ELEMENTS OF ELECTRICAL AND ELECTRONIC INSTRUMENTATION

An Introductory Textbook

Kurt S. Lion

ELEMENTS OF ELECTRICAL AND ELECTRONIC INSTRUMENTATION

An Introductory Textbook

Kurt S. Lion

Professor Emeritus
Senior Lecturer
The Massachusetts Institute of Technology

McGraw-Hill Book Company

New York St. Louis San Francisco Auckland Düsseldorf Johannesburg
Kuala Lumpur London Mexico Montreal New Delhi Panama Paris São Paulo
Singapore Sydney Tokyo Toronto

ELEMENTS OF ELECTRICAL AND ELECTRONIC INSTRUMENTATION
An Introductory Textbook

1 2 3 4 5 6 7 8 9 0 K P K P 7 9 8 7 6 5

Library of Congress Cataloging in Publication Data

Lion, Kurt Siegfried.
Elements of electrical and electronic instrumentation.
1. Electric meters. 2. Electronic instruments.
3. Transducers. I. Title.
TK301.L53 621.3′028 74-16172
ISBN 0-07-037976-9

This book was set in 8A by Bi-Comp, Incorporated. The editors were Robert H. Summersgill and J. W. Maisel; the cover was designed by Pencils Portfolio, Inc.; the production supervisor was Charles Hess. The drawings were done by J & R Services, Inc.
Kingsport Press, Inc., was printer and binder.

ELEMENTS OF ELECTRICAL AND ELECTRONIC INSTRUMENTATION

To my wife
Elsa née Strauss

Preface

Instrumentation is the science that deals with the means and methods of obtaining and processing physical and chemical information. Instrumentation methods are applied to physical and chemical problems, to biological and medical problems, and to countless problems in the engineering sciences, as well as in the social sciences, archaeology, geology, astronomy, and many other sciences. Instrumentation is practiced in research institutes, colleges, schools, in hospitals, in industry and in many government and military research and testing laboratories. Probably the largest relative amount of funds and manpower in almost any research project is absorbed by instrumentation requirements. A working familiarity with the principles of modern instrumental methods is, therefore, essential for investigators in many scientific fields. The book is an introduction to the elements of electrical and electronic instrumentation.

The word *instrumentation* means different things to different people. For some it means electric meters and recorders, for others it means electronic circuitry, for still others it means electrochemical apparatus or the application of physical instruments to biological or medical problems (bioengineering or bioinstrumentation).

It has been my intention in this book to cover more or less the entire field of electrical and electronic instrumentation. I believe that such a book is more interesting and useful than a book limited to special topics. It should make it clear to the student that usually there is not one but a variety of solutions for a given problem. This fact should contribute to the reader's innovation and creativity. The book has as its goal a broad coverage of the methodology in the field of electrical instrumentation. It is primarily a book in instrumentation physics rather than in instrumentation technology. It is written for those who are familiar with the concepts of elementary physics, but it provides material to clarify the basic concepts. This should help to fill in voids for those who were never taught correctly or for those who have forgotten these concepts. The mathematical level is limited to that of a simple differential equation. Mathematics is used sparingly since mathematical manipulations sometimes can obscure the physics behind the equation.

The presentation of the subject matter is essentially descriptive, for I believe that this is desirable for a study of instrumentation. The teaching of instrumentation at an introductory level should be directed primarily to the formation of concepts, i.e., of "mental images of a thing formed by generalization from particulars." The book is written primarily for a scientist who uses and occasionally designs instruments. The reader may be a chemist, a biologist, a medical research worker, a mechanical engineer, a textile engineer, a metallurgist, or any investigator in an experimental science—also occasionally a physicist, an electrical engineer, or an electronics technician. The book should also be useful for junior or senior students in an introductory instrumentation course.

Most of the material is presented in the form of *instrumentation elements*. An instrumentation element is a functional unit, or a module, or a single block in a block diagram, as described in further detail in Chapter 1. The concept of technical modular units was used first by C. von Bach at the end of the nineteenth century. Faced with the need for an adequate logical system to cover a great variety of machines, he created the very successful concept of *machine elements*. In a similar vein, I have used the instrumentation elements as a means to reduce the large amount of material to be covered and to describe the basic solutions for the construction of instruments.

Some topics require no detailed descriptions; one can measure time with a stopwatch without knowing the constructional details of the watch. Instrumentation elements are described in detail when the element is based on a principle that is new within the sequence of the text and when such a principle appears to have possible applications in a variety of problems, or when the detailed knowledge is needed for the correct use or operation of the element. This book differs in scope and in content from my book "Instrumentation in Scientific Research, Input Transducers" (McGraw-Hill, New York, 1959). The latter deals with input transducers only and treats them on a handbook level. The present book is an introductory treatise of the most important electrical and electronic instrumentation elements, i.e., transducers with electrical input or electrical output as well as modifiers (information processing elements).

Some teachers have claimed that knowledge in the field of instrumentation is proliferating so fast that a course given one year is outdated the next year. In my opinion an introductory course that is outdated in one year is not worthy of being taught in the first place. A course or a textbook of instrumentation should be a collection of topics that are timeless. It is just as wrong to neglect the classical methods and techniques as it is to omit those modern methods that promise to be of lasting value.

My main goal has been to simplify the subject matter and to convey to the reader basic and convincing concepts that can be used in a creative manner. It is not my intention to teach the student how to build an amplifier or how to repair a cathode-ray oscilloscope. In most cases it is more economical to buy a commercially available piece of equipment than to build it; and a research worker can hardly compete with the service man of the manufacturer.

I gratefully acknowledge the help and the numerous contributions of my long-time collaborator, Dr. Tibor L. Földvári, now Vice President of Harvard Apparatus Company and Adjunct Professor of Biology at Boston University. I should also like to express my gratitude to my former collaborator, now at Arizona State University, Professor Peter K. Stein, for his numerous suggestions and improvements. I am also grateful to my colleague at the Massachusetts Institute of Technology, Professor David N. Hume, for his help, particularly with the chapter on electrolytic systems, and to Dr. James Ross for his contribution on oxygen electrodes. I am most grateful to Mrs. E. Duncan and N. L. Duncan, who have been of invaluable help with the styling and editing of the manuscript.

I am particularly grateful to the National Science Foundation for providing me with the financial means to develop a student laboratory to teach instrumentation. The laboratory exercises described in the Appendix of this book stem from this development and are reproduced here with the kind permission of the National Science Foundation.

Kurt S. Lion

Contents

1
Definitions and Organization

The purpose of instrumentation is the procurement of *information* or the control of an object or a process in accordance with such information.

INFORMATION AND SIGNALS

Information is carried or conveyed by signals. In a broad sense, a signal is a physical or chemical quantity (e.g., a voltage or a wavelength) or a combination of physical quantities (pattern) which can exist in a variety of meaningful states, at least in two states (on or off). An unchangeable or only randomly varying voltage does not represent a signal. Information can be expressed and carried in *analog* form, i.e., in a continuously variable form, such as the position of a meniscus relative to a scale. Alternatively, information can be expressed or coded in *digital* form, i.e., in discontinuous steps, such as by a group of figures or characters.

The desired information may be a physical or chemical quantity (e.g., the strain in a turbine blade or the concentration of hydrogen ions in solution) or it may have the general character of a message. If the information has the character of a message, the relationship between signal and information is usually laid down in a code (e.g., Morse code or pattern code: "one if by land and two if by sea"). If the information is of a physical or chemical nature, the relationship between the information and the signal is usually that of a physical law expressed by a mathematical equation, or by an empirical calibration characteristic, or by a table. An ill-defined relationship between signal and information wanted may cause the information derived from an instrumentation system to be unsatisfactory. For instance, the psychogalvanic reflex meter, an instrument which measures the electric resistance of the skin (or the electrical polarization of the skin), may furnish a correct output signal reflecting the skin resistance or its variations. Used as a lie detector, it suffers from the ambiguous relationship between the skin resistance and the emotional response of the subject.

In accordance with the usual classification of physical phenomena, six different forms of physical signals can be distinguished: mechanical, thermal, magnetic, electric, optical, and molecular (chemical) signals.

INSTRUMENTATION ELEMENTS

All instruments are composed of basic units called *instrumentation elements** or *operating components.*† An instrumentation element is a modular unit which performs a specific task and is represented by a building block in a function diagram. For example, a photoelectric cell with the necessary supply source and load resistance converts light into a corresponding electric current. Another example is an amplifier, which converts a small voltage into a large one. There are two groups of instrumentation elements: *transducers* and *modifiers.*

A transducer converts a signal of *one* physical form into a corresponding signal of *another* physical form. For example, a piezoelectric transducer converts a *mechanical signal* (force) into a corresponding *electric signal* (voltage).

A modifier, or signal-processing element, converts a signal of *one* physical form into a modified signal of the *same* form. For instance, an electrical integrator produces at its output terminals an *electric* signal which is proportional to the time integral of the *electric* signal applied to its input terminals.

Since there are six different forms of input signals and six different forms of output signals, all instrumentation elements can be classified in a logical system as shown in Table 1-1.

An example of an electrical instrument composed of three elements is the vibration meter shown in Fig. 1-1. The vibration is converted into an electric voltage or current signal by a mechanical-electrical transducer. The output signal from the transducer is led to an amplifier; the amplifier output is connected to a recorder which plots the displacement-time diagram. The arrows signify the

* K. S. Lion, "Instrumentation in Scientific Research," McGraw-Hill, New York, 1959, distinguished among three groups of instrumentation elements: input transducers, output transducers, and modifiers. The distinction between input and output transducers seems unnecessary and has since been abandoned. The present book is based on only two groups of instrumentation elements.

† C. S. Draper, W. McKay, S. Lees, "Instrument Engineering," vol. 1, p. 8, McGraw-Hill, 1952.

Table 1-1 Synopsis of transducers and modifiers

Examples of transducers (T), groups of transducers or transducer systems as well as modifiers (M) and their logical grouping for different input and output signals.

Out \ *In*	*1 Mechanic*	*2 Thermal*	*3 Magnetic*	*4 Electric*	*5 Optic*	*6 Molecular*
1 Mechanic	(M) Gravity balance Ballistic pendulum Bellows	Thermometers Bimetal strip	Magnetometer Magnetostriction transducer	Electrometers Electrostrictive transducer	Crooke's radiometer Radiation pressure systems	Hydrometer Electrodeposition cell
2 Thermal	Adiabatic systems Friction calorimeter	Mixing calorimeter	Eddy-current transducer	Thermal converter	Bolometer	Combustion calorimeter
3 Magnetic	Magnetoelastic transducer	Paramagnetic transducer devices	Magnetic recorder	Electromagnetic transducer	Curie-effect radiation meter	Magnetic resonance system
4 Electric	Resistive, Inductive, Capacitive, Piezoelectric transducer	Thermistor Thermoelement	Magnetoresistance, Hall-effect transducer	(M) Transformers (T) Langmuir probe Charge collectors	Photoelectric cell Photoresistive cell Photogalvanic cell	Transducers based on potentiometry, conductimetry, polarography
5 Optic	Interferometer Photoelastic transducer	Thermal radiation transducer	Faraday cell	Kerr cell Electroluminescent transducer	(M) Geometric-optical systems	Transducers based on emission, absorption spectroscopy
6 Molecular	Ultrasonic chemical transducer	Thermal dye indicators	Paramagnetic Oxygen Analyzer	Electrolytic integrator	Photographic emulsion	Chemical systems modifiers

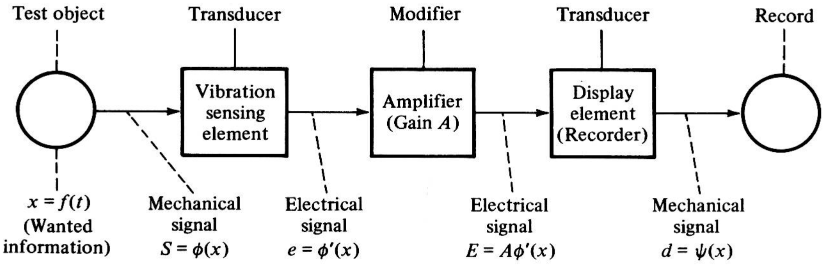

Fig. 1-1

flow of information. If only the amplitude of the vibration is to be measured, a peak voltmeter may be used instead of the recorder. If the frequency spectrum of the vibration is to be analyzed, a tuned filter may be inserted between the amplifier and the output meter. If the physical properties of the instrumentation elements are known, an instrument can be designed, its function can be predicted, and an optimum solution for a given instrumentation problem can usually be found.

It is sometimes advantageous to use several elements in sequence for the conversion of signals from one form into a more suitable form. The example in Fig. 1-2 illustrates elements to be used for the sequential conversion of pressure signals into electric signals. These elements are to be used if single-step transducers of suitable range or sensitivity are not available. Any one of the five elements in the upper horizontal row of Fig. 1-2 can be used for the conversion of a pressure signal p into a displacement d of a membrane, a spiral, or other member. Any one of the elements in the lower horizontal row can be used for the conversion of the displacement d into an electric output signal E_o. The

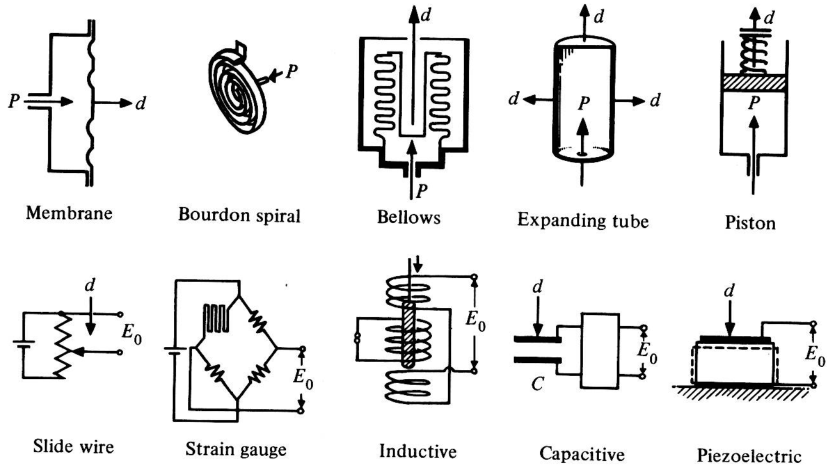

Fig. 1-2

ten basic elements in Fig. 1-2 can be used for the construction of 25 different pressure-to-electrical signal transducers.

GENERAL CRITERIA OF INSTRUMENTATION ELEMENTS

All instrumentation elements are characterized by the following criteria.

Type of input This refers to the physical form of the signal that is applied to the input of the element and that carries the desired information. In general, the applied signal has the dimension of energy or power, i.e., it contains two components, such as force and displacement or voltage and current. Frequently, however, one of the components of the signal can be neglected. For instance, the displacement of a stiff spring under the action of an applied mechanical force and displacement signal may be very small so that the spring may be considered responsive to force only. A capacitive transducer, which requires very little force to produce a measurable change of capacitance, may be called a *displacement responsive transducer*, or *displacement transducer*.

Input impedance This determines the amount of force, energy, or power required from the preceding stage or from the object under investigation. If the physical mechanism involved in the operation of an element is such that the input quantity *actuates* or *drives* the element (e.g., a galvanometer), then maximum power is transferred from the preceding stage to the element if the input impedance of the element matches the output impedance of the preceding stage (source or object). However, maximum power transfer is not always important. Many applications require an input impedance which is large compared with the output impedance of the preceding stage (see Chap. 2).

Type of output If the output signal is of an electrical nature, the information may be contained in:

1. The signal level (voltage or current, e.g., the output from a photoelectric cell)
2. The impedance (resistance, inductance, capacitance, e.g., the output signal from a resistance wire strain gauge)
3. The time function of a voltage or a current (e.g., frequency, phase or time derivative, e.g., the output of a frequency modulator)

Output impedance The output impedance determines the amount of power that can be transferred from the element to the succeeding element or stage at a given output level.

Transfer function The relationship between the output signal Q_o and the input signal Q_i,

$$Q_o = f(Q_i) \tag{1-1}$$

A linear transfer function is frequently desirable; however, linearity of the overall transfer function of a complete system may be obtained even though nonlinear elements are used in some of its stages. This is done by using compensating circuits and feedback or servosystems.

The derivative of the transfer function $dQ_o/dQ_i = S$ is the *sensitivity* of the instrumentation element.

Instrument error In general, an instrument will not follow Eq. (1-1) but will have an output

$$Q_o' = f(Q_i) + F \tag{1-2}$$

where F is the (absolute) error of the result or of the output quantity, i.e., the deviation of the observed output quantity Q_o' from the correct value Q_o

$$F = Q_o' - Q_o$$

The error can be expressed either in terms of the output or input quantity. The fractional error is $F_f = F/Q_o$, which is approximately equal to F/Q_o'; the percentage error is $F_{\%} = F/Q_o \times 100$.

The error is usually complex. It is practical to distinguish the following components:

1. *The scale error.* (*a*) The observed output may deviate from the correct output by an amount which is constant throughout the entire range of the instrument (additive constant, zero displacement). (*b*) The observed output may deviate from the correct value by a constant factor. (*c*) The experimentally observed transfer function may deviate from that postulated by theory (*nonconformity*). In particular, if a linear relationship between input and output is postulated but not experimentally realized, the error is called *nonlinearity or nonlinear distortion.* (*d*) The output may not only depend on the applied input but also on the past history of the element, i.e., on the input formerly applied to the element (*hysteresis error*).
2. *The dynamic error.* The output does not correctly follow the variations with time of the input, or it depends on the time function, such as a time derivative or the frequency of the input quantity.
3. *Noise and drift.* A signal originating in the element and varying with time appears at the output terminals or is superimposed on the output signal. The magnitude of this noise or drift output is, in principle, independent of the magnitude of the signal applied to the input. If information is available about the statistical nature of the noise output, it is possible sometimes to distinguish between the desired output signal and the undesirable noise.

If a human observer reads the output, he is a part of the instrument system, and his reaction must be included in the consideration of errors. For instance, a scale error can be caused by parallax in scale reading, or a dynamic error can be caused by the observer's reaction time or psychological anticipation of an expected result (the "personal equation" of an observer).

Response to environmental influences The performance of an instrumentation element is fully described by the transfer function and the errors, as mentioned above, provided the instrument is in a constant environment and not subjected to external disturbances. If instruments are subjected to environmental influences (such as changes of temperature, pressure, acceleration, magnetic or electric fields, or to changes of the supply voltages), variations of the transfer function and of the errors may result. Although such variations may lead to deviations in the instrument output, they are described separately, for practical reasons, from the instrument errors described in the paragraph on instrument error above

Useful range or level In general, the lower limit of the useful range is imposed by: the unavoidable random variation of the output signal (noise) or other unwanted variations contained in the output signal or originating in the element and appearing in the output, and the tolerable error of the wanted signal. If n is the mean value of the noise level and if $F_{f,\max}$ is the maximum tolerable fractional error of the output signal Q_o, then the lower limit for which the element can be used is, in terms of the output signal,

$$Q_{o,\min} \geq \frac{n}{F_{f,\max}} \tag{1-3}$$

and in terms of the input signal Q_i

$$Q_{i,\min} \geq \frac{n}{SF_{f,\max}}$$

The upper limit of a useful input level is reached, in general, when th input signal tends to damage the element or when excessive distortion of th signal sets in.

In Table 1-1 instrumentation elements are grouped according to the function they serve. In the following chapters they are grouped according to the physical principles involved in their operation.

REFERENCES

Lion, K. S.: Mechanical Input Transducers, in "Instrumentation in Scientific Research," McGraw-Hill, New York, 1959.

Stein, Peter K.: "Measurement Engineering," vol. I: Basic Principles, 6th ed., Stein Engineering Services, Inc., Phoenix, Ariz., 1970.

Neubert, H. P. K.: "Instrument Transducers," Oxford, Clarendon Press, 1963.

Norton, Harry N.: "Handbook of Transducers for Electronic Measuring Systems," Prentice-Hall, Englewood Cliffs, N.J., 1969.

Instrument Society of America: "Basic Instrumentation Lecture Notes and Study Guide," 313 Sixth Ave., Pittsburgh, Pa. 15222.

Rohrbach, Christof: "Handbuch für elektrisches Messen Mechanischer Grössen," VDI Verlag, Düsseldorf, 1968.

2
Basic Electrical Concepts

VOLTAGE AND CURRENT SOURCES

An ideal voltage source or constant-voltage source furnishes at its output terminals a voltage that is independent of the load connected to the source or of the current drawn from the source. The voltage may or may not vary in time; in fact, it must vary in time if it represents a signal.

If a constant-voltage source producing an output voltage of E volts is applied to a resistance of R ohms, as shown in Fig. 2-1*a*, it will cause in the circuit a current of I amperes:

$$I = \frac{E}{R} \tag{2-1}$$

(Ohm's law, Fig. 2-1*a*.)

A constant-voltage source in a strict sense does not exist; the output voltage will always vary with the current drawn from the source. A practical embodiment of a constant-voltage source is a source with an internal resistance which is negligibly small compared to the load resistance R to which the source is connected. Practical constant-voltage sources can also be constructed with the help of electronic systems.