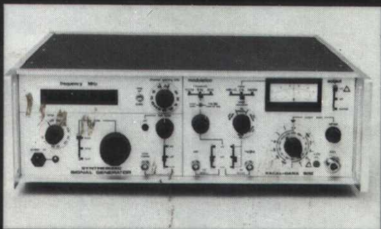
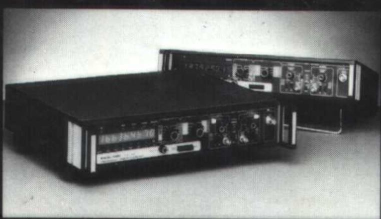
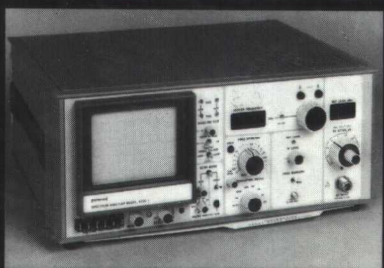
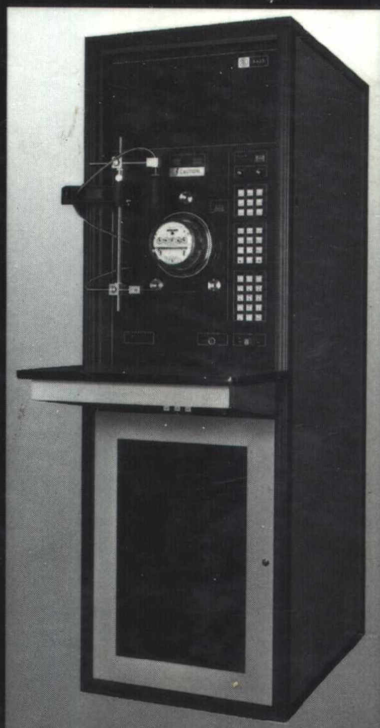
THIRD EDITION

# ELECTRONIC INSTRUMENTATION AND MEASUREMENT TECHNIQUES

W. D. COOPER
A. D. HELFRICK

3rd edition

# *Electronic Instrumentation and Measurement Techniques*

William David Cooper

Albert D. Helfrick

Prentice-Hall, Inc. / *Englewood Cliffs, New Jersey 07632*

*Library of Congress Cataloging in Publication Data*

Cooper, William David, (date)
Electronic instrumentation and measurement techniques.

Includes bibliographies and index.
1. Electric measurements. 2. Electric meters.
3. Electronic measurements. 4. Electronic instruments.
I. Helfrick, Albert D. II. Title.
TK275.C63 1985 621.3815'4 84-18185
ISBN 0-13-250721-8

*Cover design:* 20/20 Services, Inc.
*Manufacturing buyer:* Gordon Osbourne



Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-250721-8 01

Prentice-Hall International, Inc., *London*
Prentice-Hall of Australia Pty. Limited, *Sydney*
Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*
Prentice-Hall Canada Inc., *Toronto*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Prentice-Hall of Southeast Asia Pte. Ltd., *Singapore*
Whitehall Books Limited, *Wellington, New Zealand*

# PREFACE

The third edition of *Electronic Instrumentation and Measurement Techniques* is designed to serve as a text for students of electrical and electronic engineering at both two- and four-year colleges and technical institutes. The book can also serve as a refresher or handbook for the professional engineer. This text provides good groundwork for the basics of electrical measurement and then presents examples ranging from elementary measurements to the most sophisticated computer-controlled systems.

Several changes have been made from the previous edition. First, the subject of electromechanical meter movements has been reduced and compressed from two chapters to one chapter, and the subject of bridges has been similarly compressed. This was done to make way for the addition of new material on measurement systems using newer technology.

Chapter 7, on oscilloscopes, has been completely rewritten and expanded to include descriptions of the latest technology in cathode ray tubes and oscilloscope circuits. Chapters 8 and 9, on signal generation and signal analysis, comprised one chapter in the previous edition, and the expanded text reflects the advances in these instruments. Chapter 13 describes computer-controlled test equipment for automatic test systems. This material, which is entirely new, covers a rapidly growing phase of test and measurement technology.

Those elements essential to a good textbook, such as worked-out examples and chapter-end problems and review questions, have been retained. Included in the new edition to aid the student are answers to selected questions and problems.

W. D. COOPER
A. D. HELFRICK

ELECTRONIC INSTRUMENTATION
AND MEASUREMENT TECHNIQUES

# CONTENTS

# CHAPTER 1

# MEASUREMENT AND ERROR

## 1-1 DEFINITIONS

Measurement generally involves using an instrument as a physical means of determining a quantity or variable. The instrument serves as an extension of human faculties and in many cases enables a person to determine the value of an unknown quantity which his unaided human faculties could not measure. An instrument, then, may be defined as *a device for determining the value or magnitude of a quantity or variable*. The *electronic* instrument, as its name implies, is based on electrical or electronic principles for its measurement function. An electronic instrument may be a relatively uncomplicated device of simple construction such as a basic dc current meter (see Chapter 4). As technology expands, however, the demand for more elaborate and more accurate instruments increases and produces new developments in instrument design and application. To use these instruments intelligently, one needs to understand their operating principles and to appraise their suitability for the intended application.

Measurement work employs a number of terms which should be defined here.

*Instrument:* a device for determining the value or magnitude of a quantity or variable.

*Accuracy:* closeness with which an instrument reading approaches the true value of the variable being measured.

*Precision:* a measure of the reproducibility of the measurements; i.e., given a fixed value of a variable, precision is a measure of the degree to which successive measurements differ from one another.

*Sensitivity:* the ratio of output signal or response of the instrument to a change of input or measured variable.

*Resolution:* the smallest change in measured value to which the instrument will respond.

*Error:* deviation from the true value of the measured variable.

Several techniques may be used to minimize the effects of errors. For example, in making precision measurements, it is advisable to record a series of observations rather than rely on one observation. Alternate methods of measurement, as well as the use of different instruments to perform the same experiment, provide a good technique for increasing accuracy. Although these techniques tend to increase the *precision* of measurement by reducing environmental or random error, they cannot account for instrumental error.*

This chapter provides an introduction to different types of error in measurement and to the methods generally used to express errors, in terms of the most reliable value of the measured variable.

## 1-2 ACCURACY AND PRECISION

*Accuracy* refers to the degree of closeness or conformity to the true value of the quantity under measurement. *Precision* refers to the degree of agreement within a group of measurements or instruments.

To illustrate the distinction between accuracy and precision, two voltmeters of the same make and model may be compared. Both meters have knife-edged pointers and mirror-backed scales to avoid parallax, and they have carefully calibrated scales. They may therefore be read to the same *precision.* If the value of the series resistance in one meter changes considerably, its readings may be in error by a fairly large amount. Therefore the *accuracy* of the two meters may be quite different. (To determine which meter is in error, a comparison measurement with a standard meter should be made.)

Precision is composed of two characteristics: *conformity* and the number of *significant figures* to which a measurement may be made. Consider, for example, that a resistor, whose true resistance is 1,384,572 Ω, is measured by an ohmmeter which consistently and repeatedly indicates 1.4 MΩ. But can the observer "read" the true value from the scale? His estimates from the scale reading consistently yield a value of 1.4 MΩ. This is as close to the true value as he can read the scale by estimation. Although there are no deviations from the observed value, the error created by the limitation of the scale reading is a

*Melville B. Stout, *Basic Electrical Measurements,* 2nd ed. (Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1960), pp. 21–26.

*precision* error. The example illustrates that conformity is a necessary, but not sufficient, condition for precision because of the lack of significant figures obtained. Similarly, precision is a necessary, but not sufficient, condition for accuracy.

Too often the beginning student is inclined to accept instrument readings at face value. He is not aware that the accuracy of a reading is *not* necessarily guaranteed by its precision. In fact, good measurement technique demands *continuous skepticism* as to the accuracy of the results.

In critical work, good practice dictates that the observer make an independent set of measurements, using different instruments or different measurement techniques, not subject to the same systematic errors. He must also make sure that the instruments function properly and are calibrated against a known standard, and that no outside influence affects the accuracy of his measurements.

## 1-3 SIGNIFICANT FIGURES

An indication of the precision of the measurement is obtained from the number of *significant figures* in which the result is expressed. Significant figures convey actual information regarding the magnitude and the measurement precision of a quantity. The more significant figures, the greater the precision of measurement.

For example, if a resistor is specified as having a resistance of 68 Ω, its resistance should be closer to 68 Ω than to 67 Ω or 69 Ω. If the value of the resistor is described as 68.0 Ω, it means that its resistance is closer to 68.0 Ω than it is to 67.9 Ω or 68.1 Ω. In 68 Ω there are two significant figures; in 68.0 Ω there are three. The latter, with more significant figures, expresses a measurement of greater precision than the former.

Often, however, the total number of digits may not represent measurement precision. Frequently, large numbers with zeros before a decimal point are used for approximate populations or amounts of money. For example, the population of a city is reported in six figures as 380,000. This may imply that the true value of the population lies between 379,999 and 380,001, which is six significant figures. What is meant, however, is that the population is closer to 380,000 than to 370,000 or 390,000. Since in this case the population can be reported only to two significant figures, how can large numbers be expressed?

A more technically correct notation uses *powers of ten*, $38 \times 10^4$ or $3.8 \times 10^5$. This indicates that the population figure is only accurate to two significant figures. Uncertainty caused by zeros to the *left* of the decimal point is therefore usually resolved by *scientific notation* using powers of ten. Reference to the velocity of light as 186,000 mi/s, for example, would cause no misunderstanding to anyone with a technical background. But $1.86 \times 10^5$ mi/s leaves no confusion.

It is customary to record a measurement with all the digits of which we are sure nearest to the true value. For example, in reading a voltmeter, the voltage may be read as 117.1 V. This simply indicates that the voltage, read by the observer to best estimation, is closer to 117.1 V than to 117.0 V or 117.2 V. Another way of expressing this result indicates the *range of possible error.* The voltage may be expressed as 117.1 ± 0.05 V, indicating that the value of the voltage lies between 117.05 V and 117.15 V.

When a number of independent measurements are taken in an effort to obtain the best possible answer (closest to the true value), the result is usually expressed as the arithmetic *mean* of all the readings, with the range of possible error as the *largest deviation* from that mean. This is illustrated in Example 1-1.

**Example 1-1**

A set of independent voltage measurements taken by four observers was recorded as 117.02 V, 117.11 V, 117.08 V, and 117.03 V. Calculate (a) the average voltage, (b) the range of error.

**Solution**

(a)
$$E_{av} = \frac{E_1 + E_2 + E_3 + E_4}{N}$$
$$= \frac{117.02 + 117.11 + 117.08 + 117.03}{4} = 117.06 \text{ V}$$

(b)
$$\text{Range} = E_{max} - E_{av} = 117.11 - 117.06 = 0.05 \text{ V}$$

but also
$$E_{av} - E_{min} = 117.06 - 117.02 = 0.04 \text{ V}$$

The average range of error therefore equals
$$\frac{0.05 + 0.04}{2} = \pm 0.045 = \pm 0.05 \text{ V}$$

When two or more measurements with different degrees of accuracy are added, *the result is only as accurate as the least accurate measurement.* Suppose that two resistances are *added* in series as in Example 1-2.

**Example 1-2**

Two resistors, $R_1$ and $R_2$, are connected in series. Individual resistance measurements, using a Wheatstone bridge, give $R_1 = 18.7\ \Omega$ and $R_2 = 3.624\ \Omega$. Calculate the total resistance to the appropriate number of significant figures.

**Solution**

$$R_1 = 18.7\ \Omega \text{ (three significant figures)}$$
$$R_2 = 3.62\mathit{4}\ \Omega \text{ (four significant figures)}$$
$$R_T = R_1 + R_2 = 22.\mathit{324}\ \Omega \text{ (five significant figures)} = 22.\mathit{3}\ \Omega$$

The doubtful figures are written in *italics* to indicate that in the addition of $R_1$ and $R_2$ the last three digits of the sum are doubtful figures. There is no value whatsoever in retaining the last two digits (the *2* and the *4*) because one of the resistances is accurate only to three significant figures or tenths of an ohm. The result should therefore also be reduced to three significant figures or the nearest tenth, i.e., 22.*3* Ω.

The number of significant figures in *multiplication* may increase rapidly, but again only the appropriate figures are retained in the answer, as shown in Example 1-3.

**Example 1-3**

In calculating voltage drop, a current of 3.18 A is recorded in a resistance of 35.68 Ω. Calculate the voltage drop across the resistor to the appropriate number of significant figures.

**Solution**

$$E = IR = (35.6\mathit{8}) \times (3.1\mathit{8}) = 11\mathit{3.4624} = 113 \text{ V}$$

Since there are three significant figures involved in the multiplication, the answer can be written only to a maximum of three significant figures.

In Example 1-3, the current, $I$, has three significant figures and $R$ has four; and the result of the multiplication has only three significant figures. This illustrates that the answer cannot be known to an accuracy greater than the *least* poorly defined of the factors. Note also that if extra digits accumulate in the answer, they should be discarded or rounded off. In the usual practice, if the (least significant) digit in the first place to be discarded is less than five, it and the following digits are dropped from the answer. This was done in Example 1-3. If the digit in the first place to be discarded is five or greater, the previous digit is increased by one. For three-digit precision, therefore, 113.46 should be rounded off to 113; and 113.74 to 114.

*Addition* of figures with a range of doubt is illustrated in Example 1-4.

**Example 1-4**

Add 826 ± 5 to 628 ± 3.

**Solution**

$$N_1 = 826 \pm 5 \; (= \pm 0.605\%)$$

$$N_2 = 628 \pm 3 \; (= \pm 0.477\%)$$

$$\text{Sum} = 1{,}454 \pm 8 \; (= \pm 0.55\%)$$

Note in Example 1-4 that the doubtful parts are *added*, since the ± sign means that one number may be high and the other low. The worst possible combination of range of doubt should be taken in the answer. The percentage doubt in the original figure $N_1$ and $N_2$ does not differ greatly from the percentage doubt in the final result.

If the same two numbers are *subtracted*, as in Example 1-5, there is an interesting comparison between addition and subtraction with respect to the range of doubt.

**Example 1-5**

Subtract 628 ± 3 from 826 ± 5 and express the range of doubt in the answer as a percentage.

**Solution**

$$N_1 = 826 \pm 5 \ (= \pm 0.605\%)$$

$$N_2 = 628 \pm 3 \ (= \pm 0.477\%)$$

$$\text{Difference} = 198 \pm 8 \ (= \pm 4.04\%)$$

Again, in Example 1-5, the doubtful parts are added for the same reason as in Example 1-4. Comparing the results of addition and subtraction of the same numbers in Examples 1-4 and 1-5, note that the precision of the results, when expressed in *percentages*, differs greatly. The final result after subtraction shows a large increase in percentage doubt compared to the percentage doubt after addition. The percentage doubt increases even more when the difference between the numbers is relatively small. Consider the case illustrated in Example 1-6.

**Example 1-6**

Subtract 437 ± 4 from 462 ± 4 and express the range of doubt in the answer as a percentage.

**Solution**

$$N_1 = 462 \pm 4 \ (= \pm 0.87\%)$$

$$N_2 = 437 \pm 4 \ (= \pm 0.92\%)$$

$$\text{Difference} = 25 \pm 8 \ (= \pm 32\%)$$

Example 1-6 illustrates clearly that one should avoid measurement techniques depending on subtraction of experimental results because the range of doubt in the final result may be greatly increased.

## 1-4 TYPES OF ERROR

No measurement can be made with perfect accuracy, but it is important to find out what the accuracy actually is and how different errors have entered into the measurement. A study of errors is a first step in finding ways to reduce them. Such a study also allows us to determine the accuracy of the final test result.

Errors may come from different sources and are usually classified under three main headings:

*Gross errors:* largely human errors, among them misreading of instruments, incorrect adjustment and improper application of instruments, and computational mistakes.

*Systematic errors:* shortcomings of the instruments, such as defective or worn parts, and effects of the environment on the equipment or the user.

*Random errors:* those due to causes that cannot be directly established because of random variations in the parameter or the system of measurement.

Each of these classes of errors will be discussed briefly and some methods will be suggested for their reduction or elimination.

### 1-4.1 Gross Errors

This class of errors mainly covers *human* mistakes in reading or using instruments and in recording and calculating measurement results. As long as human beings are involved, some gross errors will inevitably be committed. Although complete elimination of gross errors is probably impossible, one should try to anticipate and correct them. Some gross errors are easily detected; others may be very elusive. One common gross error, frequently committed by beginners in measurement work, involves the improper use of an instrument. In general, indicating instruments change conditions to some extent when connected into a complete circuit, so that the measured quantity is altered by the method employed. For example, a well-calibrated voltmeter may give a misleading reading when connected across two points in a high-resistance circuit (Example 1-7). The same voltmeter, when connected in a low-resistance circuit, may give a more dependable reading (Example 1-8). These examples illustrate that the voltmeter has a "loading effect" on the circuit, altering the original situation by the measurement process.

**Example 1-7**

A voltmeter, having a sensitivity of 1,000 Ω/V, reads 100 V on its 150-V scale when connected across an unknown resistor in series with a milliammeter.

When the milliammeter reads 5 mA, calculate (a) apparent resistance of the unknown resistor, (b) actual resistance of the unknown resistor, (c) error due to the loading effect of the voltmeter.

**Solution**

(a) The total circuit resistance equals

$$R_T = \frac{V_T}{I_T} = \frac{100\ \text{V}}{5\ \text{mA}} = 20\ \text{k}\Omega$$

Neglecting the resistance of the milliammeter, the value of the unknown resistor is $R_X = 20\ \text{k}\Omega$.

(b) The voltmeter resistance equals

$$R_V = 1{,}000\,\frac{\Omega}{\text{V}} \times 150\ \text{V} = 150\ \text{k}\Omega$$