INSTRUMENTATION AND MEASUREMENTS

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Summary

Measurement is a process of gathering information from the physical world and comparing this information with agreed standards. Measurement is essential in order to be able to observe and test scientific and technological investigations. Instruments are developed for measuring the conditions of physical variables and for converting them into symbolic output forms so that we can interpret and understand the nature of these physical variables. Most instruments have sensors or transducers, signal conditioners, and output or termination stages. This article deals, primarily, with the general concepts of instruments. Instrument characteristics, responses, errors, error control systems, standards, designs, testing, and calibrations are discussed. Analog, digital, and virtual instruments are introduced briefly.

Systems can be described as sets of components that are connected to form and act as an entire unity. Instrumentation systems are discussed in detail in *Measurements and Systems*.

During measurement many different forms of physical variables can be investigated—such as acceleration, force, chemical process, and optical properties—by the use of suitable instruments. Nevertheless, most modern instruments rely on the equivalent voltage and/or current measurements of those physical variables. Also, accurate signal monitoring and processing, which are essential in engineering and science, largely depends on the proper voltage measurements. In the series of articles under the topic of instrumentation and measurements, two are about voltage measurement. The first article deals with the conventional ways of measuring voltage and current, and the second deals with modern electronic and digital voltmeters and ammeters.

The art of measurement and monitoring can be achieved in two different ways: using analog instruments that deal directly with analog signals, and converting analog signals into digital signals, implementing the systems using digital instruments. In modern applications, digital instruments are gradually replacing their analog counterparts. One crucial advantage of digital information is that it can be managed and communicated much more easily and reliably than analog information.

The key concept of digital instruments is the conversion from analog signals into digital signals and vice versa. In addition to analog-to-digital and digital-to-analog conversions, other indispensable operations—such as sampling or signal conditioning—are required to make the use of digital instruments feasible. The whole system carrying out all these operations is referred to as a data-acquisition system (see *Digital Instruments*).

Information about a process is gathered by the instrumentation systems, using computers and communication systems. One method of gathering information is by telemetry. In telemetry, information is transmitted from remote locations to a convenient location by various media, including optical, electrical, microwave, and radiowave techniques, as well as via the Internet and so on. The article dedicated to telemetry deals with the fundamental concepts as well as recent advances made in this area.

The development of semiconductor devices, including operational amplifiers, had an impressive impact on measurement instruments. For example, by the end of the 1970s it became apparent that the essentially planar processing integrated-circuit (IC) technology could be modified to fabricate three-dimensional electromechanical structures by the micromachining process.

Accelerometers and pressure sensors were among the first IC sensors, and today they are used extensively in many applications. Detailed treatment of sensors and the sensor technology that instrumentation depends on is given in the article *Sensors and Transducers*.

For the completeness, two further articles are included: on *High Voltage Measurements* and *Magnetic Measurements*.

1. Introduction

Instruments are designed to maintain prescribed relationships between the parameters being measured and the physical variables under investigation. The physical parameter under investigation is known as the measurand. Sensors and transducers are the primary sensing elements that respond to physical variations to produce an output. The energy output from the sensor is usually supplied to a transducer, which converts energy from one form to another to enable signal processing.

Measurement is a process of gathering information from the physical world and comparing this information with agreed standards. Measurement is carried out with instruments that are designed and manufactured to fulfill given specifications. After having generated the signals by the sensors, the type of signal processing depends on the information required from it.

In a specific application, a diverse range of sensors and transducers may be available to meet the measurement requirements of a physical system. Correct sensors must always be selected and correct signal processing must be employed to retrieve the required information. Sensors and transducers can be categorized in a number of ways depending on the input and output energy, input variables, sensing elements, and electrical or physical principles. For example, from an input and output energy point of view, there are three fundamental types of transducers: modifiers, self-generators, and modulators.

In modifiers, a particular form of energy is modified rather than converted; therefore, the same form of energy exists in both input and output stages. In self-generators, electrical signals are produced from nonelectric inputs without the application of external energy.

These transducers produce very small signals, which may need additional signal conditioning. Typical examples are piezoelectric transducers and photovoltaic cells. Modulators, on the other hand, produce electric outputs from nonelectric inputs, but they require an external source of energy. Strain gauges are typical examples of such devices.

In the applications of instruments, the information about a physical variable is collected, organized, interpreted, and generalized. Experiments are conceived, performed, and repeated; as we acquire confidence in the results, they are expressed as scientific laws. The application of instruments ranges from laboratory conditions to arduous environments, such as inside nuclear reactors or on satellite systems and spaceships. In order to meet diverse application requirements of high complexity and capability, many manufacturers have developed a large range of instruments. Some of these manufacturers are listed in Appendix 1.

The functionality of an instrument can be broken into smaller elements (see Figure 1). All instruments have some or all of these functional blocks. Generally, if the behavior of the physical system under investigation is known, its performance can be assessed by means of a suitable method of sensing, signal conditioning, and termination.

Figure 1. Essential components of an instrument

In the last ten years or so, the rapid growth of IC electronics and the easy availability of low-cost analog components, digital components, and microprocessors have led to considerable advances in measurement, instruments, and instrumentation systems. The performance of instruments has improved by the availability of online and offline backed analysis; enhanced signal processing techniques; ease in communication techniques, particularly for distributed instrumentation systems; and agreed standards.

Instruments are applied for static or dynamic measurements. Static measurements are relatively easy since the physical quantities (e.g., fixed dimensions and weights) do not change with time. If the physical quantities are changing in time, which is often the case, the measurement are said to be dynamic. In these cases, steady-state and transient behavior of physical variables must be analyzed so that they can be matched with the dynamic behavior of the instruments.

2. Characteristics and Response

Instruments respond to physical phenomena by sensing and generating signals. Depending on the type of instrument used and the nature of the physical phenomena, signals may be slow-changing or fast, and may also contain transients. The correct response of an instrument to the signal is important and can be analyzed under the headings of static and dynamic performance characteristics, as explained in Sections 2.1 and 2.2.

2.1. Static Response

Instruments are often described by their dynamic range and full-scale deflections (span). The dynamic range of an instrument is the range between the largest and smallest quantities that can be measured. The full-scale deflection refers to the maximum permissible value of the input, quoted in the units of the particular quantity to be measured.

In instruments, the change in output amplitude resulting from a change in input amplitude is called the sensitivity. System sensitivity is often a function of external physical variables, such as temperature and humidity. The relative ratio of the output signal amplitude to the input signal amplitude is the gain. Both the gain and sensitivity are dependent on the amplitude of the signals and the frequency.

In the design stages or during manufacturing there might be small differences between the input and output, which is called the offset. That is, when the input is zero, the output may not be zero or vice versa. The signal output may also change in time, which is known as drift. Drift can happen for many reasons, including temperature variations and aging. Fortunately, drift usually happens in a predictable manner, so that the necessary precaution may be taken for the correct operations over the lifetime.

2.2. Dynamic Response

The dynamic response of an instrument is characterized by its natural frequency, frequency response, phase shift, linearity and distortions, rise and settling times, slew rates, and the like. These characteristics are a common theme in many instrumentation, control, and electronics books. The detailed treatment can be very lengthy and complex; hence, the full treatment of this topic is not within the scope of this article. Interested readers should refer to the bibliography (e.g., Doebelin's *Measurement Systems: Application and Design*).
The dynamic response of an instrument can be linear or nonlinear. Fortunately, most instruments exhibit linear characteristics, leading to simple mathematical modeling by using differential equations, such as:

$$a_n \frac{d^n y}{dt^n} + a_{n-1} \frac{d^{n-1} y}{dt^{n-1}} + \cdots + a_0 y = x(t) \tag{1}$$

where x is the input variable or the forcing function; y is the output variable; and a_n, a_{n-1}, , a_0 are the coefficients or the constants of the system.

The dynamic response of instruments can be categorized as the zero-order, first-order, or second-order responses. Although higher-order instruments may exist, their behaviors can be understood adequately by the second-order system analysis. From Eq. (1):

$$a_0 y = x(t) \quad \text{zero-order} \tag{2}$$

$$a_1 \frac{dy}{dt} + a_0 y = x(t) \quad \text{first-order} \tag{3}$$

$$a_2 \frac{d^2 y}{dt^2} + a_1 \frac{dy}{dt} + a_0 y = x(t) \quad \text{second-order} \tag{4}$$

For analysis in the frequency domain, Eqs. (2)–(4) can be written in Laplace transform as:

$$\frac{Y(s)}{X(s)} = \frac{1}{a_0} \tag{5}$$

$$\frac{Y(s)}{X(s)} = \frac{1}{\tau\ s + 1} \tag{6}$$

$$\frac{Y(s)}{X(s)} = \frac{1}{(\tau_1 s+1)(\tau_2 s+1)} \qquad (7)$$

where s is the Laplace operator; and τ, τ_1, and τ_2 are the coefficients or the time constants.

In zero-order instruments, there is no frequency dependence between the input and the output. The alterations in the amplitudes are uniform across the spectrum of all possible frequencies. In practice, such instruments are difficult to obtain except in a limited range of operations.

In first-order instruments, the relation between the input and the output is dependent on the frequency. Figure 2 illustrates the response of a first-order instrument in the time domain for a unit-step input. Mathematically, the output may be written as:

$$y(t) = K\, e^{-t/\tau} \qquad (8)$$

where K and τ are constants that are determined by the system parameters.

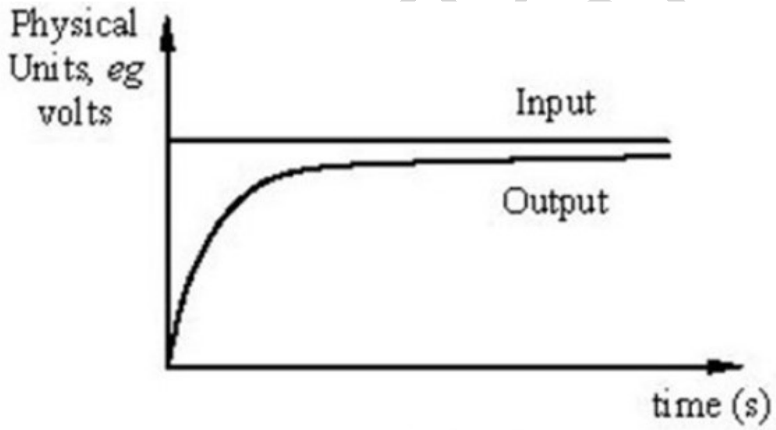

Figure 2. Time response of a first-order instrument to a step input

Second-order systems exhibit the laws of simple harmonic motion, which may be described by linear wave equations. Eq. (7) may be rearranged as:

$$\frac{Y(s)}{X(s)} = \frac{1/a_0}{s^2/\omega^2_n + 2\zeta s/\omega_n + 1} \qquad (9)$$

where ω_n is the natural or undamped frequency (rad/s) and ζ is the damping ratio.

As can be seen, the performance of instruments becomes a function of natural frequency and the damping ratio of the system. The natural frequency and the damping ratios are related to the physical parameters of the devices, such as the mass and physical dimensions. In the design stages, these physical parameters are suitably selected, tested, and modified to obtain a desired response from the instrument.

Typical time response of a second-order system to unit-step inputs is illustrated in Figure 3. The response indicates that a second-order system can oscillate in a bounded form or can even be unstable. Furthermore, the second-order system response is time-dependent; hence, the wrong readings can be taken if the instrument response is not allowed to settle in oscillations. The frequency compensation, selection of the appropriate damping parameters, acceptable time responses, and the rise times and settling times of instruments need careful attention in both the design and application stages of an instrument.

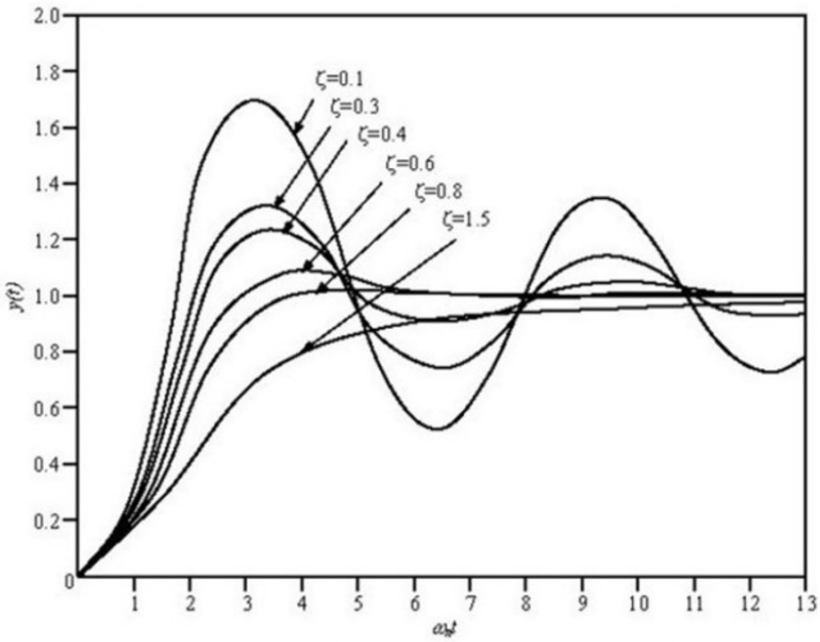

Figure 3. Time response of a second-order system instrument to a unit-step input

An important concept in instruments is response time, which can be described as the time required for an instrument to respond to a change in input signal. In the case of automatic measurements, the response time can be a limiting factor for the maximum number of readings that can be taken in one second. Response time is affected by many factors, such as analog-to-digital (A/D) conversion time, settling time, delays in electronic components, and delays in sensors.

3. Errors and Error Control

The performance of an instrument depends on its static and dynamic characteristics. The performance may be indicated by its accuracy, which may be described as the closeness of measured values to the real values of the variable. The total response is a combination of dynamic and static responses. If the signals generated by the physical variable are changing rapidly, then the dynamic properties of the instrument become important. For slow-varying systems, the dynamic errors may be neglected.

The performance of an instrument may also be decided by other factors, such as repeatability and reproducibility. The repeatability indicates the magnitude of errors and the closeness of sets of measurements made in a short period of time. The reproducibility is the closeness of sets of measurements when repeated in similar conditions over a long period.

An ideal instrument would have perfect sensitivity, reliability, and repeatability without any spread of values in measurements within the applicable standards. However, in many measurements, there may be some inaccurate results because of internal and external factors. The departure from the expected or true value is called the error. Often, sensitivity analyses are conducted to evaluate the effect of individual components that are causing these errors. If there are many parameters affecting the sensitivity, the contribution of each parameter can be obtained by varying that parameter and keeping all the others constant. This can be done, if possible, by practical observations or mathematically using appropriate models.

When determining the performance of an instrument, it is essential to appreciate how errors arise. There may be many sources of errors; therefore, it is important to identify these sources and draw up an error budget. In the error budget, there may be many factors, such as:

- imperfections in electrical and mechanical components (e.g., high tolerances and noise or offset voltages);
- changes in component performances (e.g., shift in gains, changes in chemistry, aging, and drifts in offsets);
- external and ambient influences (e.g., temperature, pressure, and humidity); and
- inherent physical fundamental laws (e.g., thermal and other electrical noises, Brownian motion in materials, and radiation).

In instrumentation systems, errors can be broadly classified as systematic, random, or gross errors.

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Biographical Sketches

Dr. Halit Eren has received the degrees of B.Eng. (1973), M.Eng. in Electrical Engineering (1975), and Ph.D. in Control Engineering—all from the University of Sheffield, UK. Recently he has obtained an MBA from Curtin University of Technology, Perth, Western Australia. Dr. Eren has been lecturing at the Curtin University of Technology since 1983, first at the Kalgoorlie School of Mines and then at the School of Electrical and Computer Engineering. He has served as the Head of Department of Electronic and Communication for some time. His expertise areas are control systems; instruments, instrumentation, and networking; mineral processing; signal processing; and engineering mathematics. His principal areas of research are ultrasonic and infrared techniques, density and flow measurements, moisture measurements, fieldbus, telemetry, telecontrolers, mobile robots, hydrocyclones, and applications of artificial intelligence. He serves as a consultant to a number of industrial establishments. He has written numerous articles in books published by CRC Press and Wiley and Sons.

Dr. C.C. Fung completed his doctoral degree from the University of Western Australia in 1994. Prior to this, he received his B.Sc. degree in Maritime Technology, with First Class Honors, and his M.Eng. degree from the University of Wales, Institute of Science and Technology, in 1981 and 1982, respectively. Currently, he is lecturing in the School of Electrical and Computer Engineering, Curtin University of Technology, Perth, Western Australia. His research interest concentrates on the applications of computational intelligence to engineering problems, which include autonomous robot control, remotely-operated underwater vehicle control, speech recognition, hydrocyclone parameters identification and control, hybrid energy system, and well log data analysis.