Experimental Methods for Engineers 7th ed

EXPERIMENTAL METHODS FOR ENGINEERS

SEVENTH EDITION

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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	$\mathscr{R} = 1545.35$ ft · lbf/lbm · mol · °R
	= 8314.41 J/kg mol · K
	= 1.986 Btu/lbm · mol · °R
	= 1.986 kcal/kg mol · K
Planck's constant	$h = 6.626176 \times 10^{-34}$ J-sec
Boltzmann's constant	$k = 1.380662 \times 10^{-23}$ J/molecule · K
	$= 8.6173 \times 10^{-5}$ eV/molecule · K
Speed of light in vacuum	$c = 2.997925 \times 10^{8}$ m/s
Standard gravitational acceleration	$g = 32.174$ ft/s^2
	= 9.80665 m/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 · ft^2 · R^4
	$= 5.669 \times 10^{-8}$ W/m^2 · K^4

Conversion factors

Length
- 12 in = 1 ft
- 2.54 cm = 1 in
- 1 μm = 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 · lbf = 1.356 J
- 1 kW · h = 3413 Btu
- 1 hp · h = 2545 Btu
- 1 Btu = 252 cal
- 1 Btu = 778 ft · 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 μbar = 1 dyn/cm^2 = 2.089 lbf/ft^2 = 0.1 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_2O = 5.203 lbf/ft^2 = 249.1 Pa
- 1 psia = 6.89476 kPa
  - = 0.070307 kgf/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 kg/m-s
- 1 N-s/m^2 $= 2.08854 \times 10^{-2}$ lbf-s/ft^2
  - = 10 P = 1000 cP
  - = 2419 lbm/h-ft = 1 kg/m-s
- 1 Poise(P) = 100 cP = 1 dyn-s/cm^2
  - = 0.1 N-s/m^2 = 0.1 kg/m-s
  - $= 2.08854 \times 10^{-3}$ lbf-s/ft^2
  - = 241.9 lbm/h-ft

Kinematic viscosity
- 1 ft^2/s $= 9.2903 \times 10^{-2}$ m^2/s
  - = 929.03 St = 929.03 cm^2/s
- 1 m^2/s = 10.7639 ft^2/s = 10^4 St
- 1 Stoke(St) = 1 cm^2/s = 100 cSt
  - $= 10^{-4}$ m^2/s $= 10.7639 \times 10^{-4}$ ft^2/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 cm^3/s
- 1 std cfm of air at 1 atm, 20°C = 0.07513 lbm/min
  - = 0.54579 g/s

Thermal conductivity
- 1 cal/s · cm · °C = 242 Btu/h · ft · °F
- 1 W/cm · °C = 57.79 Btu/h · ft · °F

Basic Data Analysis Relations

Propagation of Uncertainty

General

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

Product Function

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

Arithmetic Function

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

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

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

Normal Distribution

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

Power Function Correlation

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

Exponential Correlation

$y = ae^{bx}$; $\ln y = \ln a + bx$; 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

LIST OF WORKED EXAMPLES