RICHARD S. FIGLIOLA | DONALD E. BEASLEY

THEORY AND DESIGN FOR MECHANICAL MEASUREMENTS

SEVENTH EDITION

WILEY

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Richard S. Figliola
Clemson University

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PREFACE

The revised edition of *Theory and Design for Mechanical Measurements* continues to provide a well-founded, fundamental background in the theory and practice of engineering measurements. This edition takes advantage of web-based and interactive technology to improve the online and e-format access to materials for improved pedagogy while retaining archival material in the published edition. This format minimizes print materials in our effort to reduce text costs.

As with each other edition, we have integrated the necessary elements to conduct engineering measurements through the design of measurement systems and measurement test plans, with an emphasis on the role of statistics and uncertainty analyses in that process. The text is appropriate for undergraduate-level and graduate-level study in engineering. The text is suitably advanced and oriented to serve as a reference source for professional practitioners. Rather than a topical source of information, we have provided sufficient background material to enable intelligent selection of instruments and design of measurement systems. The pedagogical approach invites independent study or use in related fields that require an understanding of instrumentation and measurements.

The organization used in each edition of this text develops from our view that certain aspects of measurements can be generalized, such as test plan design, signal analysis and reconstruction, and measurement system response. Topics such as statistics and uncertainty analysis require a basic development of principles but are then best illustrated by integrating these topics throughout the text material. Other aspects are better treated in the context of the measurement of a specific physical quantity, such as strain or temperature.

Pedagogical Tools to Aid Learning

We have retained certain successful elements from prior editions in this textbook:

- Each chapter begins by defining a set of **learning outcomes**.
- The text develops an **intuitive understanding** of measurement concepts with its focus on test system modeling, test plan design, and uncertainty analysis.
- Each chapter includes carefully constructed **example problems** that illustrate new material and problems that build on prior material. Where appropriate case studies and vignettes illustrate current applications of measurement theory or design.
- Example problems make use of a **KNOWN, FIND, SOLVE** approach as an organizational aid toward solution. This methodology for problem solutions helps new users to link words and concepts with symbols and equations. Many problems contain **COMMENTS** that expand on the solution, provide a proper context for application of the principle, or offer design application insight.
- **End-of-chapter practice problems** are included for each chapter to exercise new concepts.
    - Practice problems range from those focused on concept development to building of advanced skills to open-ended design applications. Some problems require independent research for specific applications or measurement techniques.
    - Within each chapter, we have added new practice problems and removed some old problems from prior editions.

  - We provide online access to a solutions manual for instructors who have adopted the book and registered with Wiley. Materials are posted on the textbook website at www.wiley.com/go/figliola/Theory&designformechanicalmeasurements7e.

- Use of the software in problem solving allows in-depth exploration of key concepts that would be prohibitively time consuming otherwise. The text includes online access to **interactive software** of focused examples based on software using National Instruments Labview® or Matlab®. The Labview programs are available as executables so that they can be run directly without a Labview license. The software is available on both the Wiley student and instructor websites.

New to This Revised Edition

With this revised edition, we have new or expanded material on a number of topics:

- We have updated the end-of-chapter practice problems by removing some older problems and adding new problems. We have replaced more than 25% of the problems in the text.
- We have added a dedicated set of Student Problems with “click-to-access” to view solutions. These are roughly 25% of the end-of-chapter problems. This capability is accessible to readers who have purchased the capability through Wiley.
- Given the new e-format, we have added some data files that can be accessed electronically and used in practice problems.
- We have set aside a dedicated set of Instructor Problems with solutions to assist in lectures or assessment. These are visible only to instructors who have registered with Wiley.

Suggested Course Coverage (from Sixth Edition)

To aid in course preparation, Chapters 1–5 provide an introduction to measurement theory with statistics and uncertainty analysis, Chapters 6 and 7 provide a broad treatment of analog and digital sampling methods, and Chapters 8–12 focus on instrumentation.

Many users report to us that they use different course structures—so many that it makes a preferred order of topical presentation difficult to anticipate. To accommodate this, we have written the text in a manner that allows any instructor to customize the order of material presentation. Although the material of Chapters 4 and 5 is integrated throughout the text and should be taught in sequence, the other chapters can stand on their own. The text is flexible and can be used in a variety of course structures at both the undergraduate and graduate levels.

For a complete measurements course, we recommend the study of Chapters 1–7 with use of the remaining chapters as appropriate. For a lab course sequence, we recommend using chapters as they best illustrate the course exercises while building complete coverage over the several lab courses normally within a curriculum. The manner of the text allows it to be a resource for a lab-only course with minimal lecture. Over the years we have used it in several forums, as well as in professional development courses, and we simply rearrange material and emphasis to suit our audience and objective.

We express our sincerest appreciation to the students, teachers, and engineers who have used our earlier editions. We are indebted to the many who have written us with their constructive comments and encouragement. Special thanks to Kathy Hays-Stang, University of Texas-Arlington, and Todd Schweisinger, Clemson University, for their detailed feedback and suggestions.

Richard S. Figliola
Donald E. Beasley

Clemson, South Carolina

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Chapter 1 Problems

SS Student solution available in interactive e-text.

1.1 Select three different types of measurement systems with which you have experience, and identify which attributes of the system comprise the measurement system stages of Figure 1.4. Use sketches as needed.

1.2 For each of the following systems, identify the components that comprise each measurement system stage per Figure 1.4:

a. microphone/amplifier/speaker system

b. room heating thermostat

c. handheld micrometer

d. tire pressure (pencil-style) gauge

SS **1.3** Consider an electronic automotive speedometer. The sending unit that senses the speed operates on the principle illustrates in Figure 12.19. Describe the operation of the complete speed measuring system by:

a. Researching the operation of an electronic automotive speedometer including all of the stages illustrated in Figure 1.4

b. Identify and describe the stages of this measurement system.

1.4 Consider an electronic automotive speed control system (cruise control). Describe the operation of the complete speed measuring system by:

a. Researching the operation of an electronic cruise control including all of the stages illustrated in Figure 1.4

b. Identify and describe the stages of this measurement system.

1.5 Laser range finders provide accurate distance measurements in applications ranging from the military to golf. Describe the operation of this system by:

a. Researching the operation of this system including all of the stages illustrated in Figure 1.4.

b. Identify and describe the stages of this measurement system.

1.6 Automotive parking assist systems allow for ease in parallel parking. Describe the operation of this system by:

a. Researching the operation of this system including all of the stages illustrated in Figure 1.4. Include in the control stage the actuators that perform the steering.

b. Identify and describe the stages of this control system.

1.7 Dial temperature gauges provide cost-effective means of measuring temperature. Describe the operation of this system by:

a. Researching the operation of this system including all of the stages illustrated in Figure 1.4.

b. Identify and describe the stages of this measurement system.

1.8 Tipping bucket rain gauges provide accurate measurement of rainfall amounts. Describe the operation of this system by:

a. Researching the operation of this system including all of the stages illustrated in Figure 1.4.

b. Identify and describe the stages of this measurement system.

1.9 Consider Example 1.1. Discuss the effect of the extraneous variable barometric pressure in terms of noise and interference relative to any one test and relative to several tests. Explain how interference effects can be broken up into noise using randomization.

1.10 State whether the following are a continuous variable or a discrete variable: (new) SS

a. Time

b. Temperature

c. Bank account balance

d. Pixels in a display

1.11 Cite three examples each of a continuous variable and a discrete variable.

1.12 Suppose you found a dial thermometer in a stockroom. Could you state how accurate it is? Discuss methods by which you might estimate random and systematic error in the thermometer?

1.13 Discuss how the resolution of the display scale of an instrument could affect its uncertainty. Suppose the scale was somehow offset by one least count of resolution: How would this affect its uncertainty? Explain in terms of random and systematic error.

1.14 A bulb thermometer hangs outside a house window. Comment on extraneous variables that might affect the difference between the actual outside temperature and the indicated temperature on the thermometer.

1.15 A synchronous electric motor test stand permits either the variation of input voltage or the output shaft load with the subsequent measurement of motor efficiency, winding temperature, and input current. Comment on the independent, dependent, and extraneous variables for a motor test.

1.16 The transducer specified in Table 1.1 is chosen to measure a nominal pressure of 500 cm H_2O. The ambient temperature is expected to vary between 18 °C and 25 °C during tests. Estimate the possible range (magnitude) of each listed elemental error affecting the measured pressure.

1.17 A force measurement system (weight scale) has the following specifications:

Range	0 to 1000 N
Linearity error	0.10% FSO
Hysteresis error	0.10% FSO
Sensitivity error	0.15% FSO
Zero drift	0.20% FSO

Estimate the overall instrument uncertainty for this system based on available information. Use the maximum possible output value over the FSO in your computations.

1.18 State the purpose of using randomization methods during a test. Develop an example to illustrate your point.

1.19 Provide an example of repetition and replication in a test plan from your own experience.

1.20 Develop a test plan that might be used to estimate the average temperature that could be maintained in a heated room as a function of the heater thermostat setting.

1.21 Develop a test plan that might be used to evaluate the fuel efficiency of a production model automobile. Explain your reasoning.

1.22 A race engine shop has just completed two engines of the same design. How might you, the team engineer, determine which engine would perform better for an upcoming race (a) based on a test stand data (engine dynamometer) and (b) based on race track data? Describe some measurements that you feel might be useful, and explain how you might use that information. Discuss possible differences between the two tests and how these might influence the interpretation of the results.

1.23 Develop a test plan to compare tool life for three different types of drill bits for a drilling process in stainless steel. How would cost enter this test plan?

1.24 Develop a test plan to determine the optimum driver loft for an individual golfer. How would the test plan differ if the player wished to optimize carry or total distance? Note: A little research or a conversation with a golfer might help.

1.25 A thermodynamics model assumes that a particular gas behaves as an ideal gas: Pressure is directly related to temperature and density. How might you determine that the assumed model is correct (validation)?

1.26 Regarding the Mars Climate Orbiter spacecraft example presented, discuss how verification tests before launch could have identified the software units problem that led to the catastrophic spacecraft failure. Explain the purpose of verification testing?

1.27 A large batch of carefully made machine shafts can be manufactured on 1 of 4 lathes by 1 of 12 quality machinists. Set up a test matrix to estimate the tolerances that can be held within a production batch. Explain your reasoning.

1.28 Suggest an approach or approaches to estimate the linearity error and the hysteresis error of a measurement system.

1.29 Suggest a test matrix to evaluate the wear performance of four different brands of aftermarket passenger car tires of the same size, load, and speed ratings on a fleet of eight cars of the same make. If the cars were not of the same make, what would change?

1.30 The relation between the flow rate, Q, through a pipeline of area A and the pressure drop Δp across an orifice-type flow meter inserted in that line (Figure 1.15) is given by $Q = CA\sqrt{2\Delta p/\rho}$ where ρ is density and C is a coefficient. For a pipe diameter of 1 m and a flow range of 20 °C water between 2 and 10 m^3/min and $C = 0.75$, plot the expected form of the calibration curve for flow rate versus pressure drop over the flow range. Is the static sensitivity a constant? Incidentally, the device and test method is described by both ANSI/ASME Test Standard PTC 19.5 and ISO 5167.

1.31 The sale of motor fuel is an essential business in the global economy. Federal (U.S.) law requires the quantity of fuel delivered at a retail establishment to be accurate to within 0.5%. (a) Determine the maximum allowable error in the delivery of 25 gallons (or use 95 L). (b) Provide an estimate of the potential costs to a consumer at the maximum allowable error over 150,000 miles (240,000 km) based on an average fuel mileage of 30.2 mpg (7.8 L/100 km). (c) As a knowledgeable consumer, cite one or two ways for you to identify an inaccurate pump. SS

1.32 Using either the ASME 19.5 or ISO 5167 test standard, explain how to use a venturi flowmeter. What are the independent variable(s) and dependent variable(s) in engineering practice? Explain.

1.33 A piston engine manufacturer uses four different subcontractors to plate the pistons for a make of engine. Plating thickness is important in quality control (performance and part life). Devise a test matrix to assess how well the manufacturer can control plating under its current system.

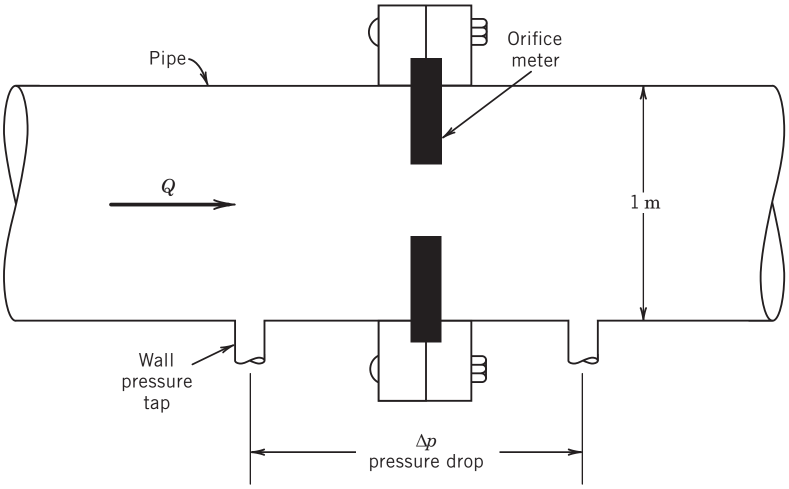

FIGURE 1.15 Orifice flow meter setup used for Problem 1.21.

1.34 A simple thermocouple circuit is formed using two wires of different alloy: One end of the wires is twisted together to form the measuring junction, and the other ends are connected to a digital voltmeter, forming the reference junction. A voltage is set up by the difference in temperature between the two junctions. For a given pair of alloy material and reference junction temperature, the temperature of the measuring junction is inferred from the measured voltage difference. What are the dependent and independent variables during practical use? What about during a calibration?

SS **1.35** A linear variable displacement transducer (LVDT) senses displacement and indicates a voltage output that is linear to the input. Figure 1.16 shows an LVDT setup used for static calibration. It uses a micrometer to apply the known displacement and a voltmeter for the output. A well-defined voltage powers the transducer. What are the independent and dependent variables in this calibration? Would these change in practical use?

1.36 For the LVDT calibration of problem 1.35, what would be involved in determining the repeatability of the instrument? The reproducibility? What effects are different in the two tests? Explain.

1.37 A manufacturer wants to quantify the expected average fuel mileage of a product line of automobiles. It decides that either it can put one or more cars on a chassis dynamometer and run the wheels at desired speeds and loads to assess this, or it can use drivers and drive the cars over some selected course instead. (a) Discuss the merits of either approach,

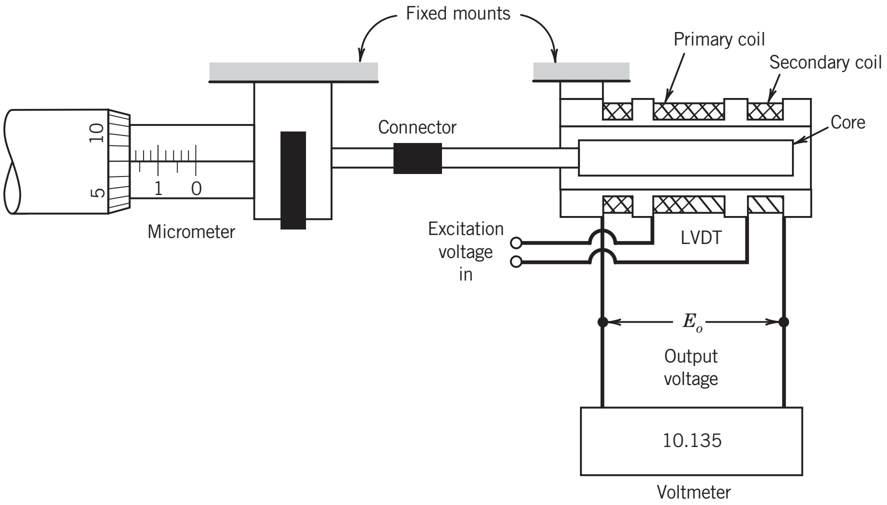

FIGURE 1.16 LVDT setup used for Problem 1.35.

considering the control of variables and identifying extraneous variables. (b) Can you recognize that somewhat different tests might provide answers to different questions? For example, discuss the difference in meanings possible from the results of operating one car on the dynamometer and comparing it to one driver on a course. Cite other examples. (c) Do these two test methods serve as examples of concomitant methods?

SS **1.38** The coefficient of restitution of a volleyball is found by dropping the ball from a known height H and measuring the height of the bounce, h. The coefficient of restitution, C_R, is then calculated as $C_R = \sqrt{h/H}$. Develop a test plan for measuring C_R that includes the range of conditions expected in college-level volleyball play.

1.39 As described in a preceding problem, the coefficient of restitution of a volleyball, $C_R = \sqrt{h/H}$, is determined for a range of impact velocities. The impact velocity is $v_i = \sqrt{2gH}$ and is controlled by the dropping the ball from a known height H. Let the velocity immediately after impact be $v_f = \sqrt{2gh}$ where h is the measured return height. List the independent and dependent variables, parameters, and measured variables.

1.40 Light gates may be used to measure the speed of projectiles, such as arrows shot from a bow. English longbows made of yew in the 1400s achieved launch speeds of 60 m/s. Determine the relationship between the distance between light gates and the accuracy required for sensing the times when the light gate senses the presence of the arrow.

1.41 Develop a plan to calibrate the following:

a. The standard National Weather Service rain gauge

b. Tipping bucket rain gauge

c. Distance measuring wheel

1.42 Estimate your car's fuel use by recording regularly the fuel volume used over a known distance. Your brother, who drives the same model car, disagrees with your claimed results based on his own experience. Suggest reasons to justify the differences? How might you test to provide justification for each of these reasons?

1.43 When discussing concomitant methods, we used the example of estimating the volume of a rod. Identify another concomitant method that you might use to verify whether your first test approach to estimating rod volume is working.

1.44 When a strain gauge is stretched under uniaxial tension, its resistance varies with the imposed strain. A resistance bridge circuit is used to convert the resistance change into a voltage. Suppose a known tensile load were applied to a test specimen using the system shown in Figure 1.17. What are the independent and dependent variables in this calibration? How do these change during actual testing?

1.45 For the strain gauge calibration of the previous problem, what would be involved in determining the repeatability of the instrument? The reproducibility? What effects are different in the tests? Explain.

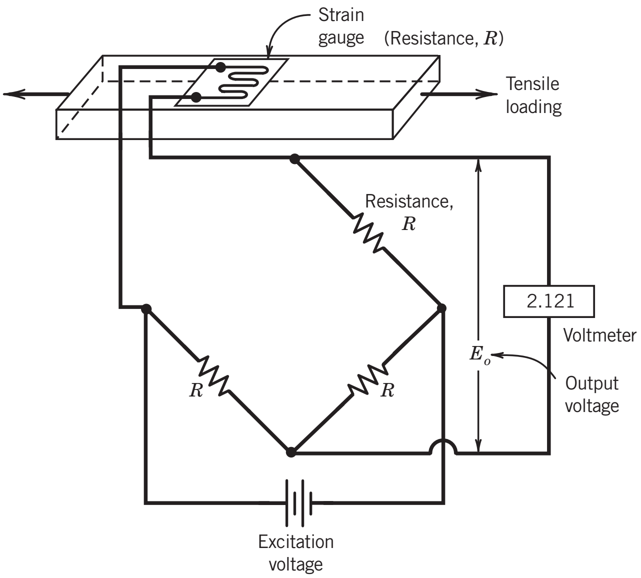

FIGURE 1.17 Strain gauge setup used for Problem 1.44.

1.46 The acceleration of a cart down a plane inclined at an angle α to horizontal can be determined by measuring the change in speed of the cart at two points, separated by a distance s, along the inclined plane. Suppose two photocells are fixed at the two points along the plane. Each photocell measures the time for the cart, which has a length L, to pass it. Identify the important variables in this test. List any assumptions that you feel are intrinsic to such a test. Suggest a concomitant approach. How would you interpret the data to answer the question?

1.47 In general, what is meant by the term "standard"? Discuss your understanding of the hierarchy of standards used in calibration beginning with the primary standard. How do these differ from test standards and codes?

1.48 A common scenario: An engineer has two pencil-style pressure gauges in her garage for setting tire pressures. She notices that the two gauges disagree by about 14 kPa (2 psi) on the same tire. How does she choose the most accurate gauge to set car tire pressures? Discuss possible strategies she might use to arrive at her best option.

1.49 Explain the potential differences in the following evaluations of an instrument's accuracy. Figure 1.11 will be useful, and you may refer to ASTM E177 if needed.

- **a.** The closeness of agreement between the true value and the average of a large set of measurements.
- **b.** The closeness of agreement between the true value and an individual measurement.

SS **1.50** Research ASTM F 558: Air Performance of Vacuum Cleaners. Write a short summary to describe the intent, and give an overview of this test standard.

1.51 Research the following test standards and codes. Write a short summary to describe the intent, and give an overview of each code:

- **a.** ANSI Z21.86 (Gas Fired Space Heating Appliances)
- **b.** ISO 10770-1 (Test Methods for Hydraulic Control Valves)
- **c.** ANSI/ASME PTC19.1 (Test Uncertainty)
- **d.** ISO 7401 (Road Vehicles: Lateral Response Test Methods)
- **e.** ISO 5167 Parts 1–4

1.52 A hotel chain based in the United States contracts with a European vacuum cleaner manufacturer to supply a large number of upright cleaner units. After delivery, the hotel raises questions about manufacturer vacuum cleaner performance claims pointing out that the units should have been tested to meet ASTM 558, an American standard. The manufacturer notes the advertised performance is based on IEC 60312, a European standard, and the two test codes will yield similar, if not exact, results. Investigate both test codes and address similarities and differences. Is there is a legitimate claim here?

1.53 Test code ASTM 558-13 allows for the comparison of the maximum potential air power available between vacuum cleaners when tested under the prescribed conditions. The test requires using at least three units for each make/model tested with the units obtained at random. Explain what might be a reasonable way to meet this requirement. Explain a possible reason for this requirement.

1.54 Suggest a reasonable number of significant digits for reporting the following common values, and give some indication of your reasoning:

- **a.** Your body weight for a passport
- **b.** A car's fuel usage (use liters per 100 km)
- **c.** The weight of a standard ("Good Delivery") bar of pure (at least 99.99%) gold

1.55 Using spreadsheet software (such as Microsoft Excel), create a list of 1,000 numbers each randomly selected between 100 and 999. Divide each number by 10 to obtain a trailing digit; this will be Column 1. Each number in Column 1 will have three significant digits. In Column 2, have the spreadsheet round each number using the default *ROUND* function to two significant digits. In Column 3, have the spreadsheet round each number in Column 1 per ASTM E29 (e.g., *(=IF(MOD(A1,1)=0.5,MROUND(A1,2),ROUND(A1,0))*. Compute the sum of each column and compare. Discuss the meaning of the operations and the results, and explain any differences due to rounding errors.

1.56 How many significant digits are present in the following numbers? Convert each to scientific notation.

1. 10.02
2. 0.00034
3. 2500
4. 042.02
5. $0.1 \text{ x } 10^{-3}$
6. 999 kg/m^3
7. Population 152,000
8. 0.000001 grams

1.57 Round the following numbers to 3 significant digits.

(i) 15.963
(ii) 1232 kPa
(iii) 0.00315
(iv) 21.750
(v) 21.650
(vi) 0.03451
(vii) 1.82512314
(viii) $1.2350 \text{ x } 10^{-4}$

1.58 Express the result by rounding to an appropriate number of significant digits.

(i) $\sin(nx) =$; $n = 0.010 \text{ m}^{-1}$, $\times = 5.73$ m
(ii) $e^{0.31} =$
(iii) $\ln(0.31) =$
(iv) $xy/z =$; $x = 423.$ J, $y = 33.42$ J, $z = 11.32$
(v) $(0.21^2 + 0.321^2 + 0.121^2)/3 =$
(vi) $107^2 + 6542 =$
(vii) $22.1^{1/2} =$
(viii) $(22.3 + 16.634) \times 59 =$

1.59 How much error could you tolerate in (1) book shelf length when two shelves are mounted one above the other, (2) differences between a car' tire pressures, (3) car tire pressure (any tire), (4) car speedometer, (5) home oven thermostat? Explain.

1.60 Apply the guidelines to determine the number of significant digits for these numbers that contain zero digits.. Write the number in scientific notation using two significant digits.

(i) 0.042
(ii) 42.0250
(iii) 420.
(iv) 427,000

1.61 Using a tape measure having 1-mm graduations, the engineer measures an object and determines its length to be just longer than 52 mm but shorter than 53 mm. Using an appropriate number of significant digits, what might be an appropriate statement regarding this measured length?

1.62 For the calibration data of Table 1.5, plot the results using rectangular and log-log scales. Discuss the apparent advantages of either presentation.

Table 1.5 Calibration Data

X [cm]	Y [V]	X [cm]	Y [V]
0.5	0.4	10.0	15.8
1.0	1.0	20.0	36.4
2.0	2.3	50.0	110.1
5.0	6.9	100.0	253.2

1.63 For the calibration data of Table 1.5, determine the static sensitivity of the system at (a) $X = 5$, (b) $X = 10$, and (c) $X = 20$. For which input values is the system more sensitive? Explain what this might mean in terms of a measurement and in terms of measurement errors.

1.64 Consider the voltmeter calibration data in Table 1.6. Plot the data using a suitable scale. Specify the percent maximum hysteresis based on full-scale range. Input X is based on a standard known to be accurate to better than 0.05 mV.

Table 1.6 Voltmeter Calibration Data

Increasing Input [mV]		Decreasing Input [mV]	
X	Y	X	Y
0.0	0.1	5.0	5.0
1.0	1.1	4.0	4.2
2.0	2.1	3.0	3.2
3.0	3.0	2.0	2.2
4.0	4.1	1.0	1.2
5.0	5.0	0.0	0.2

1.65 Each of the following equations can be represented as a straight line on an x-y plot by choosing the appropriate axis scales. Plot each, and explain how the plot operation yields the straight line. Variable y has units of volts. Variable x has units of meters (use a range of $0.01 < x < 10.0$).

a. $y = 5x^{-0.25}$
b. $y = (0.4)\,(10^{-2x})$
c. $y = 5e^{-0.5x}$
d. $y = 2/x$

1.66 Plot $y = 10e^{-5x}$ volts in semilog format (use three cycles). Determine the slope of the equation at $x = 0$, $x = 2$, and $x = 20$.

1.67 The following data have the form $y = ax^b$. Plot the data in an appropriate format to estimate the coefficients a and b. Estimate the static sensitivity K at each value of X. How is K affected by X?

Y [cm]	*X* [m]
0.14	0.5
2.51	2.0
15.30	5.0
63.71	10.0

1.68 For the calibration data given, plot the calibration curve using suitable axes. Estimate the static sensitivity of the system at each X. Then plot K against X. Comment on the behavior of the static sensitivity with static input magnitude for this system.

Y [cm]	*X* [kPa]
4.76	0.05
4.52	0.1
3.03	0.5
1.84	1.0

Basic Concepts of Measurement Methods

1

1.1 Introduction

We take measurements every day. We routinely read the temperature of an outdoor thermometer to choose appropriate clothing for the day. We add exactly 5.3 gallons (about 20 liters) of fuel to our car fuel tank. We use a tire gauge to set the correct car tire pressures. We monitor our body weight. And we put little thought into the selection of instruments for these measurements. After all, the instruments and techniques are routine or provided, the direct use of the information is clear to us, and the measured values are assumed to be good enough. But as the importance and complexity increases, the selection of equipment and techniques and the quality of the results can demand considerable attention. Just contemplate the various types of measurements and tests needed to certify that an engine meets its stated design specifications.

The objective in any measurement is to assign numbers to variables so as to answer a question. The information acquired is based on the output of some measurement device or system. We might use that information to ensure that a manufacturing process is executing correctly, to diagnose a defective part, to provide values needed for a calculation or a decision, or to adjust a process variable. There are important issues to be addressed to ensure that the output of the measurement device is a reliable indication of the true value of the measured variable. In addition, we must address some important questions:

1. How can a measurement or test plan be devised so that the measurement provides the unambiguous information we seek?
2. How can a measurement system be used so that the engineer can easily interpret the measured data and be confident in their meaning?

There are procedures that address these measurement questions.

At the onset, we want to stress that the subject of this text is real-life–oriented. Specifying a measurement system and measurement procedures represents an open-ended design problem. That means there may be several approaches to meeting a measurements challenge, and some will be better than others. This text emphasizes accepted procedures for analyzing a measurement challenge to aid selection of equipment, methodology, and data analysis.

Upon completion of this chapter, the reader will be able to:

- Identify the major components of a general measurement system and state the function of each
- Develop an experimental test plan
- Distinguish between random and systematic errors
- Become familiar with the hierarchy of units standards, and with the existence and use of test standards and codes

- Understand the international system of units and other unit systems often found in practice
- Understand and work with significant digits

1.2 General Measurement System

Measurement[1] is the act of assigning a specific value to a physical variable. That physical variable is the *measured value*. A measurement system is a tool used to quantify the measured variable. Thus, a measurement system is used to extend the abilities of the human senses, which, although they can detect and recognize different degrees of roughness, length, sound, color, and smell, are limited and relative: They are not very adept at assigning specific values to sensed variables.

A system is composed of components that work together to accomplish a specific objective. We begin by describing the components that make up a measurement system, using specific examples. Then we will generalize to a model of the generic measurement system.

Sensor and Transducer

A *sensor* is a physical element that employs some natural phenomenon to sense the variable being measured. To illustrate this concept, suppose we want to measure the profile of a surface at the nanometer scale. We discover that a very small cantilever beam placed near the surface is deflected by atomic forces. Let's assume for now that they are repulsive forces. As this cantilever is translated over the surface, the cantilever will deflect, responding to the varying height of the surface. This concept is illustrated in Figure 1.1; the device is called an atomic-force microscope. The cantilever beam is a sensor. In this case, the cantilever deflects under the action of a force in responding to changes in the height of the surface.

A *transducer* converts the sensed information into a detectable signal. This signal might be mechanical, electrical, optical, or it may take any other form that can be meaningfully quantified. Continuing with our example, we will need a means to change the sensor motion into something that we can quantify. Suppose that the upper surface of the cantilever is reflective, and we shine a laser onto the upper surface, as shown in Figure 1.2. The movement of the cantilever will deflect the laser. Employing a number of light sensors, also shown in Figure 1.2, the changing deflection of the light can be measured as a time-varying current signal with the magnitude corresponding to the height of the surface. Together the laser and the light sensors (photodiodes) form the transducer component of the measurement system.

A familiar example of a complete measurement system is the bulb thermometer. The liquid contained within the bulb of the common bulb thermometer shown in Figure 1.3 exchanges energy with its surroundings until the two are in thermal equilibrium. At that point they are at the same temperature. This energy exchange is the input signal to this measurement system. The phenomenon of thermal expansion of the liquid results in its movement up and down the stem, forming an output signal from which we determine temperature. The liquid in the bulb acts as

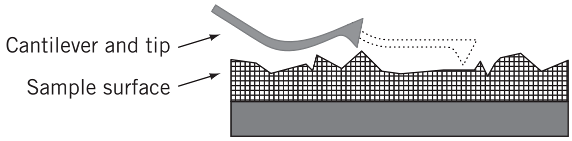

FIGURE 1.1 **Sensor stage of an atomic-force microscope.**

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[1] A glossary of the italicized terms is located in the back of the text for your reference.

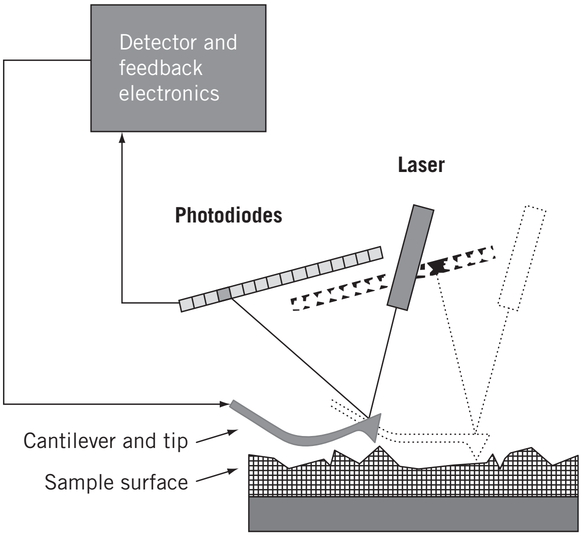

FIGURE 1.2 Atomic-force microscope with sensor and transducer stages.

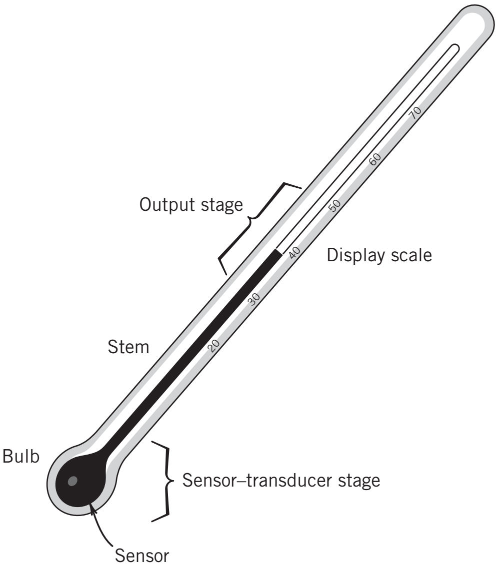

FIGURE 1.3 Components of bulb thermometer equivalent to sensor, transducer, and output stages.

the sensor. By forcing the expanding liquid into a narrow capillary, this measurement system transforms thermal information into a mechanical displacement. Hence the bulb's internal capillary acts as a transducer.

Sensor selection, placement, and installation are particularly important to ensure that the sensor output signal accurately reflects the measurement objective. After all, the interpretation of the information indicated by the system relies on what is actually sensed by the sensor.

Signal-Conditioning Stage

The *signal-conditioning stage* takes the transducer signal and modifies it to a desired magnitude or form. It might be used to increase the magnitude of the signal by amplification, remove portions of the signal through some filtering technique, or provide mechanical or optical linkage between the transducer and the output stage. The diameter of the thermometer capillary relative to the bulb volume (Figure 1.3) determines how far up the stem the liquid moves with increasing temperature.

Output Stage

The goal of a measurement system is to convert the sensed information into a form that can be easily quantified. The *output stage* indicates or records the value measured. This might be by a simple readout display, a marked scale, or even a recording device such as computer memory from which it can later be accessed and analyzed. In Figure 1.3, the readout scale of the bulb thermometer serves as its output stage.

As an endnote, the term "transducer" is often used in reference to a packaged measuring device that contains the sensor and transducer elements described above, and even some signal-conditioning elements, in one unit. This terminology differs from the term "transducer" when describing the function served by an individual stage of a measurement system. Both uses are correct, and we use both: one to refer to how a sensed signal is changed into another form and the other to refer to a packaged device. The context in which the term is used should prevent any ambiguity.

General Template for a Measurement System

A general template for a measurement system is illustrated in Figure 1.4. Essentially such a system consists of part or all of the previously described stages: (1) sensor–transducer stages, (2) signal-conditioning stage, and (3) output stage. These stages form the bridge between the input to the measurement system and the output, a quantity that is used to infer the value of the physical variable measured. We discuss later how the relationship between the input information acquired by the sensor and the indicated output signal is established by a calibration.

Some systems may use an additional stage, the feedback-control stage shown in Figure 1.4. Typical to measurement systems used for process control, the *feedback-control stage* contains a controller that compares the measured signal with some reference value and makes a decision regarding actions required in the control of the process. In simple controllers, this decision is based

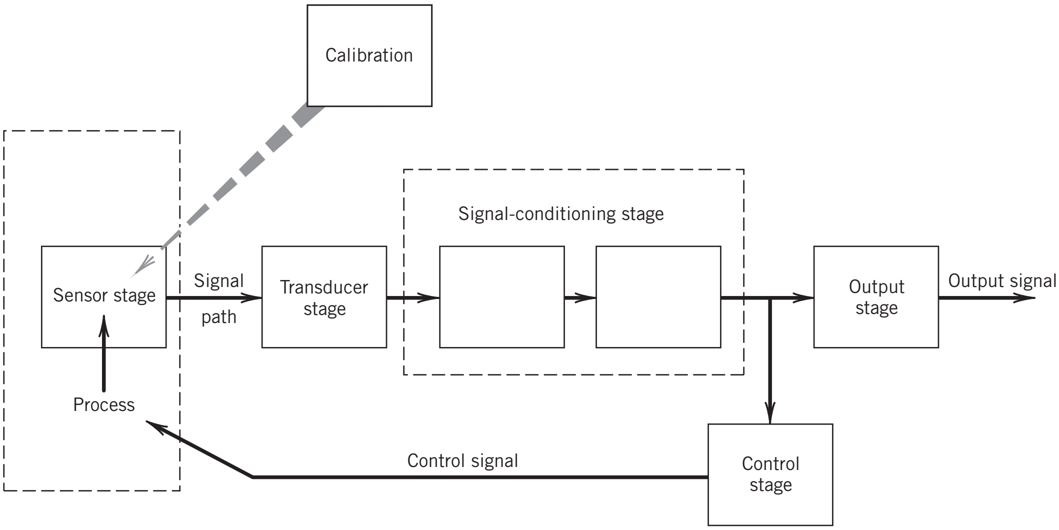

FIGURE 1.4 Components of a general measurement system.

on whether the magnitude of the signal exceeds some set point, whether high or low—a value set by the system operator. For example, a household furnace thermostat activates the furnace as the local temperature at the thermostat, as determined by a sensor within the device, rises above or falls below the thermostat set point. The cruise speed controller in an automobile works in much the same way. A programmable logic controller (PLC) is a robust industrial-grade computer and data-acquiring device used to measure many variables simultaneously and to take appropriate corrective action per programmed instructions. We discuss some features of control systems in detail in Chapter 12.

1.3 Experimental Test Plan

An experimental test is designed to make measurements so as to answer a question. The test should be designed and executed to answer that question and that question alone. Consider an example.

Suppose you want to design a test to answer the question “What fuel use can my family expect from my new car?” In a test plan, you identify the variables that you will measure, but you also need to look closely at other variables that will influence the result. Two important measured variables here will be distance and fuel volume consumption. The accuracies of the odometer and station fuel pump affect these two measurements. Achieving a consistent final volume level when you fill your tank affects the estimate of the fuel volume used. In fact, this effect, which can be classified as a zero error, could be significant. From this example, we can surmise that a consistent measurement technique must be part of the test plan.

What other variables might influence your results? The driving route, whether highway, city, rural, or a mix, affects the results and is an independent variable. Different drivers drive differently, so the driver becomes an independent variable. So how we interpret the measured data is affected by variables in addition to the primary ones measured. Imagine how your test would change if the objective were to establish the fleet average fuel use expected from a car model used by a rental company.

In any test plan, you need to consider just how accurate an answer you need. Is an accuracy within 2 liters per 100 kilometers (or, in the United States, 1 mile per gallon) good enough? If you cannot achieve such accuracy, then the test may require a different strategy. Last, as a concomitant check, is there a way to check whether your test results are reasonable, a sanity check to avoid subtle mistakes? Interestingly, this one example contains all the same elements of any sophisticated test. If you can conceptualize the factors influencing this test and how you will plan around them, then you are on track to handle almost any test.

Experimental design involves itself with developing a measurement test plan. A test plan draws from the following three steps:[2]

1. ***Parameter design plan.*** Determine the test objective and identify the process variables and parameters and a means for their control. Ask: “What question am I trying to answer? What needs to be measured?” “What variables will affect my results?”

2. ***System and tolerance design plan.*** Select a measurement technique, equipment, and test procedure based on some preconceived tolerance limits for error.[3] Ask: “In what ways can I do the measurement? How good do the results need to be to answer my question?”

3. ***Data reduction design plan.*** Plan how to analyze, present, and use the data. Ask: “How will I interpret the resulting data? How will I apply the data to answer my question? How good is my answer?

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[2] These three strategies are similar to the bases for certain design methods used in engineering system design [1].

[3] The tolerance design plan strategy used in this text draws on uncertainty analysis, an extension of sensitivity analysis. Sensitivity methods are common in design optimization.

Going through all three steps in the test plan before any measurements are taken is a useful habit of the successful engineer. Often step 3 will force you to reconsider steps 1 and 2. We will develop methods to help address each step as we proceed.

Variables

A *variable* is a physical quantity whose value influences the test result. Variables can be continuous or discrete by nature. A *continuous variable* can assume any value within its range. A *discrete variable* can assume only certain values.

Functionally, variables can be classed as being dependent, independent, or extraneous. A variable whose value is affected by changes in the value of one or more other variables is known as a *dependent variable*. Variables that do not influence each other are *independent variables*. Dependent variables are functions of independent variables. The test result is a dependent variable whose value depends on the values of the independent variables. For example, the value of strain measured in a loaded cantilever beam (dependent variable) results from the value of the loading applied (independent variable).

The values of independent variables are either purposely changed or held fixed throughout a test to study the effect on the dependent variable. A *controlled variable* is a variable whose value is held fixed. A test *parameter* is a controlled variable or grouping of variables whose fixed value sets the behavior of the process being measured. The dimensions and material properties of the beam in the loaded cantilever beam are parameters. The value of the parameter is changed when you want to change the process behavior.

In engineering, groupings of variables, such as moment of inertia or Reynolds number, are also referred to as parameters when these relate to certain system behaviors. For example, the damping ratio of an automotive suspension system affects how the displacement velocity will change with differing input conditions; this parameter affects the variables that measure vehicle behavior, such as handling and ride quality. In our treatment of statistics, we use the term parameter to refer to quantities that describe the behavior of the population of a measured variable, such as the true mean value or variance.

Variables that are not purposely manipulated or controlled during measurement but that do affect the test result are called *extraneous variables*. Dependent variables are affected by extraneous variables. If not treated properly within a test plan, extraneous variables can impose a false trend or impose variation onto the behavior of the measured variable. This influence can confuse the clear relation between cause and effect.

There are other uses of the term “control.” Experimental control describes how well we can maintain the prescribed value of an independent variable within some level of confidence during a measurement. For example, if we set the loading applied in a bending beam test to 103 kN, does it stay exactly fixed during the entire test, or does it vary by some amount on repeated tries? Different fields use variations on this term. In statistics, a control group is one held apart from the treatment under study. But the nuance of holding something fixed is retained.

EXAMPLE 1.1

Consider an introductory thermodynamics class experiment used to demonstrate phase change phenomena. A beaker of water is heated and its temperature measured over time to establish the temperature at which boiling occurs. The results, shown in Figure 1.5, are for three separate tests conducted on different days by different student groups using the same equipment and method. Why might the data from three seemingly identical tests show different results?

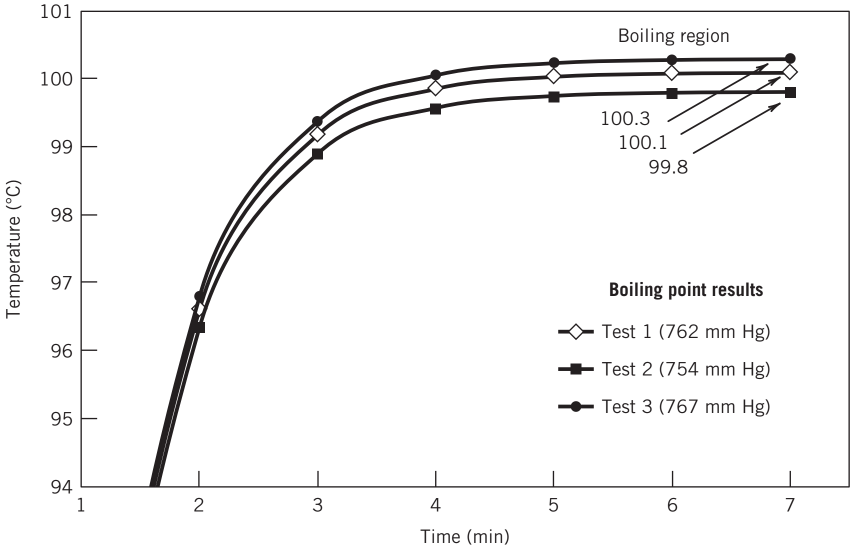

FIGURE 1.5 Results of a boiling point test for water.

KNOWN Temperature-time measurements for three tests conducted on three different days

FIND Boiling point temperature

SOLUTION

Each group of students anticipated a value of exactly 100.0°C. Individually, each test result is close, but when compared, there is a clear offset between any two of the three test results. Suppose we determine that the measurement system accuracy and natural chance account for only 0.1°C of the disagreement between tests—then something else is happening. A plausible contributing factor is an effect due to an extraneous variable.

Fortunately, an assistant recorded the local barometric pressure during each test. The boiling point (saturation) temperature is a function of pressure. Each test shows a different outcome, in part, because the local barometric pressure was not controlled (i.e., it was not held fixed between the tests).

COMMENT One way to control the effects of pressure here might be to conduct the tests inside a barometric pressure chamber. Direct control of all variables is not often possible in a test. So another way to handle the extraneous variable applies a special strategy: Consider each test as a single block of data taken at the existing barometric pressure. Then consolidate the three blocks of test data. In that way, the measured barometric pressure becomes treated as if it were an independent variable, with its influence integrated into the entire data set. That is, we can actually take advantage of the differences in pressure so as to study its effect on saturation temperature. This is a valuable control treatment called randomization, a procedure we discuss later in this chapter. *Identify and control important variables, or be prepared to solve a puzzle!*

EXAMPLE 1.2 Case Study

The golf cart industry within the United States records nearly $1 billion in sales annually. The manufacturer of a particular model of golf cart sought a solution to reduce undesirable vibrations in the cart steering column (Figure 1.6). Engineers identified the source of the vibrations as the

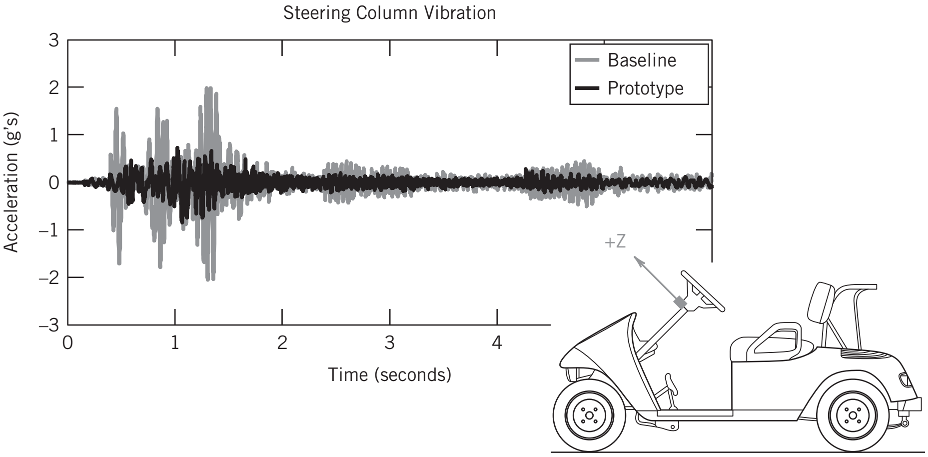

FIGURE 1.6
Measured time-based *z*-acceleration signal at the steering wheel during an engine run-up test: baseline and the attenuated prototype (proposed solution) signals.

gas-powered engine and consistent with operating the engine at certain speeds (revolutions/minute or rpm). The company management ruled out expensive suspension improvements, so the engineers looked at cheaper options to attenuate the vibrations at the steering wheel.

Using test standard ANSI S2.70-2006 [19] as a guide for placing sensors and interpreting results, accelerometers (discussed in Chapter 12) were placed on the steering column, engine, suspension, and frame. The measurement chain followed Figure 1.4. The signal from each accelerometer sensor–transducer was passed through a signal-conditioning charge amplifier (Chapter 6) and on to a laptop-based data acquisition system (DAS; Chapter 7). The amplifier converted the transducer signal to a 0–5 V signal that matched the input range of the DAS. The DAS served as a voltmeter, output display, and time-based recorder.

Measurements showed that the offensive vibration at the steering wheel was at the natural frequency of the steering column (~20 Hz). This vibration was excited at forcing function frequencies between 17 and 37 Hz, corresponding to normal operating speeds of the engine (1,000–2,200 rpm). From a lumped parameter model (Chapter 3) of the steering assembly, they determined that a slightly heavier steering column would reduce its natural frequency to below the engine idle speed and thereby attenuate the amplitude of the vibrations (Chapter 3) excited at higher engine speeds. The analysis was verified and the fix was refined based on the tests. The measured vibration signals during engine runup, both before (baseline) and with the proposed fix (prototype), are compared in Figure 1.6. Peak vibration amplitudes were shown to reduce to comfortable levels with the proposed and validated solution. The inexpensive fix was implemented by the manufacturer.

COMMENT This example illustrates how measurements applied to a mechanical test provided information to diagnose a problem and then formulate and validate a proposed solution.

Noise and Interference

Just how extraneous variables affect measured data can be described in terms of noise and interference. *Noise* is a random variation in the value of the measured signal. Noise increases data scatter. Building vibrations, variations in ambient conditions, and random thermal noise of electrons passing through a conductor are examples of common extraneous sources for the random variations found in a measured signal.

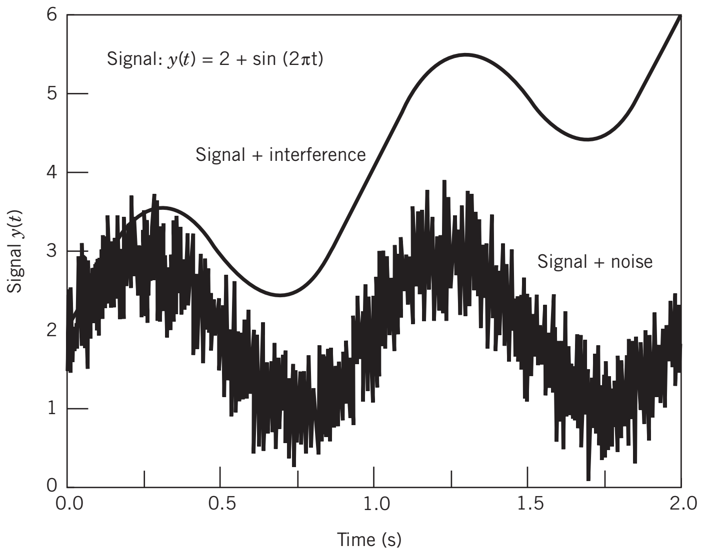

FIGURE 1.7 Effects of noise and interference superimposed on the signal $y(t) = 2 + \sin\ 2\pi t$.

Interference imposes undesirable deterministic trends on the measured signal. A common interference in electrical instruments comes from an AC power source and is seen as a sinusoidal wave superimposed onto the measured signal. Hum and acoustic feedback in public address systems are ready examples of interference effects superimposed onto a desirable signal. Sometimes the interference is obvious. But if the period of the interference is longer than the period over which the measurement is made, the false trend imposed may go unnoticed. A goal should be either to control the source of interference or to break up its trend.

Consider the effects of noise and interference on the signal, $y(t) = 2 + \sin\ 2\pi t$. As shown in Figure 1.7, noise adds to the scatter of the signal. Through statistical techniques and other means, we can sift through the fuzziness to extract desirable signal information. Interference imposes a false trend onto the signal. The test plan should be devised to break up such trends so that they become random variations in the data set. Although this increases the scatter in the measured values of a data set, noise may mask, but does not change, the deterministic aspects of a signal. It is far more important to eliminate false trends in the data set.

In Example 1.1, by combining the three tests at three random but measured values of barometric pressure into a single dataset, we incorporated the uncontrolled pressure effects into the results for boiling temperature while breaking up any offset in results found in any one test. This approach imparts some control over an otherwise uncontrolled variable.

Randomization

An engineering test purposely changes the values of one or more independent variables to determine the effect on a dependent variable. *Randomization* refers to test strategies that apply the changes in the independent variables in some random order. The intent is to neutralize effects that may not be accounted for in the test plan.

In general, consider the situation in which the dependent variable, y, is a function of several independent variables, $x_a, x_b, \ldots$. To find the dependence of y on the independent variables, they are varied in a prescribed manner. However, the measurement of y can also be influenced by extraneous variables, z_j, where $j = 1, 2, \ldots$, such that $y = f(x_a, x_b, \ldots ; z_j)$. Although the influence of the