure-Measurement Devices 260
- 6.4 Dead-Weight Tester 265
- 6.5 Bourdon-Tube Pressure Gage 266
- 6.6 Diaphragm and Bellows Gages 267

- 6.7 The Bridgman Gage 271
- 6.8 Low-Pressure Measurement 272
- 6.9 The McLeod Gage 272
- 6.10 Pirani Thermal-Conductivity Gage 274
- 6.11 The Knudsen Gage 275
- 6.12 The Ionization Gage 277
- 6.13 The Alphatron 278
- 6.14 Summary 278
- 6.15 Review Questions 279
- 6.16 Problems 280
- 6.17 References 285

Chapter 7

FLOW MEASUREMENT 287

- 7.1 Introduction 287
- 7.2 Positive-Displacement Methods 288
- 7.3 Flow-Obstruction Methods 291
- 7.4 Practical Considerations for Obstruction Meters 295
- 7.5 The Sonic Nozzle 304
- 7.6 Flow Measurement by Drag Effects 306
- 7.7 Hot-Wire and Hot-Film Anemometers 314
- 7.8 Magnetic Flowmeters 319
- 7.9 Flow-Visualization Methods 320
- 7.10 The Shadowgraph 322
- 7.11 The Schlieren 323
- 7.12 The Interferometer 326
- 7.13 The Laser Doppler Anemometer (LDA) 328
- 7.14 Smoke Methods 331
- 7.15 Pressure Probes 331
- 7.16 Impact Pressure in Supersonic Flow 340
- 7.17 Summary 341
- 7.18 Review Questions 342
- 7.19 Problems 344
- 7.20 References 351

Chapter 8

THE MEASUREMENT OF TEMPERATURE 355

- 8.1 Introduction 355
- 8.2 Temperature Scales 355
- 8.3 The Ideal-Gas Thermometer 356

- 8.4 Temperature Measurement by Mechanical Effects 358
- 8.5 Temperature Measurement by Electrical Effects 362
- 8.6 Temperature Measurement by Radiation 383
- 8.7 Effect of Heat Transfer on Temperature Measurement 390
- 8.8 Transient Response of Thermal Systems 399
- 8.9 Thermocouple Compensation 401
- 8.10 Temperature Measurements in High-Speed Flow 404
- 8.11 Summary 408
- 8.12 Review Questions 408
- 8.13 Problems 409
- 8.14 References 418

Chapter 9

THERMAL- AND TRANSPORT-PROPERTY MEASUREMENTS 420

- 9.1 Introduction 420
- 9.2 Thermal-Conductivity Measurements 421
- 9.3 Thermal Conductivity of Liquids and Gases 425
- 9.4 Measurement of Viscosity 427
- 9.5 Gas Diffusion 434
- 9.6 Calorimetry 438
- 9.7 Convection Heat-Transfer Measurements 442
- 9.8 Humidity Measurements 445
- 9.9 Heat-Flux Meters 448
- 9.10 pH Measurement 451
- 9.11 Review Questions 452
- 9.12 Problems 453
- 9.13 References 459

Chapter 10

FORCE, TORQUE, AND STRAIN MEASUREMENTS 461

- 10.1 Introduction 461
- 10.2 Mass Balance Measurements 462

- 10.3 Elastic Elements for Force Measurements 465
- 10.4 Torque Measurements 469
- 10.5 Stress and Strain 473
- 10.6 Strain Measurements 474
- 10.7 Electrical-Resistance Strain Gages 475
- 10.8 Measurement of Resistance Strain-Gage Outputs 479
- 10.9 Temperature Compensation 480
- 10.10 Strain-Gage Rosettes 481
- 10.11 The Unbonded Resistance Strain Gage 484
- 10.12 Review Questions 485
- 10.13 Problems 486
- 10.14 References 490

Chapter 11

MOTION AND VIBRATION MEASUREMENT 492

- 11.1 Introduction 492
- 11.2 Two Simple Vibration Instruments 492
- 11.3 Principles of the Seismic Instrument 494
- 11.4 Practical Considerations for Seismic Instruments 501
- 11.5 Sound Measurements 504
- 11.6 Review Questions 517
- 11.7 Problems 518
- 11.8 References 523

Chapter 12

THERMAL- AND NUCLEAR-RADIATION MEASUREMENTS 525

- 12.1 Introduction 525
- 12.2 Detection of Thermal Radiation 525
- 12.3 Measurement of Emissivity 531
- 12.4 Reflectivity and Transmissivity Measurements 534
- 12.5 Solar Radiation Measurements 535
- 12.6 Nuclear Radiation 537
- 12.7 Detection of Nuclear Radiation 538
- 12.8 The Geiger-Müller Counter 538
- 12.9 Ionization Chambers 539

- 12.10 Photographic Detection Methods 540
- 12.11 The Scintillation Counter 541
- 12.12 Neutron Detection 541
- 12.13 Statistics of Counting 542
- 12.14 Review Questions 546
- 12.15 Problems 546
- 12.16 References 549

Chapter 13

AIR-POLLUTION SAMPLING AND MEASUREMENT 552

- 13.1 Introduction 552
- 13.2 Units for Pollution Measurement 552
- 13.3 Air-Pollution Standards 553
- 13.4 General Air-Sampling Train 556
- 13.5 Gas Sampling Techniques 557
- 13.6 Particulate Sampling Techniques 558
- 13.7 Sulfur Dioxide Measurements 566
- 13.8 Combustion Products Measurements 569
- 13.9 Opacity Measurements 573
- 13.10 Odor Measurement 574
- 13.11 Review Questions 575
- 13.12 Problems 576
- 13.13 References 577

Chapter 14

DATA ACQUISITION AND PROCESSING 579

- 14.1 Introduction 579
- 14.2 The General Data Acquisition System 579
- 14.3 Signal Conditioning Revisited 582
- 14.4 Data Transmission 585
- 14.5 Analog-to-Digital and Digital-to-Analog Conversion 588
- 14.6 Data Storage and Display 596
- 14.7 The Program as a Substitute for Wired Logic 597

- 14.8 Summary 600
- 14.9 Glossary 600
- 14.10 Review Questions 602
- 14.11 Problems 602
- 14.12 References 604

Chapter 15

REPORT WRITING AND PRESENTATIONS 605

- 15.1 Introduction 605
- 15.2 Some General Comments 605
- 15.3 Types of Reports 608
- 15.4 Contents of a Report 610
- 15.5 Graphical Presentations 618
- 15.6 Miscellaneous Helpful Hints 629
- 15.7 Word Processors and Computers 630
- 15.8 Processing of Reports 631
- 15.9 Oral Presentations 633
- 15.10 Planning Sessions and Conferences 635
- 15.11 Review Questions 636
- 15.12 References 637

Chapter 16

DESIGN OF EXPERIMENTS 638

- 16.1 Introduction 638
- 16.2 Types of Experiments 638
- 16.3 Experiment Design Factors 642
- 16.4 Experiment Design Protocol and Examples 642
- 16.5 Summary 677
- 16.6 Problems 678
- 16.7 References 679

APPENDIX 680

INDEX 690

LIST OF WORKED EXAMPLES

Example 2.1	Step response of first-order system
Example 2.2	Phase lag in first-order system
Example 2.3	Harmonic response of first-order system
Example 2.4	Selection of second-order system
Example 2.5	Response of pressure transducer
Example 2.6	Rise time for different natural frequencies
Example 2.7	Power supply
Example 3.1	Uncertainty of resistance of a copper wire
Example 3.2	Uncertainty in power measurement
Example 3.3	Selection of measurement method
Example 3.4	Instrument selection
Example 3.5	Ways to reduce uncertainties
Example 3.6	Uncertainty calculation by result perturbation
Example 3.7	Calculation of population variables
Example 3.8	Sample standard deviation
Example 3.9	Tossing a coin—binomial distribution
Example 3.10	Probability for deviation from mean value
Example 3.11	Determination of number of measurements to assure a significance level
Example 3.12	Power supply
Example 3.13	Application of Chauvenet's criterion
Example 3.14	Use of probability graph paper and computer comparison
Example 3.15	Defects in plastic cups
Example 3.16	Rolling the dice
Example 3.17	Toss of coin: Influence of additional data points
Example 3.18	Effect of cigarette smoke on mice
Example 3.19	Least-squares regression
Example 3.20	Correlation coefficient
Example 3.21	Uncertainty in mean value
Example 3.22	Confidence level from t -distribution
Example 3.23	Estimate of sample size
Example 3.24	Confidence level
Example 3.25	Confidence level
Example 3.26	Lower confidence level
Example 3.27	Trade-off in number of measurements
Example 3.28	Comparison of two samples
Example 3.29	Correlation of data with power relation
Example 3.30	Alternative displays and correlation trendlines for exponential function
Example 3.31	Evolution of a correlation using computer graphics
Example 3.32	Correlation trendlines using offset points