CHAPTER 2

Generalized Configurations and Functional Descriptions of Measuring Instruments

2.1 FUNCTIONAL ELEMENTS OF AN INSTRUMENT

It is possible and desirable to describe both the operation and the performance (degree of approach to perfection) of measuring instruments and associated equipment in a generalized way without recourse to specific physical hardware. The operation can be described in terms of the functional elements of instrument systems, and the performance is defined in terms of the static and dynamic performance characteristics. This section develops the concept of the functional elements of an instrument or measurement system.

If you examine diverse physical instruments with a view toward generalization, soon you recognize in the elements of the instruments a recurring pattern of similarity with regard to function. This leads to the concept of breaking down instruments into a limited number of types of elements according to the generalized function performed by the element. This breakdown can be made in a number of ways, and no standardized, universally accepted scheme is used at present. We now give one such scheme which may help you to understand the operation of any new instrument with which you may come in contact and to plan the design of a new instrument.

Consider Fig. 2.1, which represents a possible arrangement of functional elements in an instrument and includes *all* the basic functions considered necessary for a description of any instrument. The *primary sensing element* is that which first receives energy from the measured medium and produces an output depending in some way on the measured quantity ("measurand"). It is important to note that an instrument *always* extracts some energy from the measured medium. Thus the measured quantity is *always* disturbed by the act of measurement, which makes a

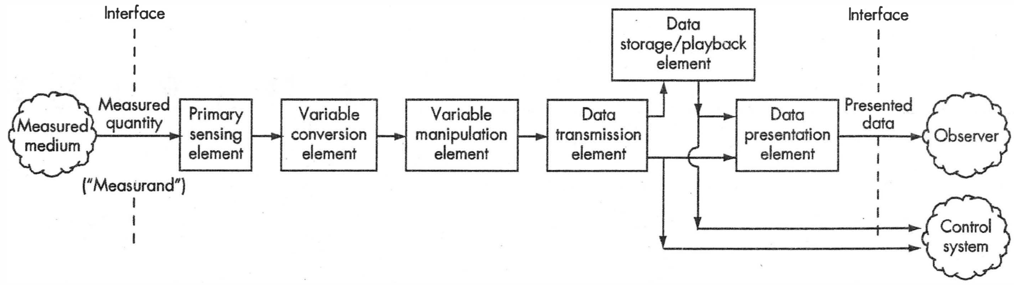


Figure 2.1
Functional elements of an instrument or a measurement system.

perfect measurement theoretically impossible. Good instruments are designed to minimize this "loading effect," but it is always present to some degree.

The output signal of the primary sensing element is some physical variable, such as displacement or voltage. For the instrument to perform the desired function, it may be necessary to convert this variable to another more suitable variable while preserving the information content of the original signal. An element that performs such a function is called a *variable-conversion element.* It should be noted that not every instrument includes a variable-conversion element, but some require several. Also, the "elements" we speak of are *functional* elements, not physical elements. That is, Fig. 2.1 shows an instrument neatly separated into blocks, which may lead you to think of the physical apparatus as being precisely separable into subassemblies performing the specific functions shown. That is, in general, not the case; a specific piece of hardware may perform *several* of the basic functions, for instance.

In performing its intended task, an instrument may require that a signal represented by some physical variable be manipulated in some way. By "manipulation," we mean specifically a change in numerical value according to some definite rule but a preservation of the physical nature of the variable. Thus an electronic amplifier accepts a small voltage signal as input and produces an output signal that is also a voltage but is some constant times the input. An element that performs such a function is called a *variable-manipulation element.* Again, you should not be misled by Fig. 2.1. A variable-manipulation element does not necessarily *follow* a variable-conversion element, but may precede it, appear elsewhere in the chain, or not appear at all.

When the functional elements of an instrument are actually physically separated, it becomes necessary to transmit the data from one to another. An element performing this function is called a *data-transmission element.* It may be as simple as a shaft and bearing assembly or as complicated as a telemetry system for transmitting signals from satellites to ground equipment by radio.

If the information about the measured quantity is to be communicated to a human being for monitoring, control, or analysis purposes, it must be put into a form recognizable by one of the human senses. An element that performs this "translation" function is called a *data-presentation element.* This function includes the simple *indication* of a pointer moving over a scale and the *recording* of a pen moving

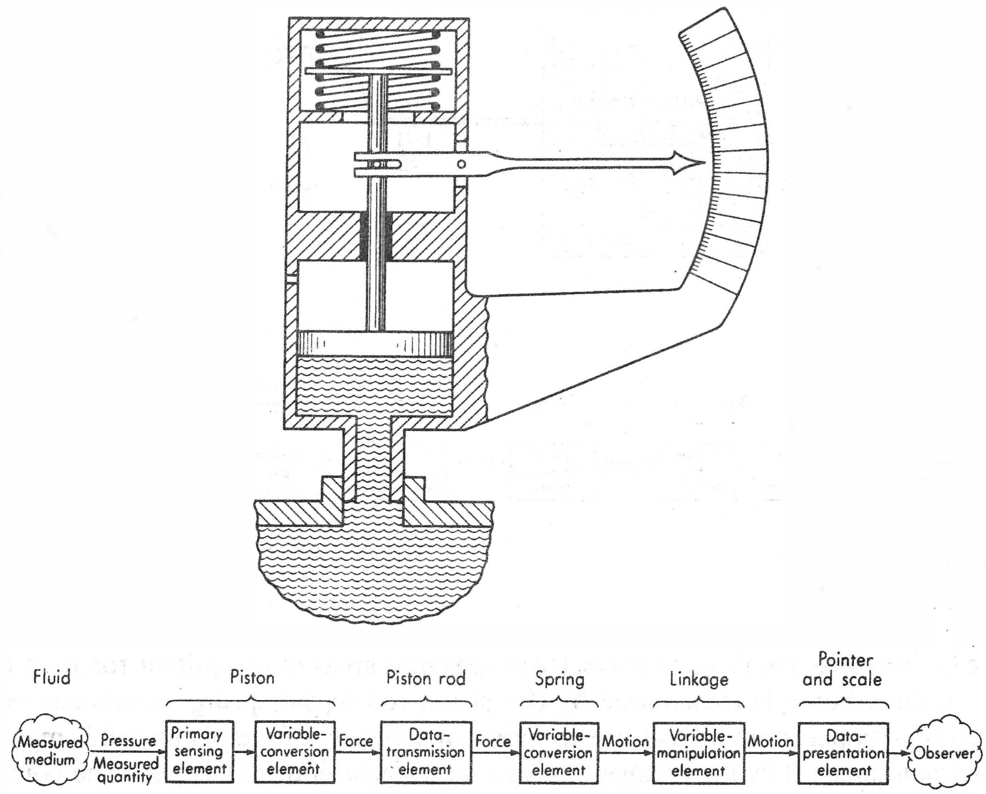


Figure 2.2
Pressure gage.

over a chart. Indication and recording also may be performed in discrete increments (rather than smoothly), as exemplified by a digital voltmeter or printer. While the majority of instruments communicate with people through the visual sense, the use of other senses such as hearing and touch is certainly conceivable.

Although data storage in the form of pen/ink recording is often employed, some applications require a distinct *data storage/playback* function which can easily recreate the stored data upon command. The magnetic tape recorder/reproducer is the classical example here. However, many recent instruments digitize the electric signals and store them in a computerlike digital memory (RAM, hard drive, floppy disk, etc.).

Before we go on to some illustrative examples, let us emphasize again that Fig. 2.1 is intended as a vehicle for presenting the concept of functional elements, and not as a physical schematic of a generalized instrument. A given instrument may involve the basic functions in any number and combination; they need not appear in the order of Fig. 2.1. A given physical component may serve several of the basic functions.

As an example of the above concepts, consider the rudimentary pressure gage of Fig. 2.2. One of several possible valid interpretations is as follows: The primary sensing element is the piston, which also serves the function of variable conversion

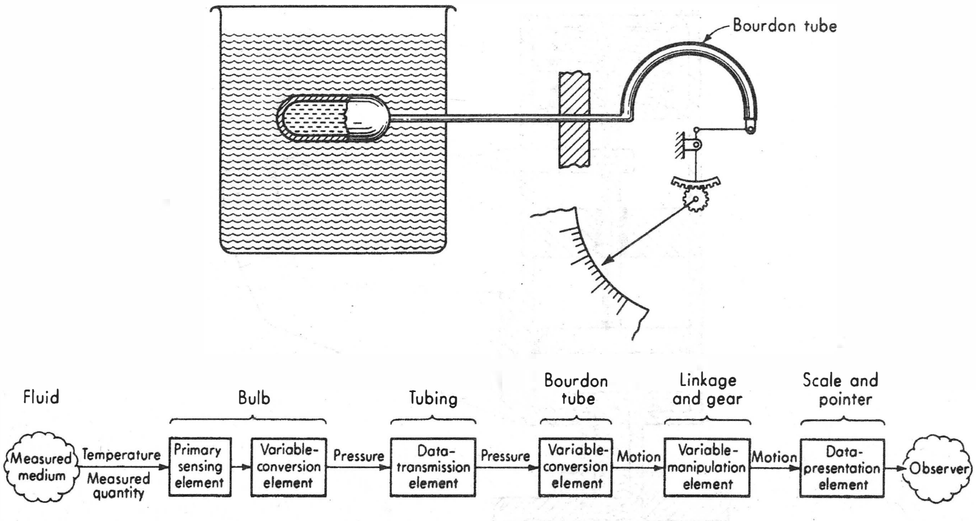


Figure 2.3
Pressure thermometer.

since it converts the fluid pressure (force per unit area) to a resultant force on the piston face. Force is transmitted by the piston rod to the spring, which converts force to a proportional displacement. This displacement of the piston rod is magnified (manipulated) by the linkage to give a larger pointer displacement. The pointer and scale indicate the pressure, thus serving as data-presentation elements. If it were necessary to locate the gage at some distance from the source of pressure, a small tube could serve as a data-transmission element.

Figure 2.3 depicts a pressure-type thermometer. The liquid-filled bulb acts as a primary sensor and variable-conversion element since a temperature change results in a pressure buildup within the bulb, because of the constrained thermal expansion of the filling fluid. This pressure is transmitted through the tube to a Bourdon-type pressure gage, which converts pressure to displacement. This displacement is manipulated by the linkage and gearing to give a larger pointer motion. A scale and pointer again serve for data presentation.

A remote-reading shaft-revolution counter is shown in Fig. 2.4. The microswitch sensing arm and the camlike projection on the rotating shaft serve both a primary sensing and a variable-conversion function since rotary displacement is converted to linear displacement. The microswitch contacts also serve for variable conversion, changing a mechanical to an electrical oscillation (a sequence of voltage pulses). These voltage pulses may be transmitted relatively long distances over wires to a solenoid. The solenoid reconverts the electrical pulses to mechanical reciprocation of the solenoid plunger, which serves as input to a mechanical counter. The counter itself involves variable conversion (reciprocating to rotary motion), variable manipulation (rotary motion to decimalized rotary motion), and data presentation.

As a final example, let us examine Fig. 2.5, which illustrates schematically a D'Arsonval galvanometer as used in oscillographs and optical scanning systems.

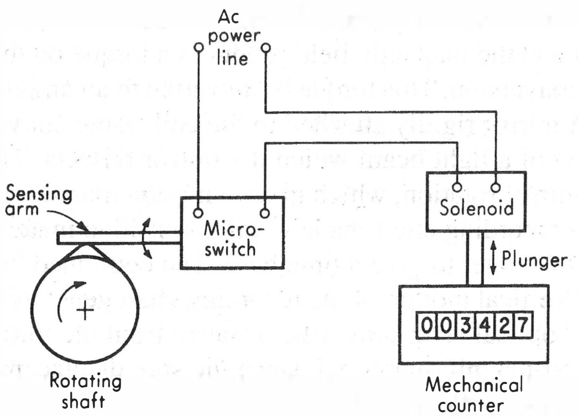


Figure 2.4
Digital revolution counter.

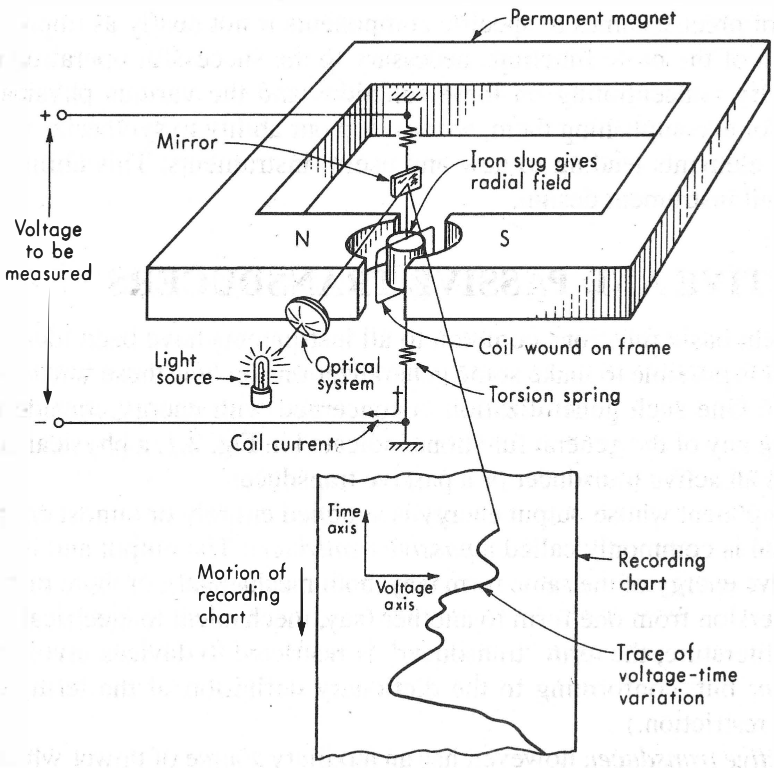


Figure 2.5
D'Arsonval galvanometer.

A time-varying voltage to be recorded is applied to the ends of the two wires which transmit the voltage to a coil made up of a number of turns wound on a rigid frame. This coil is suspended in the field of a permanent magnet. The resistance of the coil converts the applied voltage to a proportional current (ideally). The interaction between the current and the magnetic field produces a torque on the coil, which gives another variable conversion. This torque is converted to an angular deflection by the torsion springs. A mirror rigidly attached to the coil frame converts the frame rotation to the rotation of a light beam which the mirror reflects. The light-beam rotation is twice the mirror rotation, which gives a motion magnification. The reflected beam intercepts a recording chart made of photosensitive material which is moved at a fixed and known rate, to give a time base. The combined horizontal motion of the light spot and vertical motion of the recording chart generates a graph of voltage versus time. The "optical lever arm" (the distance from the mirror to the recording chart) has a motion-magnifying effect, since the spot displacement per unit mirror rotation is directly proportional to it.

In this instrument, the coil and magnet assembly probably would be considered as the primary sensing element since the lead wires (which serve a transmission function) are not really part of the instrument, and the coil resistance (which acts in a variable-conversion function) is an intrinsic part of the coil. In any case, the assignment of precise names to specific components is not nearly as important as the recognition of the basic functions necessary to the successful operation of the instrument. By concentrating on these functions and the various physical devices available for accomplishing them, we develop our ability to synthesize new combinations of elements leading to new and useful instruments. This ability is fundamental to all instrument design.

2.2 ACTIVE AND PASSIVE TRANSDUCERS

Once certain basic functions common to all instruments have been identified, then we see if it is possible to make some generalizations on *how* these functions may be performed. One such generalization is concerned with energy considerations. In performing any of the general functions indicated in Fig. 2.1, a physical component may act as an active transducer or a passive transducer.

A component whose output energy is supplied entirely or almost entirely by its input signal is commonly called a *passive transducer.* The output and input signals may involve energy of the same form (say, both mechanical), or there may be an energy conversion from one form to another (say, mechanical to electrical). (In much technical literature, the term "transducer" is restricted to devices involving energy *conversion;* but, conforming to the dictionary definition of the term, we do not make this restriction.)

An *active transducer,* however, has an auxiliary source of power which supplies a major part of the output power while the input signal supplies only an insignificant portion. Again, there may or may not be a conversion of energy from one form to another.

In all the examples of Sec. 2.1, there is only one active transducer—the microswitch of Fig. 2.4; all other components are passive transducers. The power to drive the solenoid comes not from the rotating shaft, but from the ac power line, an auxiliary source of power. Some further examples of active transducers may be in order. The electronic amplifier shown in Fig. 2.6 is a good one. The element supplying the input-signal voltage, e_i need supply only a negligible amount of power since almost no current is drawn, owing to negligible gate current and a high R_g. However, the output element (the load resistance R_L) receives significant current and voltage and thus power. This power must be supplied by the battery E_{bb}, the auxiliary power source. Thus the input *controls* the output, but does not actually supply the output power.

Another active transducer of great practical importance, the *instrument servomechanism,* is shown in simplified form in Fig. 2.7. This is actually an instrument *system* made up of components, some of which are passive transducers and others active transducers. When it is considered as an entity, however, with input voltage e_i and output displacement x_o, it meets the definition of an active transducer and is profitably thought of as such. The purpose of this device is to cause the motion x_o to follow the variations of the voltage e_i in a proportional manner. Since the motor torque is proportional to the error voltage e_e, it is clear that the system can be at rest only if e_e is zero. This occurs only when $e_i = e_{sl}$; since e_{sl} is proportional to x_o, this means that x_o must be proportional to e_i in the static case. If e_i varies, x_o will tend to follow it, and by proper design, accurate "tracking" of e_i by x_o should be possible. You should recognize this device as an instrument which uses the feedback principle of Fig. 1.1.

2.3 ANALOG AND DIGITAL MODES OF OPERATION

It is possible further to classify how the basic functions may be performed by turning attention to the analog or digital nature of the signals that represent the information.

For analog signals, the precise value of the quantity (voltage, rotation angle, etc.) carrying the information is significant. However, digital signals are basically of a binary (on/off) nature, and variations in numerical value are associated with changes in the logical state ("true/false") of some combination of "switches." In a

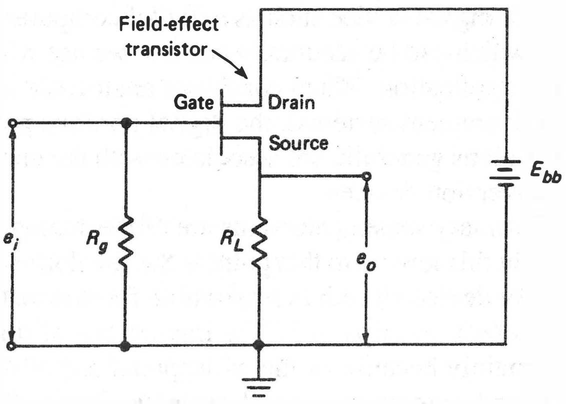


Figure 2.6
Electronic amplifier.

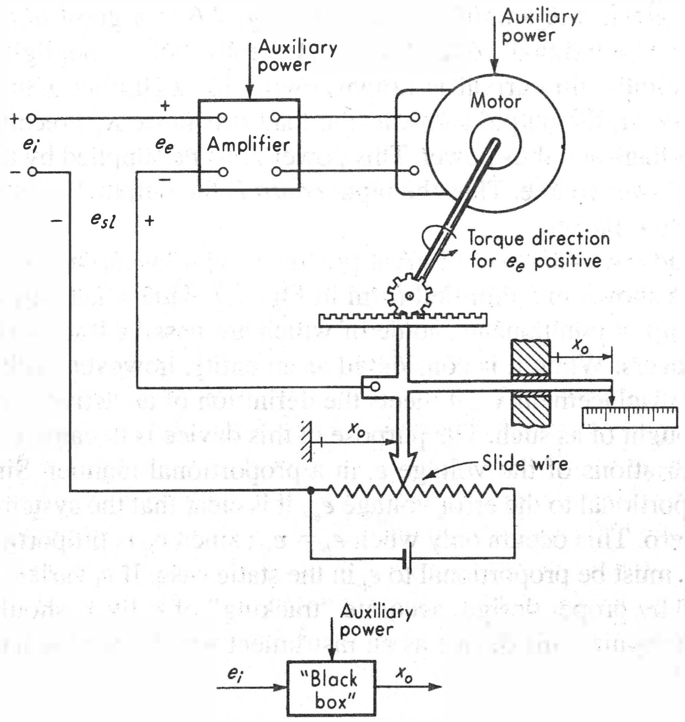


Figure 2.7
Instrument servomechanism.

typical digital electronic system, *any* voltage in the range of +2 to +5 V produces the on state, while signals of 0 to +0.8 V correspond to off. Thus whether the voltage is 3 or 4 V is of *no* consequence. The same result is produced, and so the system is quite tolerant of spurious "noise" voltages which might contaminate the information signal. In a digitally represented value of, say, 5.763, the least significant digit (3) is carried by on/off signals of the same (large) size as for the most significant digit (5). Thus in an all-digital device such as a digital computer, there is no limit to the number of digits which can be accurately carried; we use whatever can be justified by the particular application. When *combined* analog/digital systems are used (often the case in measurement systems), the digital portions need not limit system accuracy. These limitations generally are associated with the analog portions and/or the analog/digital conversion devices.

The majority of primary sensing elements are of the analog type. The only digital device illustrated in this text up to this point is the revolution counter of Fig. 2.4. This is clearly a digital device since it is impossible for this instrument to indicate, say, 0.79; it measures only in steps of 1. The importance of digital instruments is increasing, perhaps mainly because of the widespread use of digital computers in both data-reduction and automatic control systems. Since the digital computer works only with digital signals, any information supplied to it must be in digital form. The computer's output is also in digital form. Thus any communication with the computer at either the input or the output end must be in terms of digital signals. Since most measurement and control apparatus is of an analog nature, it is necessary to have both *analog-to-digital converters* (at the input to the computer) and *digital-to-analog converters* (at the output of the computer). These devices (which are discussed in greater detail in a later chapter) serve as "translators" that enable the computer to communicate with the outside world, which is largely of an analog nature.

2.4 NULL AND DEFLECTION METHODS

Another useful classification separates devices by their operation on a null or a deflection principle. In a *deflection-type* device, the measured quantity produces some physical effect that engenders a similar but opposing effect in some part of the instrument. The opposing effect is closely related to some variable (usually a mechanical displacement or deflection) that can be directly observed by some human sense. The opposing effect increases until a balance is achieved, at which point the "deflection" is measured and the value of the measured quantity inferred from this. The pressure gage of Fig. 2.2 exemplifies this type of device, since the pressure force engenders an opposing spring force as a result of an unbalance of forces on the piston rod (called the force-summing link), which causes a deflection of the spring. As the spring deflects, its force increases; thus a balance will be achieved at some deflection if the pressure is within the design range of the instrument.

In contrast to the deflection-type device, a *null-type* device attempts to maintain deflection at zero by suitable application of an effect opposing that generated by the measured quantity. Necessary to such an operation are a detector of unbalance and a means (manual or automatic) of restoring the balance. Since deflection is kept at zero (ideally), determination of numerical values requires accurate knowledge of the magnitude of the opposing effect. A pressure gage operating on a null principle is depicted in simplified form in Fig. 2.8. By adding the proper standard weights to the platform of known weight, the pressure force on the face of the piston may be balanced by gravitational force. The condition of force balance is indicated by the platform remaining at rest between the upper and lower stops. Since the weights and the piston area are all known, the unknown pressure may be computed.

Upon comparing the null and deflection methods of measurement exemplified by the pressure gages described above, we note that, in the deflection instrument, accuracy depends on the calibration of the spring, whereas in the null instrument it depends on the accuracy of the standard weights. In this particular case (and for most measurements in general), the accuracy attainable by the null method is of a higher level than that by the deflection method. One reason is that the spring is not in itself a primary standard of force, but must be calibrated by standard weights, whereas in the null instrument a *direct* comparison of the unknown force with the standard is achieved. Another advantage of null methods is the fact that, since the measured quantity is balanced out, the detector of unbalance can be made very sensitive, because it need cover only a small range around zero. Also the detector need not be calibrated since it must detect only the presence and direction of unbalance,

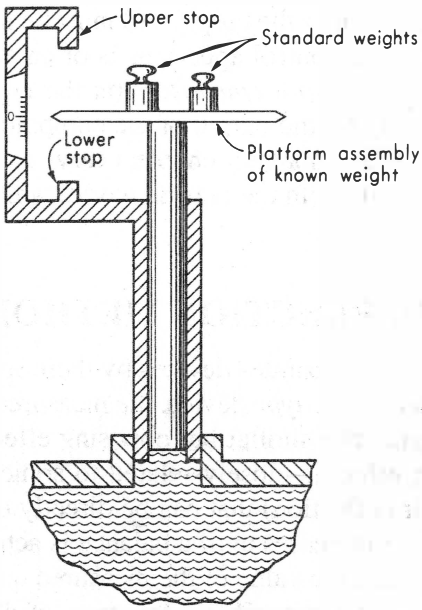


Figure 2.8
Deadweight pressure gage.

but not the amount. However, a deflection instrument must be larger, more rugged, and thus less sensitive if it is to measure large magnitudes.

The disadvantages of null methods appear mainly in dynamic measurements. Let us consider the pressure gages again. The difficulty in keeping the platform balanced for a fluctuating pressure should be apparent. The spring-type gage suffers not nearly so much in this respect. By use of automatic balancing devices (such as the instrument servomechanism of Fig. 2.7) the speed of null methods may be improved considerably, and instruments of this type are of great importance.

2.5 INPUT-OUTPUT CONFIGURATION OF INSTRUMENTS AND MEASUREMENT SYSTEMS

Before we discuss instrument performance characteristics, it is desirable to develop a generalized configuration that brings out the significant input-output relationships present in all measuring apparatus. A scheme suggested by Draper, McKay, and Lees[1] is presented in somewhat modified form in Fig. 2.9. Input quantities are classified into three categories: desired inputs, interfering inputs, and modifying inputs. *Desired inputs* represent the quantities that the instrument is specifically intended to measure. *Interfering inputs* represent quantities to which the instrument is unintentionally sensitive. A desired input produces a component of output

[1]C. S. Draper, W. McKay, and S. Lees, "Instrument Engineering," vol. 3, p. 58, McGraw-Hill, New York, 1955.

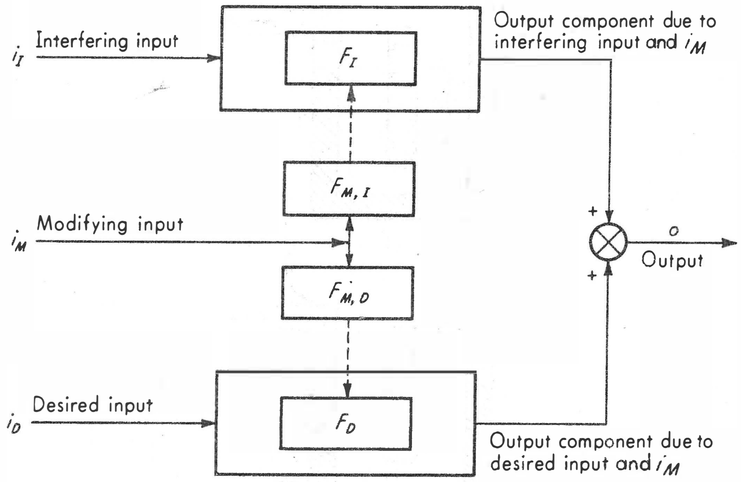


Figure 2.9
Generalized input-output configuration.

according to an input-output relation symbolized by F_D, where F_D denotes the mathematical operations necessary to obtain the output from the input. The symbol F_D may represent different concepts, depending on the particular input-output characteristic being described. Thus F_D might be a constant number K that gives the proportionality constant relating a constant static input to the corresponding static output for a linear instrument. For a nonlinear instrument, a simple constant is not adequate to relate static inputs and outputs; a mathematical *function* is required. To relate dynamic inputs and outputs, differential equations are necessary. If a description of the output "scatter," or dispersion, for repeated equal static inputs is desired, a statistical distribution function of some kind is needed. The symbol F_D encompasses all such concepts. The symbol F_I serves a similar function for an interfering input.

The third class of inputs might be thought of as being included among the interfering inputs, but a separate classification is actually more significant. This is the class of modifying inputs. *Modifying inputs* are the quantities that cause a change in the input-output relations for the desired and interfering inputs; that is, they cause a change in F_D and/or F_I. The symbols $F_{M,I}$ and $F_{M,D}$ represent (in the appropriate form) the specific manner in which i_M affects F_I and F_D, respectively. These symbols, $F_{M,I}$ and $F_{M,D}$ are interpreted in the same general way as F_I and F_D.

The block diagram of Fig. 2.9 illustrates the above concepts. The circle with a cross in it is a conventional symbol for a *summing device*. The two plus signs as shown indicate that the output of the summing device is the instantaneous algebraic sum of its two inputs. Since an instrument system may have several inputs of each of the three types as well as several outputs, it may be necessary to draw more complex block diagrams than in Fig. 2.9. This extension is, however, straightforward.

The above concepts can be clarified by means of specific examples. Consider the mercury manometer used for differential-pressure measurement as shown in

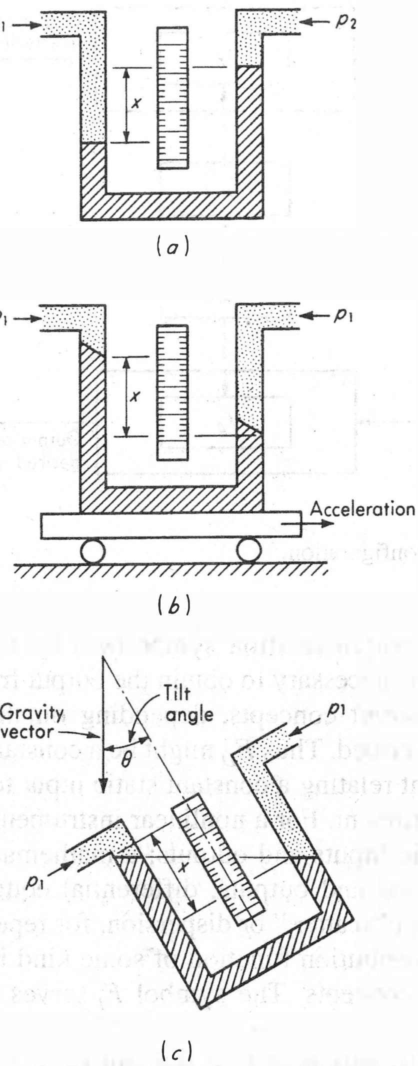


Figure 2.10
Spurious inputs for manometer.

Fig. 2.10a. The desired inputs are the pressures p_1 and p_2 whose difference causes the output displacement x, which can be read off the calibrated scale. Figures 2.10b and c show the action of two possible interfering inputs. In Fig. 2.10b the manometer is mounted on some vehicle that is accelerating. A simple analysis shows that there will be an output x even though the differential pressure might be zero. Thus if you are trying to measure pressures under such circumstances, an error will be engendered because of the interfering acceleration input. Similarly, in Fig. 2.10c, if the manometer is not properly aligned with the gravity vector, it may give an output signal x even though no pressure difference exists. Thus the tilt angle θ is an interfering input. (It is also a modifying input.)

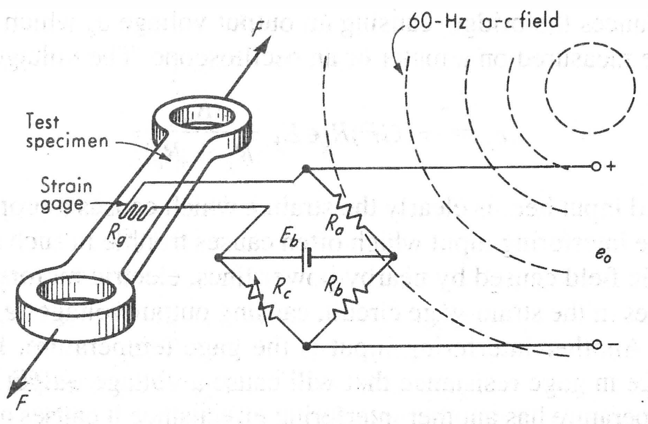


Figure 2.11
Interfering input for strain-gage circuit.

Modifying inputs for the manometer include ambient temperature and gravitational force. Ambient temperature manifests its influence in a number of ways. First, the calibrated scale changes length with temperature; thus the proportionality factor relating $p_1 - p_2$ to x is modified whenever temperature varies from its basic calibration value. Also, the density of mercury varies with temperature, which again leads to a change in the proportionality factor. A change in gravitational force resulting from changes in location of the manometer, such as moving it to another country or putting it aboard a spaceship, leads to a similar modification in the scale factor. Note that the effects of *both* the desired and the interfering inputs may be altered by the modifying inputs.

As another example, consider the electric-resistance strain-gage setup shown in Fig. 2.11. The gage consists of a fine-wire grid of resistance R_g firmly cemented to the specimen whose unit strain ϵ at a certain point is to be measured. When strained, the gage's resistance changes according to the relation

$$\Delta R_g = (GF)R_g\epsilon \tag{2.1}$$

where
$$\Delta R_g \triangleq \text{change in gage resistance, } \Omega^* \tag{2.2}$$
$$GF \triangleq \text{gage factor, dimensionless} \tag{2.3}$$
$$R_g \triangleq \text{gage resistance when unstrained, } \Omega \tag{2.4}$$
$$\epsilon \triangleq \text{unit strain, cm/cm} \tag{2.5}$$

The resistance change is proportional to the strain. Thus if we could measure the resistance, we could compute the strain. The resistance is measured by using the Wheatstone-bridge arrangement shown. When no load F is present, the bridge is balanced (e_o set to zero) by adjusting R_c. Application of load causes a strain, a ΔR_g,

*The symbol $\triangleq$ means "equal by definition."

and thus unbalances the bridge, causing an output voltage e_o which is proportional to ϵ and can be measured on a meter or an oscilloscope. The voltage e_o is given by

$$e_o = -(GF)R_g \epsilon E_b \frac{R_a}{(R_g + R_a)^2} \tag{2.6}$$

The desired input here is clearly the strain ϵ which causes a proportional output voltage e_o. One interfering input which often causes trouble in such apparatus is the 60-Hz magnetic field caused by nearby power lines, electric motors, etc. This field induces voltages in the strain-gage circuit, causing output voltages e_o even when the strain is zero. Another interfering input is the gage temperature. If this varies, it causes a change in gage resistance that will cause a voltage output even if there is no strain. Temperature has another interfering effect since it causes a differential expansion of the gage and the specimen, which gives rise to a strain ϵ and a voltage e_o even though no force F has been applied. Temperature also acts as a modifying input since the gage factor is sensitive to temperature. The battery voltage E_b is another modifying input. Both these are modifying inputs since they tend to change the proportionality factor between the desired input ϵ and the output e_o or between an interfering input (gage temperature) and output e_o.

Methods of Correction for Interfering and Modifying Inputs

In the design and/or use of measuring instruments, a number of methods for nullifying or reducing the effects of spurious inputs are available. We briefly describe some of the most widely used.

The *method of inherent insensitivity* proposes the obviously sound design philosophy that the elements of the instrument should *inherently* be sensitive to only the desired inputs. While usually this is not entirely possible, the simplicity of this approach encourages one to consider its application wherever feasible. In terms of the general configuration of Fig. 2.9, this approach requires that somehow F_I and/or $F_{M,D}$ be made as nearly equal to zero as possible. Thus, even though i_I and/or i_M may exist, they cannot affect the output. As an example of the application of this concept to the strain gage of Fig. 2.11, we might try to find some gage material that exhibits an extremely low temperature coefficient of resistance while retaining its sensitivity to strain. If such a material can be found, the problem of interfering temperature inputs is at least partially solved. Similarly, in mechanical apparatus that must maintain accurate dimensions in the face of ambient-temperature changes, the use of a material[2] of very small temperature coefficient of expansion may be helpful. Two such materials are the metal alloy Invar and the glass/ceramic Zerodur. If stiffness (such as in a spring) must be temperature insensitive, consider the metal alloy Ni-Span C.

[2]D. G. Chetwynd, "Selection of Structural Materials for Precision Devices," *Precision Eng.*, vol. 9, no. 1, pp. 3–6, January 1987.

The *method of high-gain feedback* is exemplified by the system shown in Fig. 2.12*b*. Suppose we wish to measure a voltage e_i by applying it to a motor whose torque acts on a spring, causing a displacement x_o, which may be measured on a calibrated scale. By proper design, the displacement x_o might be made proportional to the voltage e_i according to

$$x_o = (K_{Mo}K_{SP})e_i \tag{2.7}$$

where K_{Mo} and K_{SP} are appropriate constants. This arrangement, shown in Fig. 2.12*a*, is called an open-loop system. If modifying inputs i_{M1} *and* i_{M2} exist, they cause changes in K_{Mo} and K_{SP} that lead to errors in the relation between e_i and x_o. These errors are in *direct proportion* to the changes in K_{Mo} and K_{SP}. Suppose, instead, we construct a system as in Fig. 2.12*b*. Here the output x_o is measured by

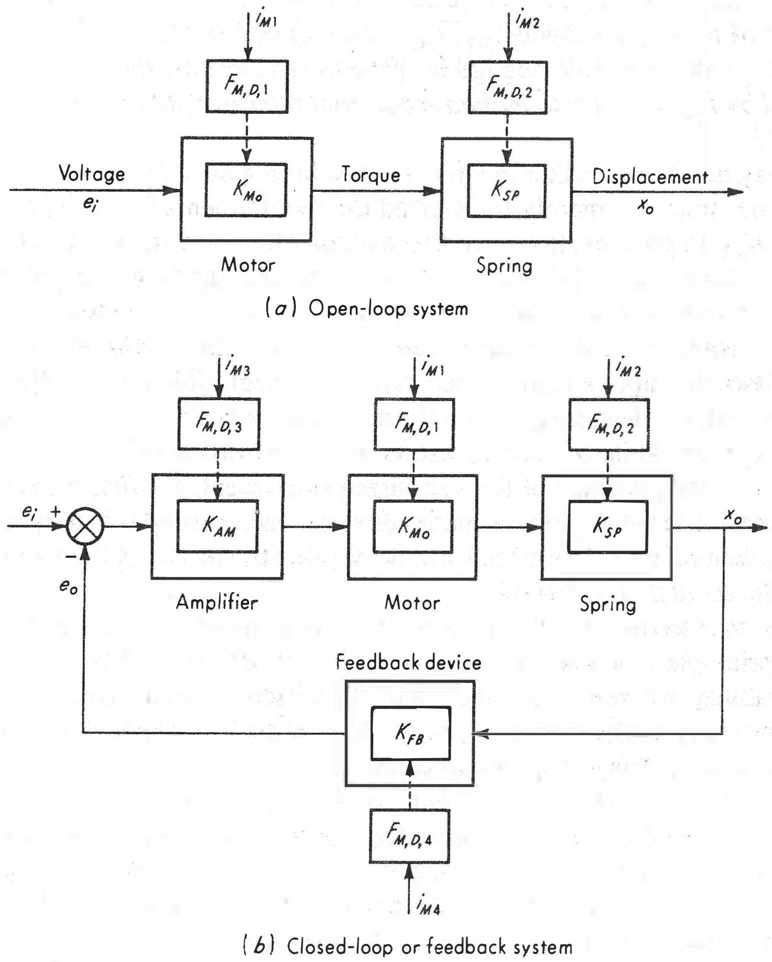


Figure 2.12
Use of feedback to reduce effect of spurious inputs.

the feedback device, which produces a voltage e_o proportional to x_o. This voltage is subtracted from the input voltage e_i, and the difference is applied to an amplifier which drives the motor and thereby the spring to produce x_o. We may write

$$(e_i - e_o)K_{AM}K_{Mo}K_{SP} = (e_i - K_{FB}x_o)K_{AM}K_{Mo}K_{SP} = x_o \tag{2.8}$$

$$e_i K_{AM}K_{Mo}K_{SP} = (1 + K_{AM}K_{Mo}K_{SP}K_{FB})x_o \tag{2.9}$$

$$x_o = \frac{K_{AM}K_{Mo}K_{SP}}{1 + K_{AM}K_{Mo}K_{SP}K_{FB}} e_i \tag{2.10}$$

Suppose, now, that we design K_{AM} to be very large (a "high-gain" system), so that $K_{AM}K_{Mo}K_{SP}K_{FB} \gg 1$. Then

$$x_o \approx \frac{1}{K_{FB}} e_i \tag{2.11}$$

The significance of Eq. (2.11) is that the effect of variations in K_{Mo}, K_{SP}, and K_{AM} (as a result of modifying inputs i_{M1}, i_{M2}, and i_{M3}) on the relation between input e_i and output x_o has been made negligible. *We now require only that K_{FB} stay constant (unaffected by i_{M4}) in order to maintain constant input-output calibration as shown by Eq. (2.11).*

You may question whether much really has been gained by this somewhat elaborate scheme, since we merely transferred the requirements for stability from K_{Mo} and K_{SP} to K_{FB}. In practice, however, this method often leads to great improvements in accuracy. One reason is that, since the amplifier supplies most of the power needed, the feedback device can be designed with low power-handling capacity. In general, this leads to greater accuracy and linearity in the feedback-device characteristics. Also, the input signal e_i need carry only negligible power; thus the feedback system extracts less energy from the measured medium than the corresponding open-loop system. This, of course, results in less distortion of the measured quantity because of the presence of the measuring instrument. Finally, if the open-loop chain consists of several (perhaps many) devices, each susceptible to its own spurious inputs, then *all* these bad effects can be negated by the use of high amplification and a stable, accurate feedback device.

Before we pass on to other methods, we should mention that application of the feedback principle is not without its own peculiar problems. The main one is dynamic instability, wherein excessively high amplification leads to destructive oscillations. The study of the design of feedback systems is a whole field in itself, and many texts treating this subject are available.[3]

The *method of calculated output corrections* requires one to measure or estimate the magnitudes of the interfering and/or modifying inputs and to know quantitatively how they affect the output. With this information, it is possible to calculate corrections which may be added to or subtracted from the indicated output so as to leave (ideally) only that component associated with the desired input. Thus, in the manometer of Fig. 2.10, the effects of temperature on both the calibrated scale's length and the density of mercury may be quite accurately computed if the

[3] E. O. Doebelin, "Control System Principles and Design," Wiley, New York, 1985.

temperature is known. The local gravitational acceleration is also known for a given elevation and latitude, so that this effect may be corrected by calculation. Since many measurement systems today can afford to include a microcomputer to carry out various functions, if we also provide sensors for the spurious inputs, the microcomputer can implement the method of calculated output corrections on an automatic basis, giving a so-called *smart sensor.*

The *method of signal filtering* is based on the possibility of introducing certain elements ("filters") into the instrument which in some fashion block the spurious signals, so that their effects on the output are removed or reduced. The filter may be applied to any suitable signal in the instrument, be it input, output, or intermediate signal. The concept of signal filtering is shown schematically in Fig. 2.13 for the

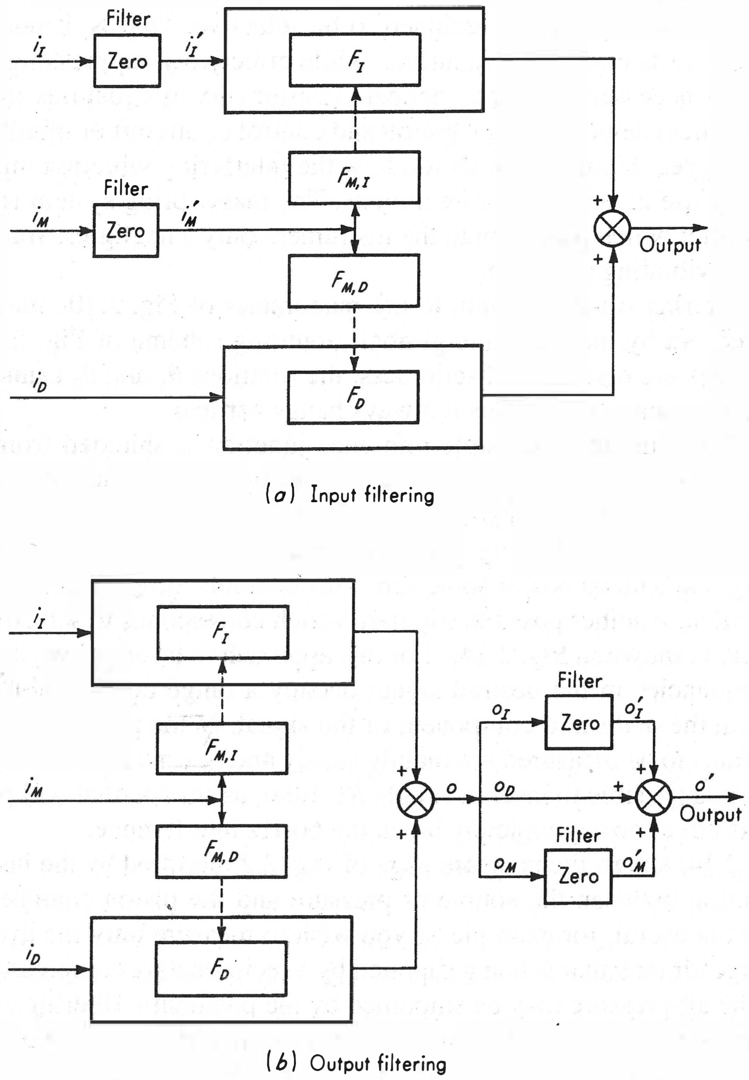


Figure 2.13
General principle of filtering.

cases of input and output filtering. The application to intermediate signals should be obvious. In Fig. 2.13*a* the inputs i_I and i_M are caused to pass through filters whose input-output relation is (ideally) zero. Thus i'_I and i'_M are zero even if i_I and i_M are not zero. The concept of output filtering is illustrated in Fig. 2.13*b*. Here the output o, though really one signal, is thought of as a superposition of o_I (output due to interfering input), o_D (output due to desired input), and o_M (output due to modifying input). If it is possible to construct filters that selectively block o_I and o_M but allow o_D to pass through, this may be symbolized as in Fig. 2.13*b* and results in o' consisting entirely of o_D.

The filters necessary in the application of this method may take several forms; they are best illustrated by examples. If put directly in the path of a spurious input, a filter can be designed (ideally) to block completely the passage of the signal. If, however, it is inserted at a point where the signal contains both desired and spurious components, the filter must be designed to be selective. That is, it must pass the desired components essentially unaltered while effectively suppressing all others.

Often it is necessary to attach delicate instruments to structures that vibrate. Electromechanical devices for navigation and control of aircraft or missiles are outstanding examples. Figure 2.14*a* shows how the interfering vibration input may be filtered out by use of suitable spring mounts. The mass-spring system is actually a mechanical filter which passes on to the instrument only a negligible fraction of the motion of the vibrating structure.

The interfering tilt-angle input to the manometer of Fig. 2.10*c* may be effectively filtered out by means of the gimbal-mounting scheme of Fig. 2.14*b*. If the gimbal bearings are essentially frictionless, the rotations θ_1 and θ_2 cannot be communicated to the manometer; thus it always hangs vertical.

In Fig. 2.14*c* the thermocouple reference junction is shielded from ambient-temperature fluctuations by means of thermal insulation. Such an arrangement acts as a filter for temperature or heat-flow inputs.

The strain-gage circuit of Fig. 2.14*d* is shielded from the interfering 60-Hz field by enclosing it in a metal box of some sort. This solution corresponds to filtering the interfering ***input***. Another possible solution, which corresponds to selective filtering of the *output*, is shown in Fig. 2.14*e*. For this approach to be effective, it is essential that the frequencies in the desired signal occupy a range considerably separated from those in the undesired component of the signal. In the present example, suppose the strains to be measured are mainly steady and never vary more rapidly than 2 Hz. Then it is possible to insert a simple *RC* filter, as shown, that will pass the desired signals but almost completely block the 60-Hz interference.

Figure 2.14*f* shows the pressure gage of Fig. 2.2 modified by the insertion of a flow restriction between the source of pressure and the piston chamber. Such an arrangement is useful, for example, if you wish to measure only the average pressure in a large air tank that is being supplied by a reciprocating compressor. The pulsations in the air pressure may be smoothed by the pneumatic filtering effect of the flow restriction and associated volume. The variation of the output-input amplitude ratio $|p_o/p_i|$ with frequency is similar to that for the electrical *RC* filter of Fig. 2.14*e*. Thus steady or slowly varying input pressures are accurately measured while

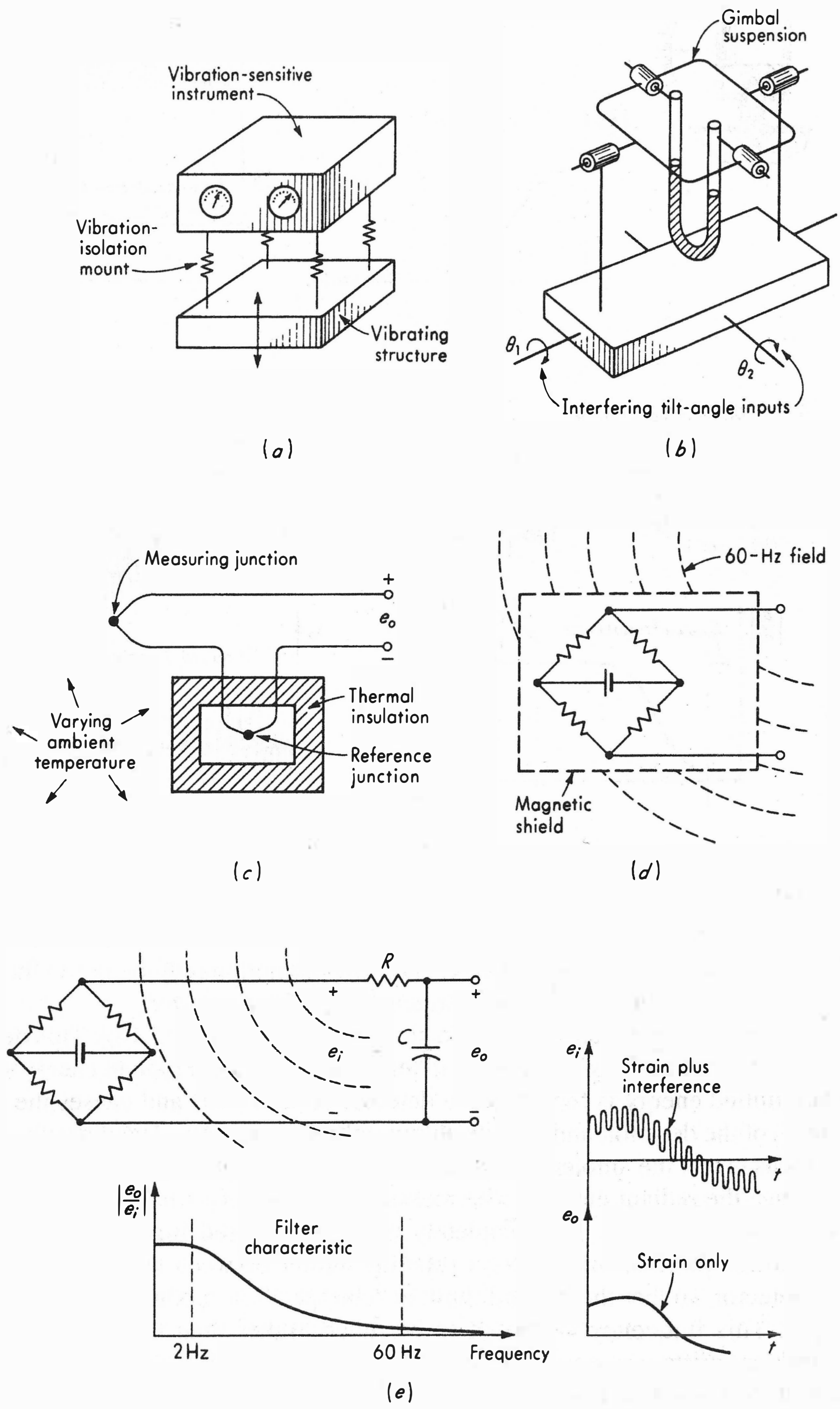


Figure 2.14
Examples of filtering.

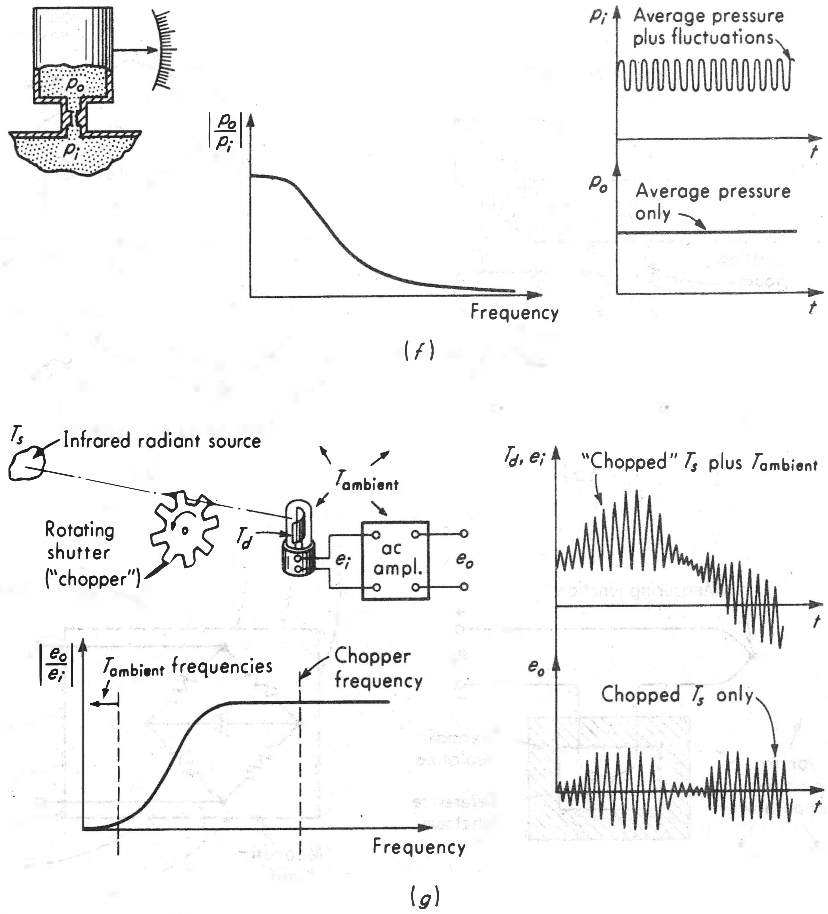


Figure 2.14
(*Continued*)

rapid variations are strongly attenuated. The flow restriction may be in the form of a needle valve, which allows easy adjustment of the filtering effect.

A "chopped" radiometer is shown in simplified form in Fig. 2.14*g*. This device senses the temperature T_s of some body in terms of the infrared radiant energy emitted. The emitted energy is focused on a detector of some sort and causes the temperature T_d of the detector, and thus its output voltage e_i, to vary. The difficulty with such devices is that the ambient temperature, as well as T_s, affects T_d. This effect is serious since the radiant energy to be measured causes very small changes in T_d; thus small ambient drifts can completely mask the desired input. An ingenious solution to this problem interposes a rotating shutter between the radiant source and the detector, so that the desired input is "chopped," or modulated, at a known frequency. This frequency is chosen to be much higher than the frequencies at which ambient drifts may occur. The output signal e_i of the detector thus is a superposition of slow ambient fluctuations and a high-frequency wave whose amplitude varies in proportion to variations in T_s. Since the desired and interfering components are thus widely separated in frequency, they may be selectively filtered. In this case, we desire a filter that rejects constant and slowly varying signals, but faithfully

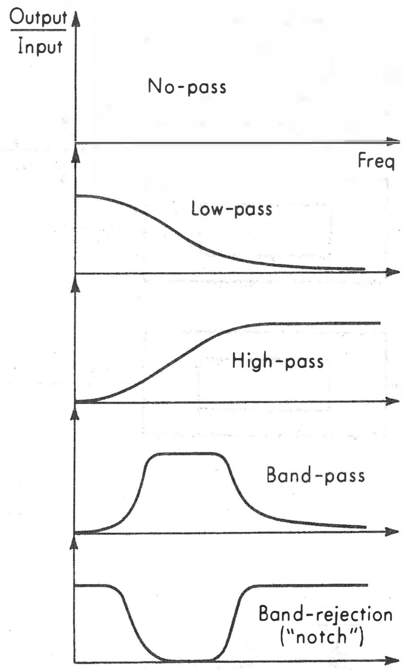


Figure 2.15
Basic filter types.

reproduces rapid variations. Such a characteristic is typical of an ordinary ac amplifier, and since amplification is necessary in such instruments in any case, the use of an ac amplifier as shown solves two problems at once.

In summing up the method of signal filtering, it may be said that, in general, it is usually possible to design filters of mechanical, electrical, thermal, pneumatic, etc., nature which separate signals according to their frequency content in some specific manner. Figure 2.15 summarizes the most common useful forms of such devices.

The *method of opposing inputs* consists of intentionally introducing into the instrument interfering and/or modifying inputs that tend to cancel the bad effects of the unavoidable spurious inputs. Figure 2.16 shows schematically the concept for interfering inputs. The extension to modifying inputs should be obvious. The intentionally introduced input is designed so that the signal o_{I1} and o_{I2} are essentially equal but act in the opposite sense; thus the net contribution $o_{I1} - o_{I2}$ to the output is nearly zero. This method actually might be considered as a variation on the method of calculated output corrections. However, the "calculation" and application of the correction are achieved automatically owing to the structure of the system, rather than by numerical calculation by a human operator. Thus the two methods are similar; however, the distinction between them is a worthwhile one since it helps to organize your thinking in inventing new applications of these generalized correction concepts.

Some examples of the method of opposing inputs are shown in Fig. 2.17. A millivoltmeter, shown in Fig. 2.17*a*, is basically a *current*-sensitive device.

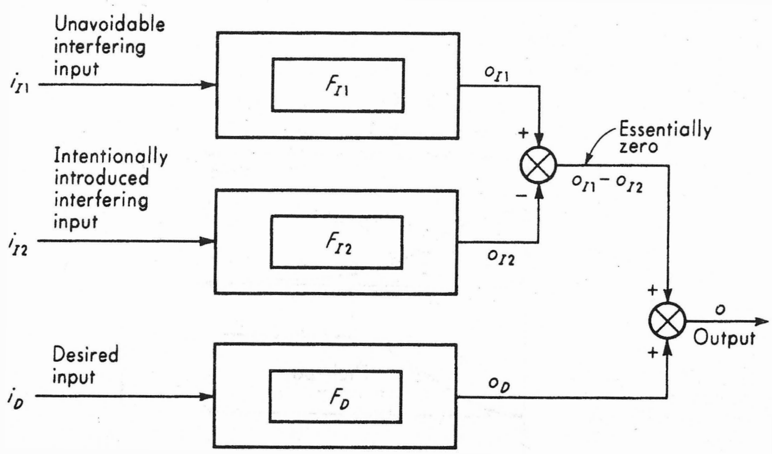


Figure 2.16
Method of opposing inputs.

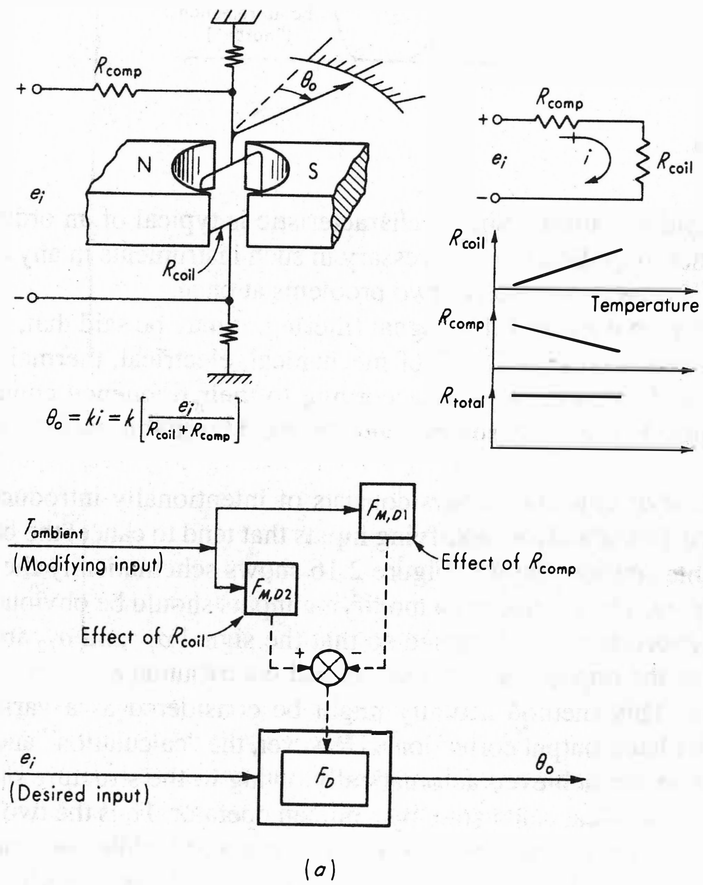


Figure 2.17
Examples of method of opposing inputs.

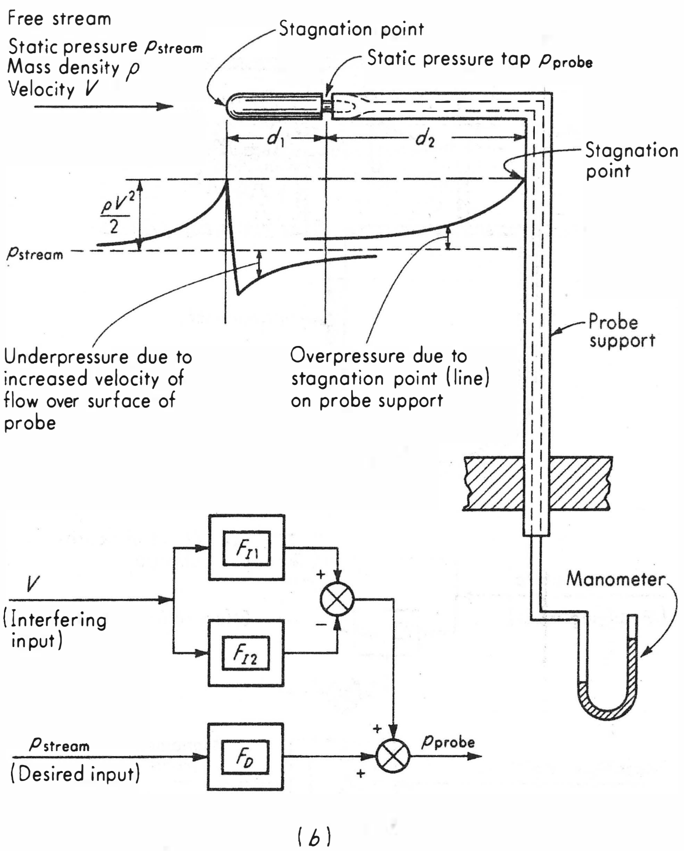
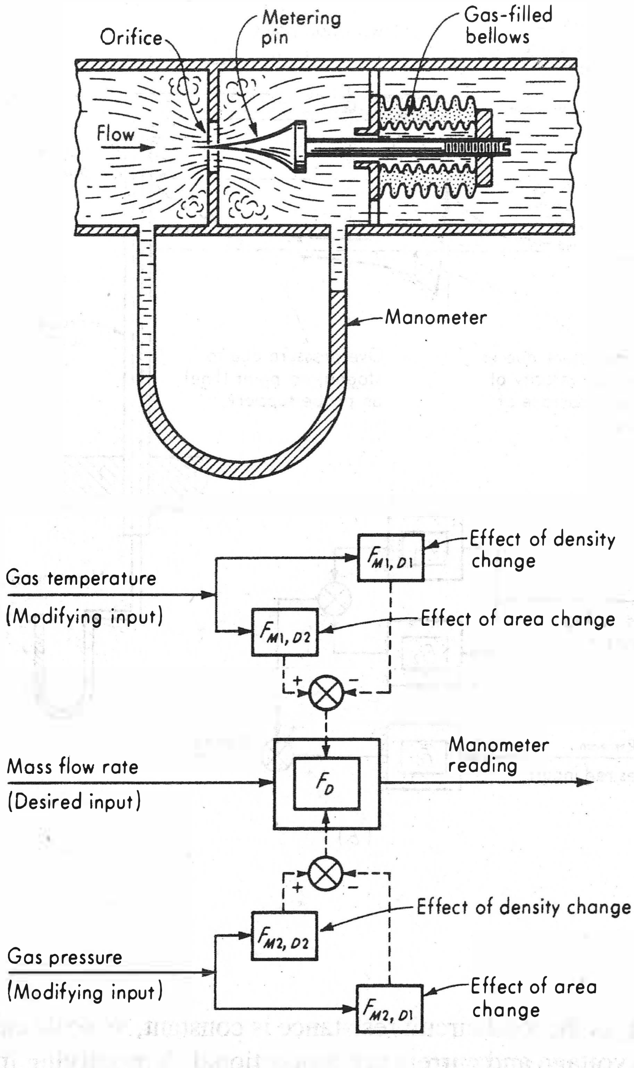


Figure 2.17
(Continued)

However, as long as the total circuit resistance is constant, its scale can be calibrated in voltage, since voltage and current are proportional. A modifying input here is the ambient temperature, since it causes the coil resistance R_{coil} to change, thereby altering the proportionality factor between current and voltage. To correct for this error, the compensating resistance R_{comp} is introduced into the circuit, and its material is carefully chosen to have a temperature coefficient of resistance *opposite* to that of R_{coil}. Thus when the temperature changes, the total resistance of the circuit is unaffected and the calibration of the meter remains accurate.

Figure 2.17*b* shows a static-pressure-probe design due to L. Prandtl. As the fluid flows over the surface of the probe, the velocity of the fluid must increase since these streamlines are longer than those in the undisturbed flow. This velocity increase causes a drop in static pressure, so that a tap in the surface of the probe gives an incorrect reading. This underpressure error varies with the distance d_1 of the tap from the probe tip. Prandtl recognized that the probe support will have a stagnation point (line) along its front edge and that this overpressure will be felt upstream, the effect decreasing as the distance d_2 increases. By properly choosing



(c)

Figure 2.17
(Continued)

distances d_1 and d_2 (by experimental test), these two effects can be made exactly to cancel, giving a true static-pressure value at the tap.

A device for the measurement of the mass flow rate of gases is shown in Fig. 2.17*c*. The mass flow rate of gas through an orifice may be found by measuring the pressure drop across the orifice, perhaps by means of a U-tube manometer. Unfortunately, the mass flow rate also depends on the density of the gas, which varies with pressure and temperature. Thus the pressure-drop measuring device usually cannot be calibrated to give the mass flow rate, since variations in gas temperature and pressure yield different mass flow rates for the same orifice pressure drop. The instrument of Fig. 2.17*c* overcomes this problem in an ingenious fashion. The flow

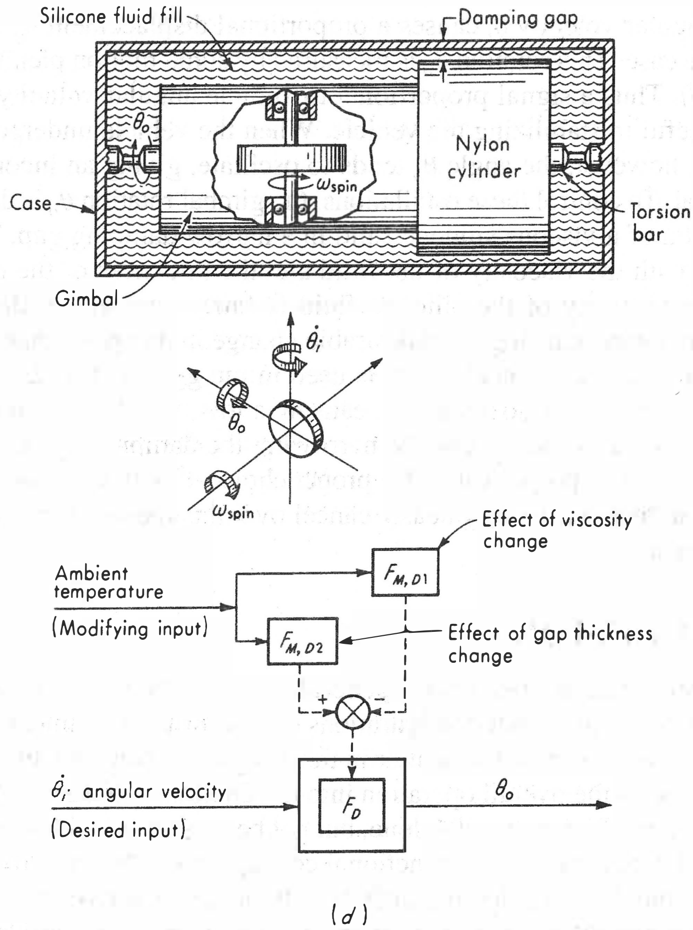


Figure 2.17
(Concluded)

rate through the orifice also depends on its flow area. Thus if the flow area could be varied in just the right way, this variation could compensate for pressure and temperature changes so that a given orifice pressure drop would *always* correspond to the same mass flow rate. This is accomplished by attaching the specially shaped metering pin to a gas-filled bellows as shown. When the temperature drops (causing an increase in density and therefore in mass flow rate), the gas in the bellows contracts, which moves the metering pin into the orifice and thereby reduces the flow area. This returns the mass flow rate to its proper value. Similarly, should the pressure of the flowing gas increase, causing an increase in density and mass flow rate, the gas-filled bellows would be compressed again, reducing the flow area and correcting the mass flow rate. The proper shape for the metering pin is revealed by a detailed analysis of the system.

A final example of the method of opposing inputs is the rate gyroscope of Fig. 2.17*d*. Such devices are widely used in aerospace vehicles for the generation of stabilization signals in the control system. The action of the device is that a vehicle rotation at angular velocity $\dot{\theta}_i$ causes a proportional displacement θ_o of the gimbal relative to the case. This rotation θ_o is measured by some motion pickup (not shown in Fig. 2.17*d*). Thus a signal proportional to vehicle angular velocity is available, and this is useful in stabilizing the vehicle. When the vehicle undergoes rapid motion changes, however, the angle θ_o tends to oscillate, giving an incorrect angular-velocity signal. To control these oscillations, the gimbal rotation θ_o is damped by the shearing action of a viscous silicone fluid in a narrow damping gap. The damping effect varies with the viscosity of the fluid and the thickness of the damping gap. Although the viscosity of the silicone fluid is fairly constant, it does vary with ambient temperature, causing an undesirable change in damping characteristics. To compensate for this, a nylon cylinder is used in the gyro of Fig. 2.17*d*. When the temperature increases, viscosity drops, causing a loss of damping. Simultaneously, however, the nylon cylinder expands, narrowing the damping gap and thus restoring the damping to its proper value. By proper choice of materials and geometry, the two effects can be made to very nearly cancel over the operating temperature range of the equipment.

2.6 CONCLUSION

In this chapter we developed useful generalizations with regard to the functional elements and the input-output configurations of measuring instruments and systems. In the analysis of a given instrument or in the design of a new one, the starting point is the separation of the overall operation into its functional elements. Here you must take a broad view of *what* must be done, but not be concerned with *how* it is actually accomplished. Once the general functional concepts have been clarified, the details of operation may be considered fruitfully. The ideas of active and passive transducers, analog and digital modes of operation, and null versus deflection methods give a systematic approach for either analysis or design.

Finally, compensation of spurious inputs and detailed evaluation of performance are facilitated by application of input-output block diagrams. These configuration diagrams show clearly which physical analyses must be made to evaluate performance with respect to accurate measurement of the desired inputs and rejection of spurious inputs. The evaluation of the relative quality of different instruments (or the same instrument with different numerical parameter values) requires the definition of performance criteria against which competitive designs may be compared. This is the subject of Chapter 3.

PROBLEMS

2.1 Make block diagrams such as Fig. 2.1, showing the functional elements of the instruments depicted in the following:
(*a*) Fig. 2.7.
(*b*) Fig. 2.8.
(*c*) Fig. 2.10*a*.
(*d*) Fig. 2.11. Take F as input and e_o as output.
(*e*) Fig. 2.14*g*. Take T_s as input and e_o as output.
(*f*) Fig. 2.17*b*. Take V as input and manometer Δh as output.
(*g*) Fig. 2.17*d*. Take θ_i as input and θ_o as output.

2.2 Identify the active transducers, if any, in the instruments of (*a*) Fig. 2.8, (*b*) Fig. 2.10*a*, (*c*) Fig. 2.11, (*d*) Fig. 2.17*b*, (*e*) Fig. 2.17*c*.

2.3 Consider a man, driving a car along a road, who sees the opportunity to pass and decides to accelerate.
(*a*) If the light waves entering his eyes are considered input and accelerator-pedal travel is taken as output, is the man functioning as an active or a passive transducer?
(*b*) If the accelerator-pedal travel is considered input and car velocity as output, is the automobile engine an active or a passive transducer?

2.4 Give an example of a null method of force measurement.

2.5 Give an example of a null method of voltage measurement.

2.6 Sketch and explain two possible modifications of the system of Fig. 2.4 that will allow measurement to 1/10 revolution.

2.7 Identify desired, interfering, and modifying inputs for the systems of (*a*) Fig. 2.2, (*b*) Fig. 2.3, (*c*) Fig. 2.4, (*d*) Fig. 2.5.

2.8 Why is tilt angle in Fig. 2.10*c* a modifying input?

2.9 Suppose in Eq. (2.7) that $K_{Mo} = K_{SP} = e_i = 1.0$. Now let K_{Mo} change by 10 percent to 1.1. What is the change in x_o? In Eq. (2.10), let $K_{Mo} = K_{SP} = K_{FB} = e_i = 1.0$, and $K_{AM} = 100$. Now let K_{Mo} change by 10 percent to 1.1. What is the change in x_o? Investigate the effect of similar changes in K_{AM}, K_{SP}, and K_{FB}.

2.10 The natural frequency of oscillation of the balance wheel in a watch depends on the moment of inertia of the wheel and the spring constant of the (torsional) hairspring. A temperature rise results in a reduced spring constant, which lowers the oscillation frequency. Propose a compensating means for this effect. Non-temperature-sensitive hairspring material is not an acceptable solution.