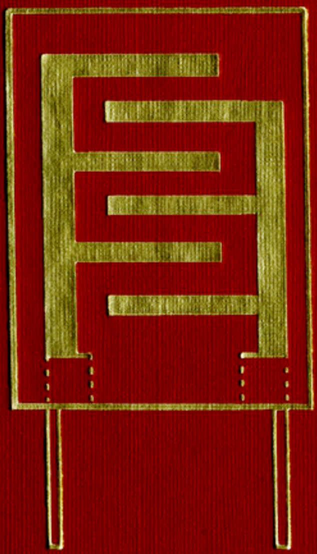
SENSORS AND SIGNAL CONDITIONING

Second Edition



Ramon Pallàs-Areny / John G. Webster

SENSORS AND SIGNAL CONDITIONING

SENSORS AND SIGNAL CONDITIONING

Second Edition

RAMON PALLÀS-ARENY
Universitat Politècnica de Catalunya

JOHN G. WEBSTER
University of Wisconsin—Madison

A Wiley-Interscience Publication
JOHN WILEY & SONS, INC.
New York • Chichester • Weinheim • Brisbane • Singapore • Toronto

This book is printed on acid-free paper.⊗

Published simultaneously in Canada.

For ordering and customer service, call 1-800-CALL-WILEY.

Library of Congress Cataloging-in-Publication Data:
Pallàs-Areny, Ramon.
Sensors and signal conditioning/Ramon Pallàs-Areny, John G. Webster.—2nd ed.
p. cm.
"A Wiley-Interscience publication."
Includes bibliographical references.
ISBN 0-471-33232-1 (cloth: alk. paper)
1. Transducers. 2. Detectors. 3. Interface circuits. I. Webster, John G., 1932- II. Title.
TK7872.T6 P25 2000
621.3815—dc21 00-028293

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

CONTENTS

PREFACE

Sensors have been traditionally used for industrial process control, measurement, and automation, often involving temperature, pressure, flow, and level measurement. Nowadays, sensors enable a myriad of applications fostered by developments in digital electronics and involving the measurement of several physical and chemical quantities in automobiles, aircraft, medical products, office machines, personal computers, consumer electronics, home appliances, and pollution control.

Many of the new application areas for sensors do not pose any severe working conditions and are high-volume consumers. This makes those applications a target for semiconductor-based sensors, particularly sensors built by microfabrication techniques (microsensors), which can be manufactured in large scale. Annual sales of accelerometers and pressure sensors in the automotive industry, along with the annual sales of blood pressure sensors in the medical industry, amount to tens of millions units. Gas sensors, rate sensors, CMOS image sensors, and biosensors can similarly boom.

Classical sensors (or macrosensors) have not been superseded by the new microsensors. Many conventional sensors are still required for specialized applications, so there is no replacement for them in the foreseeable future. Nevertheless, the performance of several integrated circuits commonly used in signal conditioning has improved and allows the design of simpler circuits. Also, there are specific integrated circuits intended for conditioning the signals of common sensors such as thermocouples, RTDs, capacitive sensors, and LVDTs, and microcontrollers have become an inexpensive resource for low-cost, low-resolution analog-to-digital interfacing. Furthermore, the low cost of digital computing has moved part of the calculations and compensations closer to the sensor. The communication with a central controller is increasingly digital, and intelligent (or smart) sensors are being installed in new factories.

This second edition responds to this new scenario from the same point of view of the first edition: that of electronic engineering students or professionals interested in designing measurement systems using available sensors and integrated circuits. For each sensor we describe the working principle, advantages, limitations, types, equivalent circuit, and relevant applications. To clarify sensor types and materials, there is a new section on sensor materials and another on microsensor technology. Microsensors available for different applications are mentioned in the corresponding sections. Sensors are grouped depending on whether (a) they are variable resistors, inductors, capacitors, (b) they generate voltage, charge, or current, or (c) they are digital, semiconductor-junction based, or use some form of radiation. This approach simplifies the study of signal conditioners, which are instrumental in embedding sensors in any electronic system. Basic measurement methods and primary sensors for common physical quantities are described in an expanded section. Further information can be found in J. G. Webster (ed.), *The Measurement, Instrumentation, and Sensors Handbook*, CRC Press, 1999.

Some new sensors covered are giant magnetoresistive sensors, resistive gas sensors, liquid conductivity sensors, magnetostrictive sensors, SQUIDs, fluxgate magnetometers, Wiegand and pulse-wire sensors, position-sensitive detectors (PSDs), semiconductor-junction nuclear radiation detectors, CMOS image sensors, and biosensors. Several of these have moved from the research stage to the commercialization stage since the publication of the first edition. Velocity sensors, fiber-optic sensors, and chemical sensors, in general, receive expanded coverage because of their wider use.

Signal conditioners use new ICs with improved parameters, which often enable novel approaches to circuit design. Some new topics are error analysis of single-ended amplifiers, current feedback amplifiers, composite amplifiers, and IC current integrators. The section on noise now includes noise fundamentals, noise analysis of transimpedance and charge amplifiers, and noise and drift in resistors. Chapter 8, on digital and intelligent sensors, has been expanded by adding sections on variable oscillators including a sensor, direct microcomputer interfacing, sensor communications, and intelligent sensors.

Because the selection of the sensor influences the sensitivity, accuracy, and stability of the measurement system, we describe a broad range of sensors and list the actual specifications of several commercial sensors in tables elsewhere in the book. We have summarized several relevant specifications of common integrated circuits for signal conditioning in tables. New sections deal with basic statistical analysis of measurement results, and reliability. We give 68 worked-out examples and include a total of 103 end-of-chapter problems, many from actual design cases. The annotated solution to the problems is in an appendix at the end of the book. End-of-chapter references have been updated. For ease of reference, figures for examples or problems are respectively preceded by an E or a P. Line crossings in figures are not a connection, unless indicated by a dot.

In the study of any field, the knowledge of important dates adds perspective. Hence, this book names the discoverer and approximate date of the discovery of different physical laws applied in sensors. This may also help in preventing professionals from thinking that sensors are subsequent to the transistor (1947), the operational amplifier (1963), or the microprocessor (1971). Some sensors existed long before all of them. It is the work of electronic engineers to apply all the capabilities of integrated circuits in order that the information provided by sensors results in more economical, reliable, and efficient systems for the benefit of the humans, who certainly have limited perception but who have unmatched intelligence and creativity.

RAMON PALLÀS-ARENY
elerpa@eel.upc.es

JOHN G. WEBSTER
webster@engr.wisc.edu

Barcelona, Spain
Madison, Wisconsin
August, 2000

SENSORS AND SIGNAL CONDITIONING

1

INTRODUCTION TO SENSOR-BASED MEASUREMENT SYSTEMS

Measurements pervade our life. Industry, commerce, medicine, and science rely on measurements. Sensors enable measurements because they yield electric signals with embedded information about the measurand. Electronic circuits process those signals in order to extract that information. Hence, sensors are the basis of measurement systems. This chapter describes the basics of sensors, their static and dynamic characteristics, primary sensors for common quantities, and sensor materials and technology.

1.1 GENERAL CONCEPTS AND TERMINOLOGY

1.1.1 Measurement Systems

A system is a combination of two or more elements, subsystems, and parts necessary to carry out one or more functions. The function of a measurement system is the objective and empirical assignment of a number to a property or quality of an object or event in order to describe it. That is, the result of a measurement must be independent of the observer (objective) and experimentally based (empirical). Numerical quantities must fulfill the same relations fulfilled by the described properties. For example, if a given object has a property larger than the same property in another object, the numerical result when measuring the first object must exceed that when measuring the second object.

One objective of a measurement can be process monitoring: for example, ambient temperature measurement, gas and water volume measurement, and clinical monitoring. Another objective can be process control: for example, for temperature or level control in a tank. Another objective could be to assist

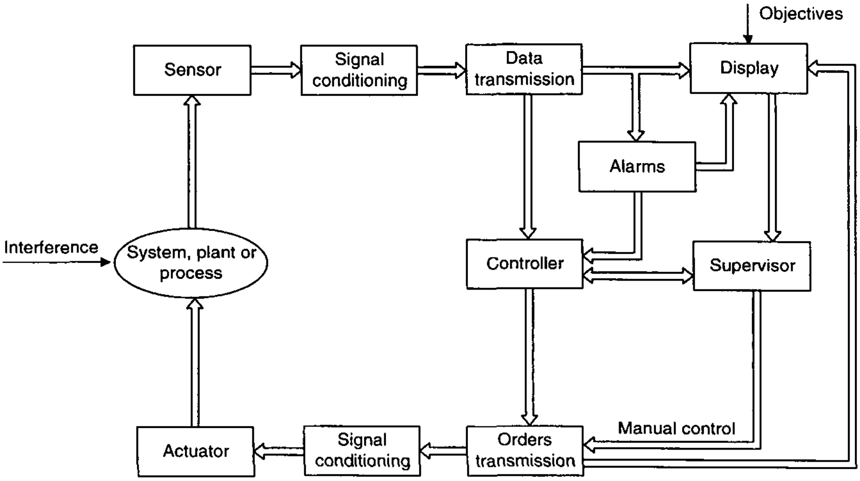


Figure 1.1 Functions and data flow in a measurement and control system. Sensors and actuators are transducers at the physical interface between electronic systems and processes or experiments.

experimental engineering: for example, to study temperature distribution inside an irregularly shaped object or to determine force distribution on a dummy driver in a car crash. Because of the nature of the desired information and its quantity, computer-aided design (CAD) does not yield complete data for these experiments. Thus measurements in prototypes are also necessary to verify the results of computer simulations.

Figure 1.1 shows the functions and data flow of a measurement and control system. In general, in addition to the acquisition of information carried out by a sensor, a measurement requires the processing of that information and the presentation of the result in order to make it perceptible to human senses. Any of these functions can be local or remote, but remote functions require information transmission. Modern measurement systems are not physically arranged according to the data flow in Figure 1.1 but are instead arranged according to their connection to the digital bus communicating different subsystems (Sections 8.6 and 8.7).

1.1.2 Transducers, Sensors, and Actuators

A *transducer* is a device that converts a signal from one physical form to a corresponding signal having a different physical form. Therefore, it is an energy converter. This means that the input signal always has energy or power; that is, signals consist of two component quantities whose product has energy or power dimension. But in measurement systems, one of the two components of the measured signal is usually so small that it is negligible, and thus only the remaining component is measured.

When measuring a force, for example, we assume that the displacement in the transducer is insignificant. That is, that there is no "loading" effect. Otherwise it might happen that the measured force is unable to deliver the needed energy to allow the movement. But there is always some power taken by the transducer, so we must ensure that the measured system is not perturbed by the measuring action.

Since there are six different kinds of signals—mechanical, thermal, magnetic, electric, chemical, and radiation (corpuscular and electromagnetic, including light)—any device converting signals of one kind to signals of a different kind is a transducer. The resulting signals can be of any useful physical form. Devices offering an electric output are called *sensors*. Most measurement systems use electric signals, and hence rely on sensors. Electronic measurement systems provide the following advantages:

1. Sensors can be designed for any nonelectric quantity, by selecting an appropriate material. Any variation in a nonelectric parameter implies a variation in an electric parameter because of the electronic structure of matter.
2. Energy does not need to be drained from the process being measured because sensor output signals can be amplified. Electronic amplifiers yield (low) power gains exceeding 10^{10} in a single stage. The energy of the amplifier output comes from its power supply. The amplifier input signal only controls (modulates) that energy.
3. There is a variety of integrated circuits available for electric signal conditioning or modification. Some sensors integrate these conditioners in a single package.
4. Many options exist for information display or recording by electronic means. These permit us to handle numerical data and text, graphics, and diagrams.
5. Signal transmission is more versatile for electric signals. Mechanical, hydraulic, or pneumatic signals may be appropriate in some circumstances, such as in environments where ionizing radiation or explosive atmospheres are present, but electric signals prevail.

Sensor and transducer are sometimes used as synonymous terms. However, sensor suggests the extension of our capacity to acquire information about physical quantities not perceived by human senses because of their subliminal nature or minuteness. Transducer implies that input and output quantities are not the same. A sensor may not be a transducer. The word *modifier* has been proposed for instances where input and output quantities are the same, but it has not been widely accepted.

The distinction between input-transducer (physical signal/electric signal) and output-transducer (electric signal/display or actuation) is seldom used at present. Nowadays, input transducers are termed *sensors*, or *detectors* for radiation, and output transducers are termed *actuators* or *effectors*. Sensors are intended to acquire information. Actuators are designed mainly for power conversion.

Sometimes, particularly when measuring mechanical quantities, a *primary sensor* converts the measurand into a measuring signal. Then a sensor would convert that signal into an electric signal. For example, a diaphragm is a primary sensor that stresses when subject to a pressure difference, and strain gages (Section 1.7.2 and Section 2.2) sense that stress. In this book we will designate as sensor the whole device, including the package and leads. We must realize, however, that we cannot directly perceive signals emerging from sensors unless they are further processed.

1.1.3 Signal Conditioning and Display

Signal conditioners are measuring system elements that start with an electric sensor output signal and then yield a signal suitable for transmission, display, or recording, or that better meet the requirements of a subsequent standard equipment or device. They normally consist of electronic circuits performing any of the following functions: amplification, level shifting, filtering, impedance matching, modulation, and demodulation. Some standards call the sensor plus signal conditioner subsystem a *transmitter*.

One of the stages of measuring systems is usually digital and the sensor output is analog. Analog-to-digital converters (ADCs) yield a digital code from an analog signal. ADCs have relatively low input impedance, and they require their input signal to be dc or slowly varying, with amplitude within specified margins, usually less than ±10 V. Therefore, sensor output signals, which may have an amplitude in the millivolt range, must be conditioned before they can be applied to the ADC.

The display of measured results can be in an analog (optical, acoustic, or tactile) or in a digital (optical) form. The recording can be magnetic, electronic, or on paper, but the information to be recorded should always be in electrical form.

1.1.4 Interfaces, Data Domains, and Conversion

In measurement systems, the functions of signal sensing, conditioning, processing, and display are not always divided into physically distinct elements. Furthermore, the border between signal conditioning and processing may be indistinct. But generally there is a need for some signal processing of the sensor output signal before its end use. Some authors use the term *interface* to refer to signal-modifying elements that operate in the electrical domain, even when changing from one data domain to another, such as an ADC.

A *data domain* is the name of a quantity used to represent or transmit information. The concept of data domains and conversion between domains helps in describing sensors and electronic circuits associated with them [1]. Figure 1.2 shows some possible domains, most of which are electrical.

In the *analog domain* the information is carried by signal amplitude (i.e.,

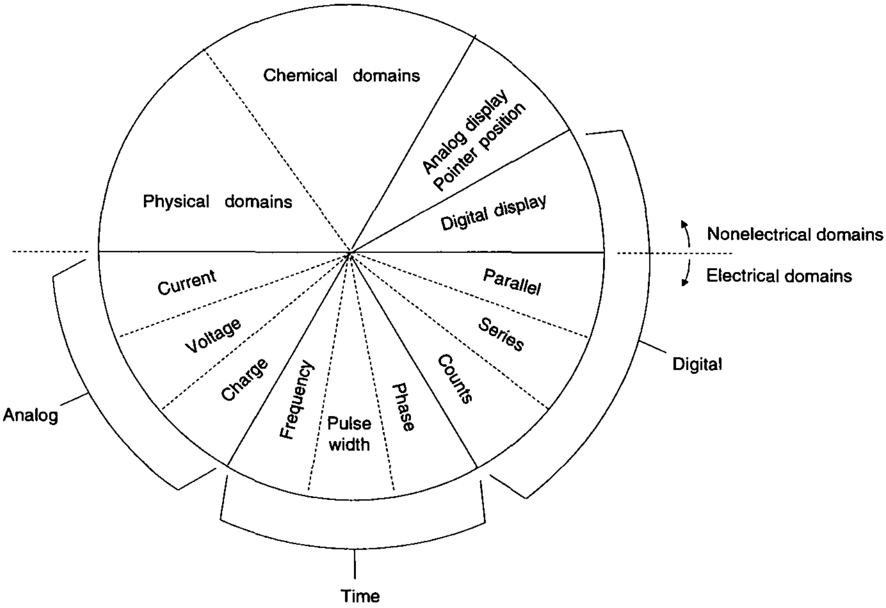


Figure 1.2 Data domains are quantities used to represent or transmit information [1]. (From H. V. Malmstadt, C. G. Enke, and S. R. Crouch, *Electronics and Instrumentation for Scientists*, copyright 1981. Reprinted by permission of Benjamin/Cummings, Menlo Park, CA.)

charge, voltage, current, or power). In the *time domain* the information is not carried by amplitude but by time relations (period or frequency, pulse width, or phase). In the *digital domain*, signals have only two values. The information can be carried by the number of pulses or by a coded serial or parallel word.

The analog domain is the most prone to electrical interference (Section 1.3.1). In the time domain, the coded variable cannot be measured—that is, converted to the numerical domain—in a continuous way. Rather, a cycle or pulse duration must elapse. In the digital domain, numbers are easily displayed.

The structure of a measurement system can be described then in terms of domain conversions and changes, depending on the direct or indirect nature of the measurement method.

Direct physical measurements yield quantitative information about a physical object or action by direct comparison with a reference quantity. This comparison is sometimes simply mechanical, as in a weighing scale.

In *indirect physical measurements* the quantity of interest is calculated by applying an equation that describes the law relating other quantities measured with a device, usually an electric one. For example, one measures the mechanical power transmitted by a shaft by multiplying the measured torque and speed of rotation, the electric resistance by dividing dc voltage by current, or the traveled distance by integrating the speed. Many measurements are indirect.

1.2 SENSOR CLASSIFICATION

A great number of sensors are available for different physical quantities. In order to study them, it is advisable first to classify sensors according to some criterion. White [10] provides additional criteria to those used here.

In considering the need for a power supply, sensors are classified as modulating or self-generating. In modulating (or active) sensors, most of the output signal power comes from an auxiliary power source. The input only controls the output. Conversely, in self-generating (or passive) sensors, output power comes from the input.

Modulating sensors usually require more wires than self-generating sensors, because wires different from the signal wires supply power. Moreover, the presence of an auxiliary power source can increase the danger of explosion in explosive atmospheres. Modulating sensors have the advantage that the power supply voltage can modify their overall sensitivity. Some authors use the terms *active* for self-generating and *passive* for modulating. To avoid confusion, we will not use these terms.

In considering output signals, we classify sensors as analog or digital. In *analog sensors* the output changes in a continuous way at a macroscopic level. The information is usually obtained from the amplitude, although sensors with output in the time domain are usually considered as analog. Sensors whose output is a variable frequency are called *quasi-digital* because it is very easy to obtain a digital output from them (by counting for a time).

The output of *digital sensors* takes the form of discrete steps or states. Digital sensors do not require an ADC, and their output is easier to transmit than that of analog sensors. Digital output is also more repeatable and reliable and often more accurate. But regrettably, digital sensors cannot measure many physical quantities.

In considering the operating mode, sensors are classified in terms of their function in a deflection or a null mode. In *deflection sensors* the measured quantity produces a physical effect that generates in some part of the instrument a similar but opposing effect that is related to some useful variable. For example, a dynamometer to measure force is a sensor where the force to be measured deflects a spring to the point where the force it exerts, proportional to its deformation, balances the applied force.

Null-type sensors attempt to prevent deflection from the null point by applying a known effect that opposes that produced by the quantity being measured. There is an imbalance detector and some means to restore balance. In a weighing scale, for example, the placement of a mass on a pan produces an imbalance indicated by a pointer. The user has to place one or more calibrated weights on the other pan until a balance is reached, which can be observed from the pointer's position.

Null measurements are usually more accurate because the opposing known effect can be calibrated against a high-precision standard or a reference quantity. The imbalance detector only measures near zero; therefore it can be very

TABLE 1.1 Sensor Classifications According to Different Exhaustive Criteria

Criterion	Classes	Examples
Power supply	Modulating	Thermistor
	Self-generating	Thermocouple
Output signal	Analog	Potentiometer
	Digital	Position encoder
Operation mode	Deflection	Deflection accelerometer
	Null	Servo-accelerometer

sensitive and does not require any calibration. Nevertheless, null measurements are slow; and despite attempts at automation using a servomechanism, their response time is usually not as short as that of deflection systems.

In considering the input–output relationship, sensors can be classified as zero, first, second, or higher order (Section 1.5). The order is related to the number of independent energy-storing elements present in the sensor, and this affects its accuracy and speed. Such classification is important when the sensor is part of a closed-loop control system because excessive delay may lead to oscillation [6].

Table 1.1 compares the classification criteria above and gives examples for each type in different measurement situations. In order to study these myriad devices, it is customary to classify them according to the measurand. Consequently we speak of sensors for temperature, pressure, flow, level, humidity and moisture, pH, chemical composition, odor, position, velocity, acceleration, force, torque, density, and so forth. This classification, however, can hardly be exhaustive because of the seemingly unlimited number of measurable quantities. Consider, for example, the variety of pollutants in the air or the number of different proteins inside the human body whose detection is of interest.

Electronic engineers prefer to classify sensors according to the variable electrical quantity—resistance, capacity, inductance—and then to add sensors generating voltage, charge, or current, and other sensors not included in the preceding groups, mainly *p–n* junctions and radiation-based sensors. This approach reduces the number of groups and enables the direct study of the associated signal conditioners. Table 1.2 summarizes the usual sensors and sensing methods for common quantities.

1.3 GENERAL INPUT–OUTPUT CONFIGURATION

1.3.1 Interfering and Modifying Inputs

In a measurement system the sensor is chosen to gather information about the measured quantity and to convert it to an electric signal. A priori it would be unreasonable to expect the sensor to be sensitive to only the quantity of interest

TABLE 1.2 Usual Sensors and Sensing Methods for Common Quantities

Sensor type	Acceleration Vibration	Flow Rate Point velocity	Force	Humidity Moisture
Resistive	Mass–spring + strain gage	Anemometer	Strain gage	Humistor
		Thermistor		
		Target + strain gage		
Capacitive	Mass–spring + variable capacitor		Capacitive strain gage	Dielectric-variation capacitor
Inductive and electromagnetic	Mass–spring + LVDT	Faraday's law	Load cell + LVDT	
		Rotameter + LVDT	Magnetostriction	
Self-generating	Mass–spring + piezoelectric sensor	Thermal transport + thermocouple	Piezoelectric sensor	
Digital		Impeller, turbine		SAW sensor
		Positive displacement		
		Vortex shedding		
PN junction				
Optic, fiber optic		Laser anemometry		Chilled mirror
Ultrasound		Doppler effect		
		Travel time		
		Vortex		
Other		Differential pressure		
		Variable area + level sensor (open channel)		
		Variable area + displacement		
		Coriolis effect + force		

Quantity				
Level	Position Distance Displacement	Pressure	Temperature	Velocity Speed
Float + potentiometer	Magnetoresistor	Bourdon tube + potentiometer	RTD	
LDR	Potentiometer	Diaphragm + strain gage	Thermistor	
Thermistor	Strain gage			
Variable capacitor	Differential capacitor	Diaphragm + variable capacitor		
Magnetostriction	Eddy currents	Diaphragm + LVDT		Eddy currents
Magnetoresistive	Hall effect	Diaphragm + variable reluctance		Hall effect
Float + LVDT	Inductosyn			Faraday's law
Eddy currents	LVDT			LVT
	Resolver, synchro			
	Magnetostriction			
		Piezoelectric sensor	Pyroelectric sensor	
			Thermocouple	
Vibrating rod	Position encoder	Bourdon tube + encoder	Quartz oscillator	Incremental encoder
Float + pulley		Bourdon tube or bellows + quartz resonator		
		Diaphragm + vibrating wire		
Photoelectric	Photoelectric sensor		Diode	
			Bipolar transistor	
			T/I converter	
		Diaphragm + light reflection		
Absorption	Travel time			Doppler effect
Travel time				
Differential pressure		Liquid-based manometer + level sensor		
Microwave radar				
Nuclear radiation				

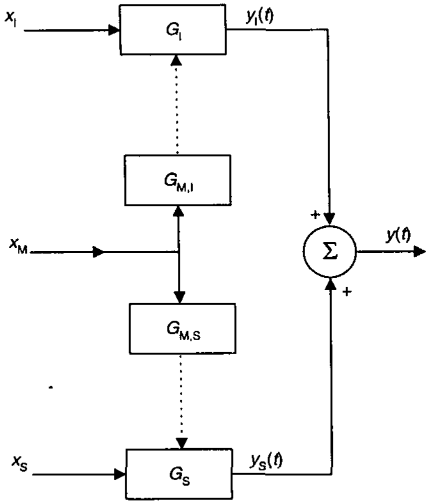


Figure 1.3 Effect of internal and external perturbations on measurement systems. x_S is the signal of interest. $y(t)$ is the system output. x_I is an interference or external perturbation. x_M is a modifying input. (From E. O. Doebelin, *Measurement Systems Application and Design*, 4th ed., copyright 1990. Reprinted by permission of McGraw-Hill, New York.)

and also to expect the output signal to be entirely due to the input signal. No measurement is ever obtained under ideal circumstances; therefore we must address real situations. We follow here the method proposed by Doebelin [2]. Figure 1.3 shows a general block diagram for classifying desired signal gains and interfering input gain for instruments. The desired signal x_S passes through the gain block G_S to the output y. Interfering inputs x_I represent quantities to which the instrument is unintentionally sensitive. These pass through the gain block G_I to the output y. Modifying inputs x_M are the quantities that through $G_{M,S}$ cause a change in G_S for the desired signal and through $G_{M,I}$ cause a change in G_I for interfering inputs. The gains G can be linear, nonlinear, varying, or random.

For example, to measure a force, it is common to use strain gages (Section 2.2). Strain gages operate on the basis of variation in the electric resistance of a conductor or semiconductor when stressed. Because temperature change also yields a resistance variation, we can regard any temperature variation as an interference or external disturbance x_I with gain G_I. At the same time, to measure resistance changes as a result of the stress, an electronic amplifier is required. Since any temperature change x_M through $G_{M,S}$ affects the amplifier gain G_S and therefore the output, it turns out that a temperature variation also acts as a modifying input x_M. If the same force is measured with a capacitive gage (Section 4.1), a temperature variation does not interfere but can still modify the amplifier gain.

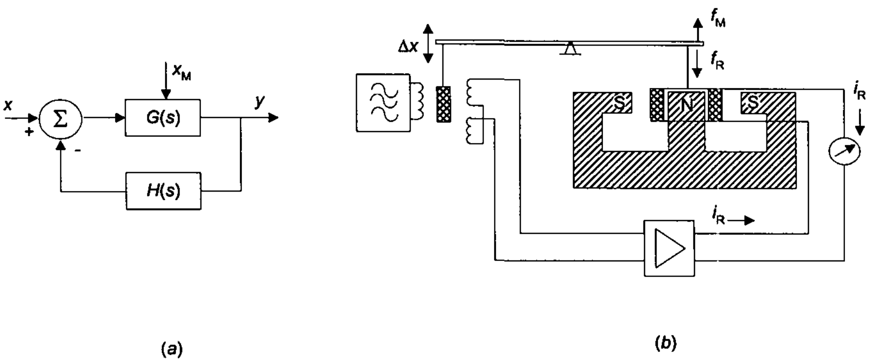


Figure 1.4 (*a*) Negative feedback method to reduce the effect of internal perturbations. Block *H* may be insensitive to those perturbations because it handles lower power than block *G*. (*b*) Force-to-current converter that relies on negative feedback and a balance sensor.

1.3.2 Compensation Techniques

The effects of interfering and modifying inputs can be reduced by changing the system design or by adding new elements to it. The best approach is to design systems insensitive to interference and that respond only to the desired signals. In the preceding example, it would have been best to use strain gages with a low temperature coefficient ($G_I = 0$). Thin, narrow, long magnetic sensors are only sensitive to magnetic fields parallel to their long dimension. In designing sensors for vector mechanical quantities, it would be best to obtain a unidirectional sensitivity and a low transverse sensitivity—that is, in directions perpendicular to the desired direction. In electronic circuits, low-drift components such as metal-film resistors and NPO capacitors are less sensitive to temperature. Nevertheless, this method is not always possible for obvious practical reasons.

Negative feedback is a common method to reduce the effect of modifying inputs, and it is the method used in null measurement systems. Figure 1.4*a* shows the working principle. It assumes that the measurement system and the feedback are linear and can be described by their respective transfer functions $G(s)$ and $H(s)$. The input–output relation is

$$\frac{Y(s)}{X(s)} = \frac{G(s)}{1 + G(s)H(s)} \cong \frac{1}{H(s)} \tag{1.1}$$

where the approximation is valid when $G(s)H(s) \gg 1$. If the negative feedback is insensitive to the modifying input, and it has been designed so that the system remains stable, then the output signal is not affected by the modifying input.

The advantage of such a solution stems from the different physical characteristics of the elements described by $G(s)$ and $H(s)$. The probable insensitivity of H to a modifying input is a consequence of its lower power-handling capacity than G. This also results in higher accuracy and linearity for H. Moreover, negative feedback results in less energy extracted from the measured system because G is designed very large. The force-to-current converter in Figure 1.4*b* relies on negative feedback. The force to be measured, f_M, is compared with a restoring force f_R, generated by an internal moving-coil system. f_R is proportional to the current i_R in the coil, and i_R is proportional to the output voltage from the displacement sensor—here an LVDT (Section 4.2.3)—that senses the balance between f_M and f_R. If the amplifier gain is high enough, a very small input voltage from the sensor yields a current high enough to produce a force f_R able to balance f_M. Because i_R is proportional to f_R and $f_R \approx f_M$, we can determine f_M from i_R, regardless, for example, of the sensor linearity.

Filtering is a common method for interference reduction. A filter is any device that separates signals according to their frequency or another criterion. Filters are very effective when frequency spectra of signals and interference do not overlap. Filters can be placed at the input or at any intermediate stage. They can be electric, mechanical (e.g., to reduce vibrations), pneumatic, thermal (e.g., a high mass covering to reduce turbulence effects when measuring the average temperature of a flowing fluid), or electromagnetic. Filters placed at intermediate stages are usually electric.

Another common compensation technique for interfering and modifying inputs is the use of opposing inputs, often applied to compensate for temperature variations. If, for example, a gain that depends on a resistor having a positive temperature coefficient changes due to a temperature change, another resistor can be placed in series with the affected resistor. If the added resistor has a negative temperature coefficient, it is possible to keep the gain constant in spite of temperature changes. This method is also used for temperature compensation in strain gages, sensor-bridge supply, catalytic gas sensors, resistive gas sensors, and copper-wire coils (e.g., in electromagnetic relays, galvanometers, and tachometers), as well as to compensate vibration in piezoelectric sensors.

Finally, when the mathematical relationship between the interference and sensor output is known, interference can be compensated by digital calculation after measuring the magnitude of the interfering variable—for example, temperature in a pressure sensor. This method is common in smart sensors.

1.4 STATIC CHARACTERISTICS OF MEASUREMENT SYSTEMS

Because the sensor influences the characteristics of the whole measurement system, it is important to describe its behavior in a meaningful way. In most measurement systems the quantity to be measured changes so slowly that it is only necessary to know the static characteristics of sensors.

Nevertheless, the static characteristics influence also the dynamic behavior of the sensor—that is, its behavior when the measured quantity changes with time. However, the mathematical description of the joint consideration of static and dynamic characteristics is complex. As a result, static and dynamic behavior are