The Transducer as a Circuit Element

Chapter 1

TRANSDUCERS – ACTIVE AND PASSIVE

Webster's New Collegiate Dictionary defines *transducer* as "a device that is actuated by power from one system and supplies power, usually in another form, to a second system." In this book we are concerned with *input transducers*—actuated by physical variables representing force, pressure, temperature, flow, and level—that supply electrical signals to the front end of a measurement and control system (which may range in complexity from a simple analog meter to a multi-input, multi-output, multiprocessor, multi-loop digitally controlled system).*

The input transducers with which we are concerned may be categorized in a number of ways. Number of energy ports, input variable, sensing element, and electrical circuit configuration are some specific forms of differentiation that will be treated here.

From the standpoint of energy, there are two broad classes, *active* and *passive* transducers.† A *passive*, or self-generating, transducer is one which has an input and an output (i.e., two *energy ports*). All of the electrical energy at the output is derived from the physical input; examples include thermocouples, crystal microphones, and photodiodes in the photovoltaic mode. Since the electrical output is limited by the physical input, such transducers tend to have low-energy outputs requiring amplification, but this is not always true: a piezoelectric accelerometer may furnish *watts* of

*Input transducers may be contrasted with *output transducers*, which convert electrical to other forms of energy, e.g., loudspeakers, solenoids, etc.

†These terms are restricted cases of the more-general *active* and *passive circuits*. (*IEEE Standard Dictionary of Electrical and Electronics Terms*, 2nd Edition, Institute of Electrical and Electronics Engineers, Inc., New York, 1977)

power for short periods during explosions or hammer blows.

An *active* transducer has a physical input, an electrical output, and an electrical *excitation* input (i.e., three energy ports). The physical input, in effect, modulates the excitation. Examples of this type of transducer include resistance strain gages* and bridges, platinum resistance thermometers, and semiconductor temperature sensors. Active transducers are usually of the *open-loop* type, with fixed excitation. However, there is a subclass of active transducers in which the electrical output serves as an indication of unbalance (or *error*), and the excitation or the physical parameter is manipulated in a feedback configuration to maintain balance; the feedback signal is then a measure of the physical variable. Some members of this class are known (appropriately) as *force-balance* transducers.

To the interface designer, one significance of these two categories is that passive transducers must be dealt with strictly on their own terms. The form of response—and its sensitivity—are limited by the energy available in the phenomenon and the device's conversion efficiency; very little negotiating, cajoling, or finagling is possible. For example, with thermocouples, we are stuck with their low sensitivity, low output level, and nonlinear response. While we can choose different combinations of metals to produce different outputs over varying temperature ranges, we cannot budge the characteristics of a given thermocouple. On the other hand, their structure is simple, their characteristics are consistent, interchangeable, and reliable (when properly implemented), and standard output tables are published for the various couplings.†

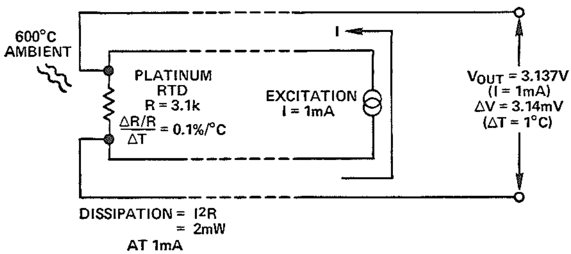
With active transducers, there is an additional degree of freedom. Although they rely on fundamental properties of materials in the same way that passive devices do, the excitation can be used (in many instances, but by no means always) to provide an increased output level, but there are tradeoffs.

Consider a simple resistance temperature-detector circuit (Figure 1-1). The current source, I, develops across resistance R—which

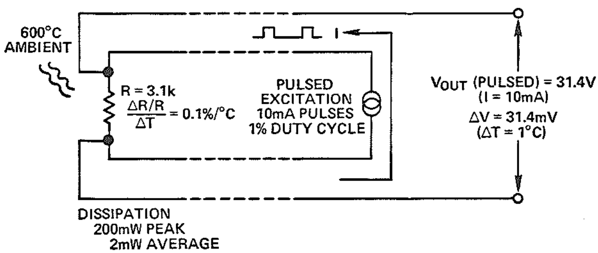
*It can be argued (correctly) that the proper spelling of this word is "gauges". However, through consistent usage in the industry, the simplified spelling—when used in the term "strain gage"—has become a *de facto* standard and will be so employed throughout this book when used in that context.

†Increased sensitivity can be gained by connecting sets of junctions—physically associating alternate junctions—to form *thermopiles*, but their cost and complexity restrict their applicability.

varies predictably with temperature—a small voltage. For accurate resolution of small temperature changes, with correspondingly small resistance changes, it would be useful to increase I. For example, if I were increased tenfold, the resolution would increase in the same degree. However, a tenfold increase in I produces a hundredfold increase in dissipation. When I is sufficiently great, the power dissipated in R will itself cause the temperature to rise perceptibly, introducing a measurement error.



a. Constant-current excitation, I = 1mA



b. Pulsed excitation, 10mA rectangular pulses

Figure 1-1. Active transducers may provide increased output if the excitation is increased in an appropriate way

A possible solution to this problem would be to *pulse* the current at 10I, using accurate rectangular pulses with a duty cycle of 1% at a frequency that is high compared to the thermal response of the device. The average dissipation would be the same as for continuous I, but the sampled pulses would provide a tenfold improvement in sensitivity. This example is mentioned here, not as a specific technique, but rather as a demonstration of the additional degree of freedom available to the designer for obtaining improved performance via modifications to the circuit parameters of the active transducer's circuitry.*

INTERFACING AND SIGNAL CONDITIONING

Once a particular form of transducer has been chosen—or mandated—for a given job, provisions must be made for appropriate excitation and for conditioning the output signal. The nature of the conditioning depends on the electrical characteristics of the transducer and the destination of the signal. Typical processes include galvanic isolation, impedance transformation, level translation, amplification, linearization, and a variety of computations (analog or digital). These processes may occur in the vicinity of the transducer, at a remote data-acquisition subsystem, or piecemeal at several locations. A common initial form of conditioning is to amplify the signal to a standard voltage range for data acquisition (e.g., 0 to +10V); another is to translate it to a standard process-control current range (e.g., 4 to 20mA) for transmission over a twisted pair to a remote destination. The equipment used for signal conditioning might range from user-designed equipment using electronic components, such as op amps and instrumentation amplifiers, to packaged signal-conditioning modules, to intelligent data-acquisition subsystems.†

Whatever form the conditioning takes, however, the circuitry and performance will be governed by the electrical character of the transducer and its output. Accurate characterization of the transducer in terms of parameters appropriate to the application, e.g., sensitivity, voltage and current levels, linearity, impedances, gain,

*Hardened system designers and veteran micro—and milli—volt chasers among our readers will recognize what a prize has been won here; a tenfold increase in output of a transducers is really substantial. On the other hand, although the strategy outlined for this particular example will (and has) worked well, it may well be a last resort: in the case of a strain-gage bridge with 100V pulses in lieu of a continuous 10V, one should bear in mind the possible mechanical effects and contribution to "creep" (see page 20) of a fast-rising 100V pulse applied to the low-impedance bridge. Also, the requirements for circuitry to implement an accurate measurement while minimizing electromagnetic interference are not trivial.

†Analog Devices manufactures a wide variety of useful products for these applications. Examples of products in these categories that the reader may meet later in this volume include the AD521 and AD522 instrumentation amplifiers, Models 261 and AD517 op amps, 2B31 signal conditioners, 2B20 and 2B22 voltage to current-loop transducers, Model 289 isolators, and the unique MACSYM intelligent Measurement And Control sub-SYsteM. Technical data on these and many other products are available from Analog Devices. A variety of other useful publications from Analog Devices are described in the first section of the Bibliography.

offset, drift, time constants, maximum electrical ratings, and stray impedances, as well as any other germane considerations, can spell the difference between substandard and successful application of the device, especially in cases where high resolution and precision, or low-level measurements are involved.

TRANSDUCER CHARACTERISTICS

In this chapter, we will characterize a number of the more-common types of transducer. In the discussions to follow, some devices will be given cursory treatment, while others will be treated in some detail, in the interest of keeping this text to manageable size and serving the major part of the needs of the majority of our readers, an objective expressed in the Preface. For those who desire greater depth, some useful references with fanout are provided in the Bibliography. As noted in the Preface, the quantities to be measured (measurands) that will be discussed in this book are:

Temperature
Force
Pressure
Flow
Level

Temperature Transducers

Temperature is perhaps the most common and fundamental physical parameter an engineer is likely to be called upon to measure. The intimate relationship between processes–physical, chemical, and biological–and temperature, as an index of state, is a primary consideration, from the molecular level to the completed system. In electronics, no other physical phenomenon is as pervasive in its influence on circuitry and systems as is temperature. Consequently, there are a number of phenomena that can be called upon to perform electrical operations as a function of temperature. Those to be discussed here include thermal expansion (bimetallic elements and mercury-column switches), Seebeck voltage (thermocouples), resistance effects (RTD's and thermistors), and semiconductor junction effects (diodes and PTAT* current-output devices, such as the AD590).

The *bimetallic thermal switch* is perhaps the most elementary of

*Proportional To Absolute Temperature

electrical sensors. Devices of this type utilize metals with differing thermal coefficients of expansion to physically make or break an electrical contact at a preset temperature. Familiar examples are the sensors in thermostats used in heating, ventilating, and air-conditioning systems. Disc-shaped bimetallic elements are used to provide snap action (Figure 1-2). They will function from sub-zero temperatures to almost 300°C. Contacts are available in a variety of forms and will handle low-current *dry-circuit* switching as well as currents to beyond 15 amperes. In addition, the hysteresis of the switching point can be specified (for insensitivity to small temperature fluctuations), and the devices are inexpensive.

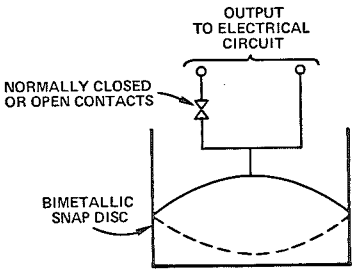


Figure 1-2. Bimetallic disc will snap into position indicated by the dotted lines at the transition temperature

Although the high mass of these units results in a slow thermal response, they are suitable for the many control applications in which temperature tends to change slowly, such as crystal ovens and gyroscopes. They are popular as temperature-limit and override sensors; and they are reliable. Manufacturers* include Elmwood Sensors, Fenwal, Texas Instruments' Klixon Division.

The *electrical-output mercury thermometer* is generically related to the bimetallic thermoswitch, because it relies on differential thermal expansion–in this case, a column of mercury in a glass stem. Fine wires extend into the path of the mercury column, which closes the circuit when the trip point has been reached (Figure 1-3). The trip point can be sharply defined, hysteresis is almost negligible, and life can be quite long (in a physically protected environment). Response time is 1 to 5 seconds (at the trip

*Companies named in these pages are representative manufacturers of the devices with which our transducer people have had the most experience. Mention here should not necessarily imply a recommendation. Buyers' Guides are available with more-complete listings and should be consulted. Some sources of vendor information are to be found in the Bibliography.

point), absolute accuracy to within 0.05°C is available, and multiple—or adjustable—contacts are standard options. These thermometers, with appropriate buffering are excellent choices for control applications and can control a load (that is properly designed) with stability to within 0.01°C. Units of this type can be obtained from P.S.G. Industries.

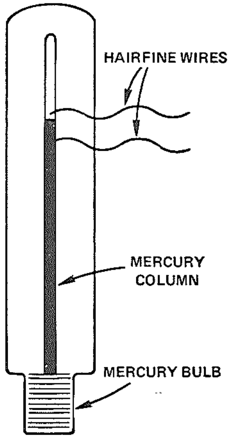


Figure 1-3. The electrical-output mercury thermometer. An electrical contact is established when the mercury column bridges the hairfine wires.

Since the contacts of these thermometers must pass low switching current (typically less than a few milliamperes), transistors, comparators, or sensitive relays can be used to sense the state of the contact closure and provide power for controlling an external device.

Thermocouples are economical and rugged; they have reasonably good long-term stability. Because of their small size, they respond quickly and are good choices where fast response is important. They function over temperature ranges from cryogenics to jet-engine exhaust and have reasonable linearity and accuracy.

Because the number of free electrons in a piece of metal depends on both temperature and composition of the metal, two pieces of dissimilar metal in isothermal contact will exhibit a potential difference that is a repeatable function of temperature. In general, these voltages are small. Table 1-1 lists a number of standard thermocouples, their useful temperature range, and the voltage swing over that range; it can be seen that the average change of voltage with temperature ranges from 7 to about 75μV/°C.

TABLE 1. SOME COMMON THERMOCOUPLES

Junction Materials	Typical Useful Temp Range (°C)	Voltage Swing Over Range (mV)	ANSI Designation
Platinum-6% Rhodium – Platinum-30% Rhodium	38 to 1800	13.6	B
Tungsten-5% Rhenium – Tungsten-26% Rhenium	0 to 2300	37.0	(C)
Chromel – Constantan	0 to 982	75.0	E
Iron – Constantan	-184 to 760	50.0	J
Chromel – Alumel	-184 to 1260	56.0	K
Platinum – Platinum-13% Rhodium	0 to 1593	18.7	R
Platinum – Platinum-10% Rhodium	0 to 1538	16.0	S
Copper – Constantan	-184 to 400	26.0	T

Since *every pair* of dissimilar metals in contact constitutes a thermocouple (including copper/solder, about 3μV/°C and Kovar/rhodium), and since a useful electrical circuit requires at least two contacts in series, measurements with thermocouples must be implemented in a manner which minimizes undesired contributions of incidental thermocouples and provides a suitable reference.

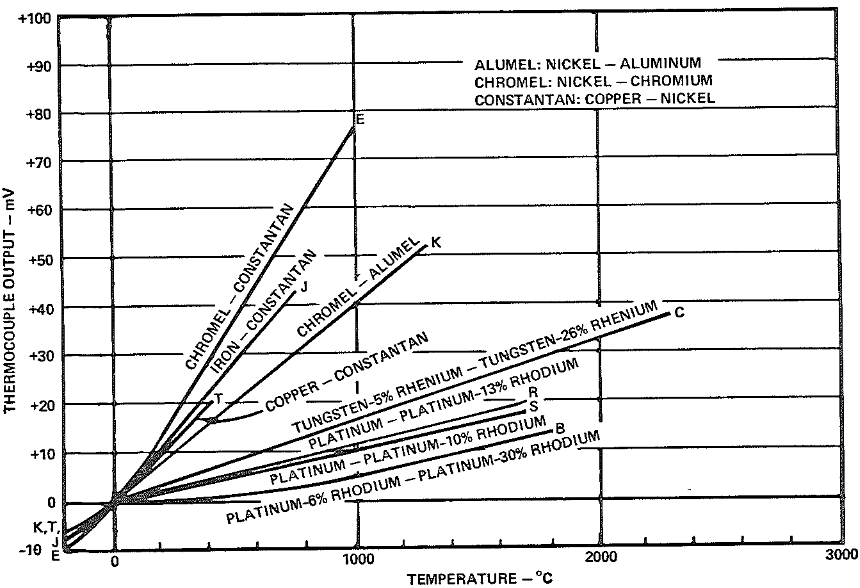
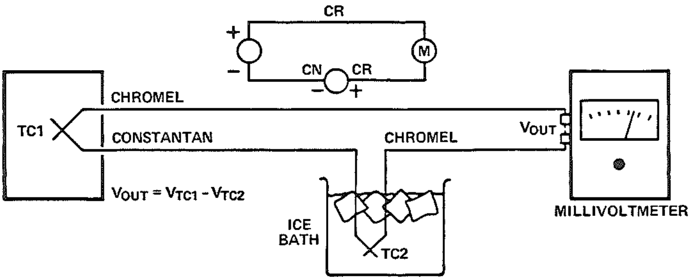
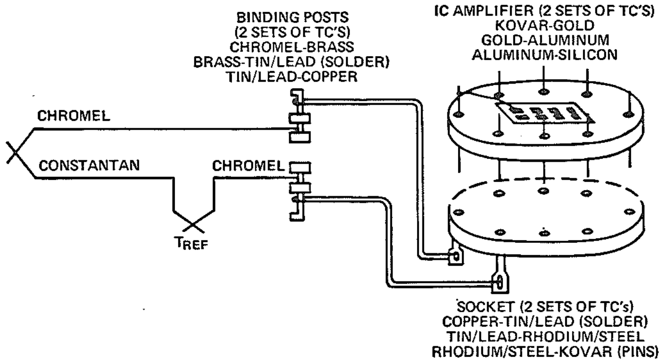


Figure 1-4. Output Characteristics of Thermocouples

Figure 1-4 is a comparative plot of thermocouple output as a function of temperature, referred to a 0°C fixed-temperature reference junction. Figure 1-5a shows a circuit for making a measurement with a thermocouple, using an ice bath to maintain the reference junction at 0°C. Figure 1-5b shows the large number of possible thermocouples in series in a simple circuit.



a. Simple temperature measuring circuit using an ice bath at the reference junction. Thermocouple measurements are inherently differential.



b. The twenty thermocouples in series in a two thermocouple measuring circuit

Figure 1-5. Basic thermocouple circuits

Because thermocouples are low-level (albeit low-impedance) devices, signal conditioning is not a trivial matter. The millivolt-level signals call for low-drift relatively expensive electronics if resolutions better than 1°C are required. Linearity in many types is poor, but the relationships are predictable and repeatable, so either analog or digital techniques can be used for linearizing downstream.

Providing a suitable temperature reference and minimizing the effects of unwanted thermocouples may prove challenging. Techniques include physical references (ice-point cells at +0.01°C, which are accurate and easy to construct but unwieldy to maintain); ambient-temperature reference junctions (acceptable so long as the ambient temperature range in the vicinity of the reference junction is smaller than the desired resolution of the temperature being measured); and electronic cold-junction compensators, which provide an artificial reference level and compensate for ambient temperature variations in the vicinity of the reference junction* (this technique requires careful attention to both the electronics and the physical configuration at that location). Examples of electronic references, which offer good accuracy and require minimal maintenance, will be discussed in Chapter 5 and the Applications section.

The *RTD (Resistance Temperature Detector)* is an electrical circuit element consisting of a solid conductor, usually in the form of wire, characterized by a positive coefficient of resistivity. Platinum, nickel, and nickel-iron alloy are the types in widest use. In general, RTD's are low-level, nonlinear devices with potentially excellent stability and accuracy, when properly implemented and instrumented. Table 1-2 compares several RTD materials.

TABLE 1-2 CHARACTERISTICS OF COMMONLY USED RTD MATERIALS

Material	Temp Range °C	≈T.C.%/°C @ 25°C
Platinum	-200 to +850	0.39
Nickel	-80 to +320	0.67
Copper	-200 to +260	0.38
Nickel-Iron	-200 to +260	0.46

Platinum resistance wire has been generally acknowledged as the standard for accuracy and repeatability in a temperature sensor; it is the standard interpolation device between critical temperatures from -259°C to 631°C. Some units have histories of years of agreement to within a millidegree of reference devices at the calibration facilities at the U.S. National Bureau of Standards. These generic cousins of wirewound resistors are heavily relied upon in transfer-type measurements; though nonlinear, in a predictable way, they can provide linearity to within several degrees over 100°C spans. Operation from -250°C to +850°C is feasible. Units used for standards laboratories can have absolute accuracies to within ±0.001°.

Platinum RTD's are available in ranges from tens of ohms to kilohms with a temperature coefficient of about 0.4%/°C of the resistance value at 25°C. Because they are wirewound, they tend

*In addition to producing a number of modular and system products incorporating cold-junction compensation, Analog Devices expects to have announced a monolithic-IC cold-junction-compensator-preamplifier during 1980.

to be physically large; but platinum-film versions not much larger than 1/8-watt resistors are available at low cost. Platinum sensors for industrial applications have performance approaching that of the standards, but at considerably lower cost. A good industrial sensor can be purchased for much less than $100; a standard with documented history can cost thousands.

Since resistors dissipate energy, platinum sensors require attention to dissipation limitations. Manufacturers provide data on allowable power dissipation for a given accuracy level. The relatively low resistance of platinum sensors requires that the designer consider the potentials used for excitation in voltage dividers or bridges to avoid excessive dissipation. At the same time, the designer must also consider the resistance of the lead wires to the point of measurement. Not only will they have voltage drops; they also have different temperature coefficients. In many cases, current drive, with a separate set of leads carrying no current to measure the voltage directly across the device, is essential.

As noted earlier, platinum is not the only metal used for RTD's, although its high resistance, wide temperature range, and high stability are essential for many applications. Nickel, for example, is popular because it has a relatively high sensitivity (nearly twice that of Pt), is inexpensive, and is usable over a fairly wide range of temperatures. Copper's tempco is similar to that of platinum, but—because of its inherently low resistance—it is difficult to use for precision measurement without extraordinary instrumentation. Other metals, such as gold, silver, and wolfram (tungsten) could be used, in concept, but practical limitations (low resistance for Ag and Au, difficult fabrication for W) prohibit significant usage. RTD's made from a nickel-iron alloy are in use, featuring high resistance, usable tempco (about 0.46%/°C), and low cost. Platinum RTD's are now also available in the form of thin film on a ceramic substrate, for reduced size, increased ruggedness, and lower cost.

Thermistors (a contraction for *thermally sensitive resistors*) are electrical circuit elements formed of solid semiconducting materials that are characterized by a high negative* coefficient or resistivity. At any given temperature, a thermistor acts like a resistor; if the temperature changes because of internal dissipation or ambient temperature variations, the resistance changes reproducibly as a

*Though most thermistors have negative temperature coefficients, *positive-temperature-coefficient* (PTC) thermistors are available. Some are characterized by a sharply discontinuous response, useful in on-off control.

function of temperature, in a generally exponential fashion.

They are low in cost and have the highest sensitivity among common temperature transducers (Figure 1-6). At 25°C, a typical unit may have a resistance change of –4.5%/°C. They are manufactured in a range of values from tens of ohms to megohms at 25°C. The response curve is nonlinear but predictable. Typical commercially available sensors provide usable outputs from -100°C to +450°C. Some types can function at temperatures up to 1000°C, with limited accuracy, stability, and sensitivity. Like RTD's, their temperature is manifested electrically by a resistance change, often measured by a bridge circuit. Because of their high sensitivity, they are frequently the best choice in high-resolution measurement-and-control apparatus.

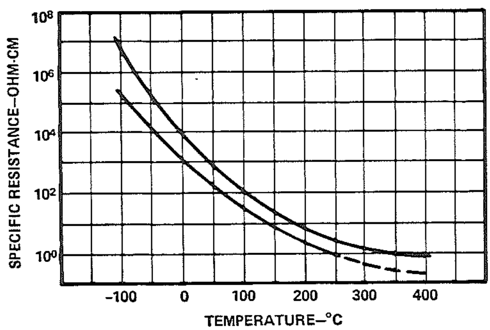


*Figure 1-6. Resistance versus temperature characteristic of two typical thermistor materials (*DESIGN NEWS *11/22/76)*

In the earliest days, thermistors acquired a reputation for being unpredictable and unstable devices, due to problems in manufacture and in application (self-heating effects, for example, could cause wide variations in reading and even thermal runaway). With increased user familiarity and modern manufacturing technologies (which include the production of linearized high-accuracy devices having somewhat less sensitivity and higher cost), they can be used with a great deal of confidence.

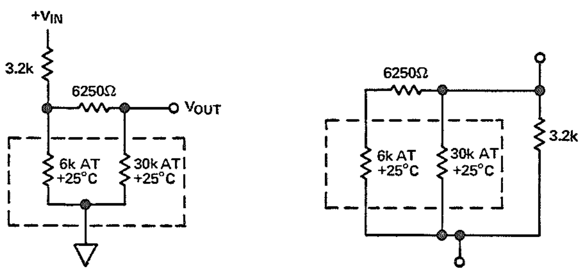
For example, the Yellow Springs YSI 44000-series sensors have interchangeability and uniformity to within 0.1°C from –40°C to +100°C and 0.2% from -80°C to +150°C, with cost less than $12*. Thermometrics makes devices that have accuracy and long-term-stability specifications comparable with those of platinum

*At the time this was written. Because prices vary, readers should consider any prices mentioned here as indicative of relative (rather than absolute) cost.

(at comparable cost) but with greater sensitivity, thus simplifying the signal conditioning. Absolute accuracy can run to within 0.01°C from 0°C to 60°C.

Thermistors are generally quite small and fast response is a typical feature. A common *bead* unit may have a time constant measured in seconds, while small *flakes*, such as those manufactured by Veeco, can respond in milliseconds.

Linearized thermistors have two or more devices in a single package, used with fixed resistors, to provide output potentiometrically (3-terminal network) or as a linear resistance variation, as Figure 1-7 shows. Thermistors are well-suited to sensitive bridge-type measurements because of their high (and selectable) impedance. As with RTD's, thermistors have dissipation limitations which must be observed if desired optimum performance is to be obtained, since internal heating affects accuracy. On the other hand, self-heating is used in feedback null-type linearity-independent measurements.



a. Voltage divider *b. Variable resistor*

Figure 1-7. Linearized thermistors. Fixed resistors and two thermistors are arranged in a network (Yellow Springs Inst. CO 44000 series) to provide linear, accurate response. In "A" the network has three terminals and functions as a temperture dependent voltage divider. In "B" the same network is used in the two-terminal mode to provide a linear shift in resistance vs. temperature.

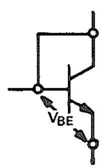
Semiconductor Sensors, generally based on the temperature sensitivity of silicon devices, are economical and available in many forms.* We will limit the discussion here to devices having two terminals, since they are usually the most suitable devices for remote measurement. The three classes of device to be mentioned

*Some circuit designers are convinced that there are too many incidental forms!

are bulk resistors (e.g., "Tempsistors"), diodes, and integrated circuits (e.g., the AD590).

The simplest form of semiconductor temperature sensor consists of a piece of bulk silicon. Devices of this type are available at low cost. They feature a positive temperature coefficient, about 0.7%/°C, and linearity to within ±0.5% from −65°C to 200°C. Nominal resistance ranges from 10Ω to 10kΩ, with tolerances from 1% to 20%. Physically, they look like 1/4-watt resistors. Since operation is specified at zero power (i.e., with no current flowing through the device), self-heating effects must be taken into account. Like other resistive devices, silicon resistors may be used in bridge circuits.

Junction semiconductor devices are well-suited to temperature measurement. The junction potential of silicon transistors and diodes, though differing from device to device, changes at about 2.2mV/°C over a wide range of temperature and can be used as the basis of an inexpensive sensor having fast response. Since diode voltage is also a function of current, the source of excitation may be a constant current. Figure 1-8 shows the relationships between temperature and V_{BE} for Motorola MTS105-series devices having several initial values of V_{BE}. In order to obtain accurate output, the diodes must be either calibrated or used in matched pairs in bridge-type circuits; though diodes are low in cost, these considerations make them less competitive.



1. Determine Value of TC:
2. Determine the V_{BE} Value at the Extremes, −40°C and +150°C:
3. Plot the V_{BE} Versus T_A Curve Using Two V_{BE} Values: $V_{BE(-40°C)}$, $V_{BE(25°C)}$, or $V_{BE(+150°C)}$.
4. Given Any Measured V_{BE}, the Value of T_A Can Be Read from the Above Curve, or Calculated from Equation 2.

(1) $TC = -2.25 + 0.0033\,(V_{BE} - 600)$

(2) $V_{BE(T_A)} = V_{BE(25°C)} + (TC)(T_A - 25°C)$

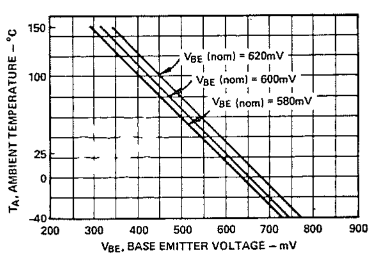
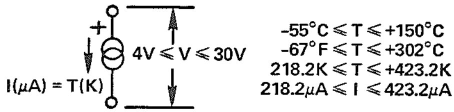


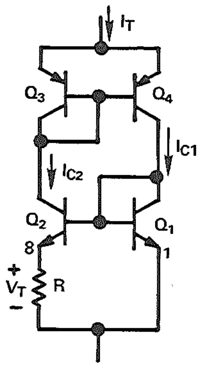
Figure 1-8. Using a diode as a temperature sensor: Motorola MTS105 series

Two-terminal temperature-sensitive current sources in the form of monolithic IC's are exemplified by the Analog Devices AD590.

Available in cans, miniature flat packages, chip form, and stainless steel probes, it is a current source which passes a current numerically equal (microamperes) to absolute temperature (kelvin), when excited by a voltage from +4V to +30V (Figure 1-9a), at temperatures from –55°C to +150°C. Figure 1-9b is a simplified schematic, which shows how it works. Figure 1-9c shows how it might be simply used to implement a remote measurement.



a. AD590 as a 2-terminal device



ASSUMING PERFECT TRANSISTORS, THE CURRENT MIRROR Q3-Q4 ENFORCES THE DIVISION OF I_T INTO TWO EQUAL CURRENTS, I_{C1} AND I_{C2}. Q2 CONSISTS OF 8 TRANSISTORS IDENTICAL TO Q1, CONNECTED IN PARALLEL. THEREFORE, THE CURRENT DENSITY IN Q1, J_1, IS 8X THE CURRENT DENSITY IN Q2, J_2.

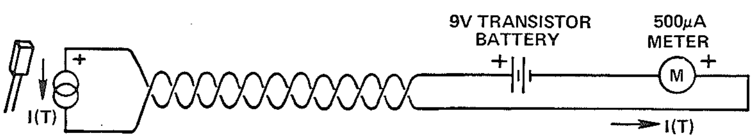
SINCE THE DIFFERENCE BETWEEN THE V_{BE}'S OF TWO IDENTICAL TRANSISTORS WITH DIFFERENT COLLECTOR CURRENTS IS PROPORTIONAL TO ABSOLUTE TEMPERATURE (PTAT), i.e.

$$V_T = V_{BE1} - V_{BE2} = \frac{kT}{q} \ln \frac{I_1}{I_2} = \frac{k}{q} (\ln 8)\, T = 179 \times 10^{-6} T \text{ VOLTS}$$

V_T, THE VOLTAGE ACROSS R, IS THUS PROPORTIONAL TO ABSOLUTE TEMPERATURE; THEREFORE, THE CURRENT THROUGH R, I_{C2}, MUST ALSO BE PTAT, AND, SINCE $I_T = 2\, I_{C2}$, THE TOTAL CURRENT THROUGH THE DEVICE, I_T, MUST ALSO BE PTAT.

IF R = 358Ω, $I_T/T = 1\mu A/K$.

b. How the AD590 works—simplified circuit



c. Simple implementation of the AD590

Figure 1-9. Absolute temperature-to-current IC transducer

The AD590 has a standardized (1μA/K) output (in several accuracy grades—see Appendix); it embodies an inherently linear relationship and is easy to use, not requiring bridges, low-level voltage measurement, or linearizing circuitry. Since its output is a current, long leads may be used without errors due to voltage drops or induced voltage noise; and since it is a high-impedance current source, it is insensitive to excitation voltage (in order to minimize self-heating effects, use the lowest excitation voltage consistent with the desired output voltage and expected line drops; however, even in the worst case, the maximum dissipation is only 13mW).

It may be worth noting that digital meters (AD2040) and scanners (AD2038), for directly instrumenting measurements in kelvin, °F, and °C, are available from Analog Devices. Measurements in °C are implemented by subtracting (in effect) a fixed current of 273.2μA; measurements in °F require subtraction of 255.4μA* and scaling by 9/5. Differential Celsius measurements with reference to any fixed temperature are obtained by subtracting a current numerically equal to the absolute (kelvin) equivalent of that temperature.

Force Transducers

The most popular electrical elements used in force measurements include the resistance strain gage, the semiconductor strain gage, and piezoelectric transducers; they are described briefly below. In general, the strain gage measures force indirectly by measuring the deflection it produces in a calibrated carrier; the piezoelectric transducer responds directly to the force applied. Implementation in bridges will be described in the next chapter; and further details of their application will be found in the descriptions in the Applications section.

The *resistance strain gage* is a resistive element which changes in length, hence resistance, as the force applied to the base on which it is mounted causes stretching or compression. It is perhaps the most well-known transducer for converting force into an electrical variable.

Unbonded strain gages consist of a wire stretched between two points. Force acting on the wire will cause the wire to elongate or shorten, which will cause the resistance to increase or decrease ($R = \rho L/A$, $\Delta R/R = K\Delta L/L$, where K is the gage factor†).

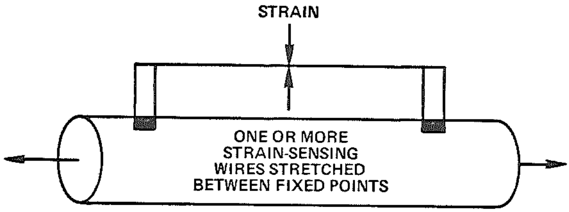
Bonded strain gages consist of a thin wire of conducting film arranged in a coplanar pattern and cemented to a base or carrier.

*$°C = K - 273.2$, and $°F = \frac{9}{5}°C + 32°$. Hence,

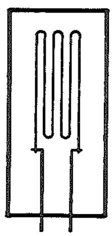
$°F = \frac{9}{5}(K - 273.2 + \frac{5}{9} \circ 32°) = \frac{9}{5}(K - 255.4°)$

†Gage factor is a function of the conductor material, ranging from a minimum of 2.0 to 4.5 for metals and more than 150 for semiconductors.

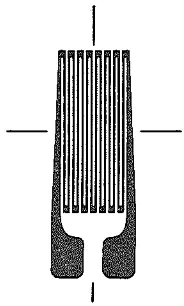
The gage is normally mounted so that as much as possible of the length of the conductor is aligned in the direction of the stress that is being measured. Lead wires are attached to the base and brought out for interconnection. Bonded devices are considerably more practical and are in much wider use than the unbonded devices. Figure 1-10 shows several typical patterns in use.



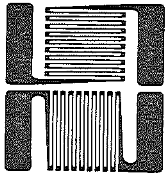
a. Unbonded strain gage



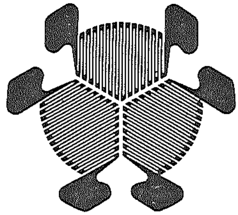
b. Bonded wire strain gage



c. Foil strain gage



d. 2-Element rosette 90° planar foil strain gage



e. 3-Element rosette 60° planar foil strain gage

Figure 1-10. Strain gages. Multiple-element rosettes measure components of strain in different directions. For example, the elements at 90° can measure magnitude and direction of stretch. Many patterns with various numbers and configurations of elements are available. (Courtesy of BLH Electronics—SR-4 Strain Gage Handbook)

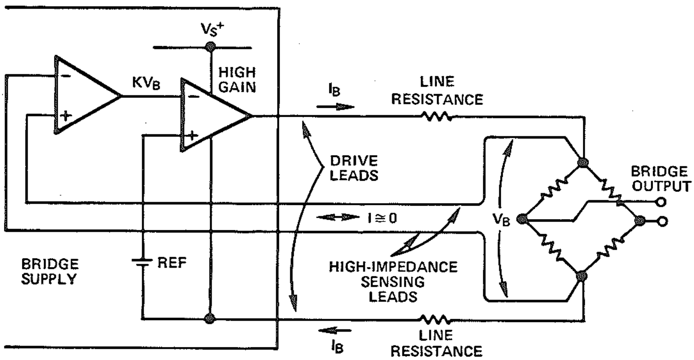
A great deal of effort has been devoted to making the strain gage the reliable and stable device it is today. Though the relationship between mechanical strain and electrical resistance change was observed by Lord Kelvin in 1856, more than 75 years elapsed before the effect was utilized in high-performance devices. Perhaps the most popular modern adaptation is the foil-type gage, produced by photo-etching techniques, and using similar metals to the wire types (alloys of copper-nickel (Constantan), nickel-chromium (Nichrome), nickel-iron, platinum-tungsten, etc.).

Gages having wire sensing elements present a small surface area to the specimen; this reduces leakage currents at high temperatures and permits higher isolation potentials between the sensing element and the specimen. Foil sensing elements, on the other hand, have a large ratio of surface area to cross-sectional area; they are more stable under extremes of temperature and prolonged loading. The large surface area and thin cross section also permit the device to follow the specimen temperature and facilitate the dissipation of self-induced heat.

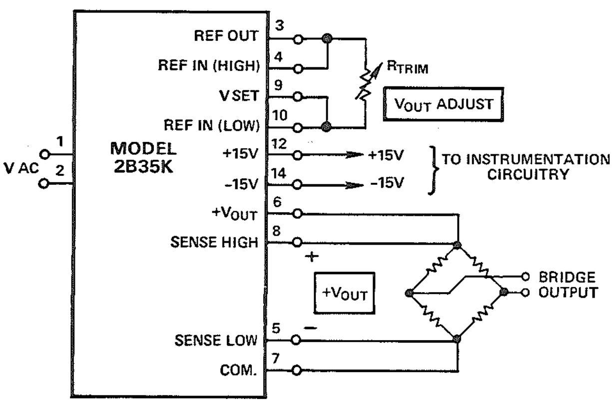
The *load cell* is a commonly used form of strain-gage-based transducer. It converts an applied force (weight) into a bridge output potential. In a load cell, the strain gage is mounted on some form of mechanical sensing element (column, beam, etc.), and the gage (or gages) is (are) usually wired into a bridge configuration. Compensation for temperature and nonlinearity is provided for by the manufacturer in the selection of resistance values for the arms of the bridge and in series with the bridge.

Strain gages are low-impedance devices; they require significant excitation power to get output voltage at reasonable levels. A typical strain-gage-based load cell will have a 350Ω impedance and is specified as having a sensitivity in terms of *millivolts per volt of excitation at full scale*. The maximum excitation potential, as well as the recommended potential, will be specified. For a 10V device with a rating of 3mV/V, 30 millivolts of signal will be available at full-scale loading. The output can be increased by increasing the drive to the bridge, but self-heating effects are a significant limitation to this approach: they can cause erroneous readings or even device destruction if prolonged.

The low output of load-cell transducers in most cases is due to the small shifts of resistance in the strain gages. However, while this is a severe constraint on gain, it is a boon to linearity (as will be shown, the output of a bridge is linear only for small changes in resistance, in the most-frequently used configurations, even if the gage resistance-change is perfectly linear with applied force). The low impedance employed in strain-gage bridges may require remote sensing for fixed excitation. Because the bridge operates off-null, shifts or inaccuracies in the excitation voltage will contribute directly to shifts in the bridge output. The low impedance of the bridge means that voltage drops in the wires leading to the bridge input can contribute significantly to variations in excita-



a. Basic scheme. Voltage across bridge terminals is compared with reference; high-gain feedback loop causes output of bridge supply to be at whatever voltage is necessary for null ($V_{REF} - KV_B = 0$) at comparator input, hence $V_B = V_{REF}/K$



$+V_{OUT}$ (V) ±3%	R_{TRIM}* (kΩ)
1	0.34
3	1.15
5	2.26
7.5	4.42
10	8.06
12	14.0
15	54.9

*25ppm/°C OR BETTER

b. Regulated excitation voltage, from +1V to +15V, using the 2B35 transducer supply

Figure 1-11. Remote bridge drive using voltage sensing tion, hence error. To correct this, manufacturers often employ four-wire (Kelvin) connections to the bridge input. Two wires carry the bridge current, and two wires sense the actual voltage at the bridge; the fed-back voltage is compared with the reference, and the power-supply output is adjusted to whatever voltage is necessary to maintain the bridge voltage at the desired value (Figure 1-11).*

Load cells are manufactured in capacities ranging from pounds to kilotons (kg to Gg). Response time is usually limited to periods measureable in tenths of seconds. Responses also may have "long tails" due to *creep*, a small, persistent change in cell output well after the output of the load cell has apparently settled in response to a step input; the phenomenon is analogous to dielectric absorption in capacitors. It is usually unimportant, except for high-precision measurements.

The output of the load-cell bridge is usually trimmed to furnish a small degree of offset for zero input; the magnitude and polarity of the offset are specified (e.g., an offset specification might read: "Offset +1mV – 0". The interface designer can then be sure that all load cells of this type will have offsets of the same polarity, a fact that simplifies the zero-adjustment in the interface. Linearity, temperature coefficients, overrange capability,† and other self-explanatory specifications are usually provided. Typical manufacturers of load cells are BLH Electronics, NCI, and Transducers, Inc.

Semiconductor strain gages make use of the resistance change in semiconductor materials in order to obtain greater sensitivity and higher-level output. Such bridges may have 30 times the sensitivity of bridges employing metal films, but they are temperature-sensitive and are not easy to compensate. They have not come

*The 2B31 signal conditioner and the 2B35 transducer power supply both utilize sense feedback for precision voltage or current excitation.

†It is common to specify the maximum static load which will not damage the device. However, it is worth noting that transient loading must also be considered. A 150-pound-maximum-load transducer, which will be damaged by a 300-lb static load might also be damaged by a 75-lb load dropped it from a distance of one or two feet, since the instantaneous force developed by rapid deceleration from the speed reached due to gravitational pull may greatly exceed the specification. This is not exactly an academic afterthought: if one considers the instantaneous force generated by dropping a large pumpkin on an inadequately damped supermarket electronic scale, one can appreciate the plight of a scale manufacturer (perhaps legendary) who suffered a flurry of warranty replacements after a disastrous Halloween season. Cures for such situations might include more-adequately specified load cells, increased damping, or mechanical stops.

into as widespread use as the more stable metal-film devices for precision work; however, where sensitivity is important and temperature variations are not great, and in null-type measurements where the bridge is always in balance, they may have some advantage. Instrumentation is similar to that for metal-film bridges but is less critical because of the higher signal levels and decreased transducer accuracy.

Piezoelectric force transducers are employed where the forces to be measured are dynamic (i.e., continually changing over the period of interest—usually of the order of milliseconds). These devices utilize the effect discovered by Pierre & Jacques Curie in 1880, that changes in charge are produced in certain materials when they are subjected to physical stress. Piezoelectric devices produce substantial output voltage in instruments such as accelerometers for vibration studies. Output impedance is high, and charge amplifier configurations, with low input capacitance, are required for signal conditioning.

The output of a piezoelectric transducer may be modeled as a voltage source in series with a small capacitor. Step inputs of physical force result in an effective capacitance change. When instrumented with feedback amplifiers (op amps), as in Figure 1-12, the summing-point voltage is held at zero, and the change in charge is effectively transferred to the feedback capacitor, developing an output voltage at low impedance. The output of this circuit is inversely proportional to the value of feedback capacitance. Practical examples and considerations in the design of the charge amplifier appear in the Applications section. Manufacturers of piezoelectric devices often furnish calibrated charge amplifiers, cables, and other accessories.

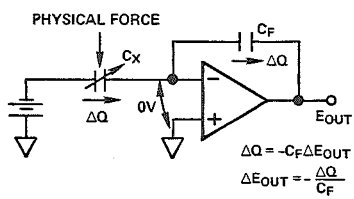


Figure 1-12. Charge Amplifier—commonly used in piezoelectric accelerometers

Piezoelectric force transducers are available from Endevco, Columbia Research Labs, Kistler Instrument Corporation, and others.

Pressure Transducers

Pressures in liquids and gases are measured electrically by a variety of pressure transducers. A variety of mechanical converters, including diaphragms, capsules, bellows, manometer tubes, and Bourdon tubes, are used to measure pressure by measuring an associated length, distance, displacement, and to measure pressure *changes* by the motion produced. As with most transducers, a great deal of expertise (some would say, aided by witchcraft) is required to obtain a stable, accurate, linearly responding pressure transducer. The output of this mechanical interface is then applied to an electrical converter.

Rheostats and potentiometers are often used to convert linear or rotary motion to an electrical output. A rheostat, like a strain gage, simply produces a varying resistance over a range of pressure inputs. A potentiometer may be used as a pair of series arms in a linear-output bridge configuration. Temperature effects are minimized by the use of wirewound rheostats, but resolution may suffer as the wiper arm indexes between adjacent turns of multiturn wirewound elements. Conductive plastic and metal films achieve higher resolution at some cost in stability with temperature. Potentiometric elements provide good tracking, and temperature is not troublesome.

Strain gages are also used in pressure transducers. The mechanical output of the transducer produces a resistance change in a strain gage, which is configured electrically in similar manner to a load cell.

Piezoelectric pressure transducers are used for high-frequency pressure measurements. They are also employed in sound-level pressure measurement (and are better-known here as *crystal microphones*). Signal conditioning for piezoelectrics involves high-impedance (voltage mode) or charge-type amplifiers.

There are three general categories of pressure measurement—absolute, gauge, and differential (Figure 1-13). *Absolute*-pressure devices measure pressure with reference to zero pressure (i.e., vacuum). *Gauge* pressure is measured in relation to ambient (which may be standard sea-level atmospheric pressure, or an arbitrary level). *Differential*-pressure transducers measure the difference between two pressures (for example, across a valve or an orifice). In a sense, a gauge measurement is a special form of differential measurement in which one of the pressures, being ambient, does not require special provisions for connections.

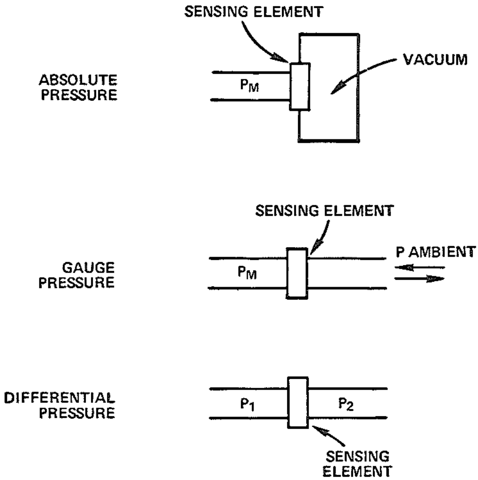


Figure 1-13. Three types of pressure transducer

Specifications regarding accuracy, temperature coefficient, linearity, etc., are usually self-explanatory or are defined by the manufacturer. The range of pressures may be unipolar ("pressure" or "vacuum") or bipolar (positive or negative), and the measurement may be offset to cover a limited range, for example 75-to-85psi. Piezoelectric types respond most readily to fast changes. In some applications, response to rapid changes is undesirable, and damping is provided ("noise filtering"). In many applications, changes are slow and considerations such as frequency or time response are irrelevant.

One of the most frequent sources of error in the application of pressure transducers is inappropriate application within a given medium. Many transducers are intended only for use with gases and liquids which are non-corrosive or in other ways benign to the transducer. The system designer should always determine from the manufacturer what substances may come into contact with the transducer (it may be necessary to place a buffer substance between the measurand and the transducer–a more common necessity than one might suspect, and one that is easily implemented.

Another frequently overlooked consideration is the temperature of the measurand. While the ambient may be at 30°C, the inlet temperature of the liquid or gas at the transducer might be 125°C, in which case transducer selection or rebudgeting of allowable error tolerances may be required.

Manufacturers include Rosemount, BLH, and others.

Flow Transducers

There are many ways of defining flow (mass flow, volume flow, laminar flow, turbulent flow). Since the "bottom line" of a flow measurement is the amount of the substance flowing that is useful for some purpose (e.g., the number of molecules of hydrocarbon available for combustion), the desirable measurement is most-often *mass flow* (kg/s); however, if the fluid's density varies but little, a *volume flow* measurement (m^3/s) is a useful substitute that is generally easier to perform. The measured flow may vary, depending on the type of sensor, where it is located in the stream and the way in which it interacts with the fluid. There are many ways of measuring flow, and we cannot even pretend to do lip service to them. However, it is important to note that electrical outputs in the form of voltage, current, or frequency tend to be handled in much the same way, irrespective of the physical mechanism involved in the measurement.

One commonly used class of transducers, which measure flow rate indirectly, involves the measurement of pressure. Flow can be derived by taking the differential pressure across two points in a flowing medium—one at a static point and one in the flow stream. *Pitot tubes* (Figure 1-14) are one form of device used to perform this function. The flow rate is obtained by measuring the differential pressure with standard pressure transducers, and calibrating (or otherwise dealing with) the nonlinear relationship.

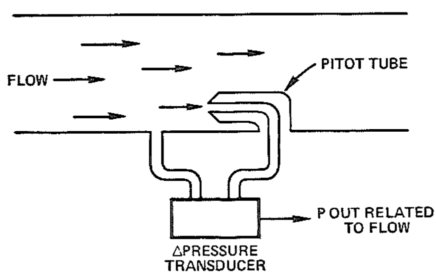


Figure 1-14. Pitot tube/static pressure flow measurement

Some transducers produce frequency signals. Examples include propellers, turbines, "positive displacement" meters, for accurate measurement of quantity, and various paddle-wheel arrangements, as well as vortex-shedding obstructions. The frequency signals, picked off electrically, optically, or magnetically, can be directly transduced to digital form.

The cantilevered vane (Figure 1-15A) is simple and amenable to strain-gage instrumentation. The hinged vane is also simple and works well with potentiometers (Figure 1-15b).

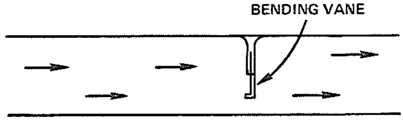


Figure 1-15a. Cantilevered vane flow meter

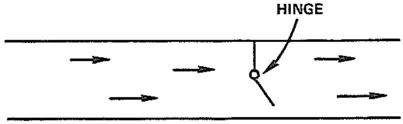


Figure 1-15b. Hinged vane flow meter

The application considerations for flow transducers using pressure transducers are the same as for the latter. Among frequency-output types, some require signal conditioning, while others have direct high-level pulses available at the output. Very low flow-rate detection with frequency-output devices is sometimes difficult or tedious because of the low resolution at low frequencies.

Anemometers comprise a special class of flowmeters, which are used almost exclusively to measure wind speed. Anemometers using propellors or cups usually drive some sort of tachometric device which interfaces to the readout. *Hot-wire* anemometers (and flowmeters) consist of a heated wire, supported at the ends, which loses heat to the fluid stream being measured. This convective loss varies approximately with the square-root of velocity. The resistance of the heated wire is measured and used to provide a readout. In another form of circuitry, a feedback circuit is employed to maintain the wire at constant temperature through self-heating; the power input to the wire is then a good measure of the wind speed, and response to changes in speed can be quite fast since only the electrical input power changes, not the temperature.[1]

[1]*Analog Dialogue*, Volume 5, No. 1, page 13, "Measuring Air Flow Using a Self-Balancing Bridge," by José Miyara

Hot-wire techniques have also been used to measure speed of ships through water.

Other types of flowmeters include electromagnetic and ultrasonic Doppler, especially for non-invasive measurements and for supersonic flow. They are generally supplied as complete instruments.

Level Transducers

A better name for these devices is "volume transducers", since level transducers are most-often used to measure the contents of containers. The best-known level transducer (except for the calibrated stick) is the float type, using in millions of automobile gas tanks. A float controls a potentiometer or a rheostat, which provides an electrical output. The output may be discrete as well as continuous, if the potentiometer is replaced by a set of switch contacts.

The liquid itself may be used as the "rheostat" if the conductance between two rods, immersed in the liquid, is measured (Figure 1-16a). Discrete level information may be taken similarly, as Figure 1-16b shows. Capacitance may also be used as the parameter. Measurements are ac-type (easy to amplify), and the method will work with conductive or nonconductive materials—wet or dry.

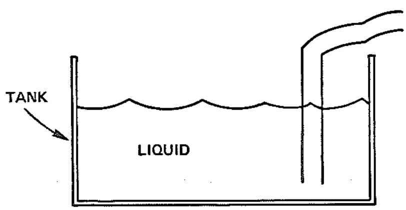


Figure 1-16a. Sensing level by sensing conductance or capacitance

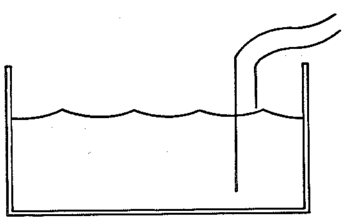


Figure 1-16b. Discrete level sensing

A popular method for discrete level detection involves the principle that the rate of heat transfer is much greater in a liquid than in a gas. Thermistors and other temperature detectors, if deliberately operated in a self-heating mode when surrounded by a gas, will show a pronounced shift in temperature reading when in contact with a liquid. This shift can be detected by simple electronic circuitry which produces contact closures or any desired form of indication.

Discrete sensing can be performed optically by detection of the state of an optical path (Figure 1-17). The presence of fluid causes scattering or absorption of light, which breaks up the optical path.

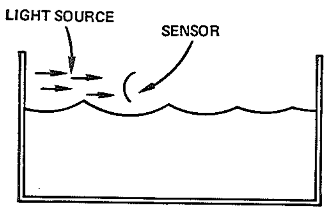


Figure 1-17. Discrete level sensing by optical scattering

Pressure transducers can be used to determine the level in a tank by measuring the differential pressure between the unoccupied area in the top of the tank and the liquid-covered area (Figure 1-18). The level will be directly proportional to the differential pressure for any given specific weight of liquid in the cylindrical tank. The electrical considerations for pressure transducers were described earlier in this chapter.

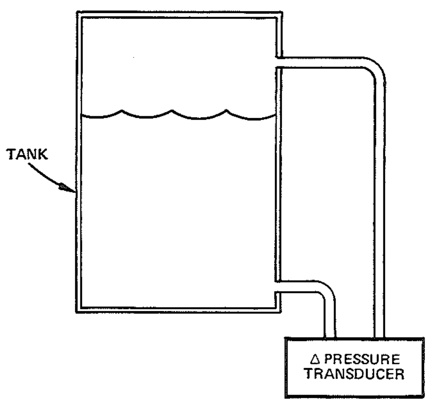


Figure 1-18. Level-by-differential pressure

In many systems, level (or *mass*) is sensed accurately by simply weighing the tank and subtracting the necessary offsets (*tare* in weighing terminology). Load-cell transducers are almost always used in such applications.

Acoustic (sonar) techniques, involving an echo-delay measurement are in use. The method works well with both liquids and solids, in both discrete and continuous versions. Another technique (among many) is a floating ring magnet surrounding a protective insulating vertical tube containing a string of magnetically operated reed relays; a thermal version of this utilizes a string of AD590 temperature sensors.

COMMON TRANSDUCERS SUMMARIZED

TYPE	TEMPERATURE ELECTRICAL I/O CHARACTERISTICS	COMMENTS
Thermoswitches	Switch closure. Simple on-off output	Many types available, covering a wide range of temperatures, contact configurations, and current-handling capabilities.
Thermocouples	Low source impedance, typically 10Ω. Voltage-output devices. Output shift is 10's of microvolts/°C. Outputs typically in the millivolts at room temperature.	Low voltage output requires low-drift signal conditioning. Small size and wide temperature range are advantages. Requires reference to a known temperature. Nonlinear response.
Platinum and other RTD's	Resistance changes with temperature. Positive temperature coefficient. Typical impedance (0°C) 20Ω to 2kΩ. Typical sensitivities 0.1%/°C to 0.66%/°C, depending on material.	Highly repeatable. Good linearity over wide ranges. Requires bridge or other network for typical interface.
Thermistors	Resistance changes with temperature. Negative temperature coefficient. Typical impedances (25°C) of 50Ω to 1MΩ available. Sensitivity at 25°C is about 4%/°C. Linearized networks available with with 0.4%/°C sensitivity.	Highest sensitivity among common temperature transducers. Inherently nonlinear (exponential function) but accurate linearized networks available.
Semiconductor sensors	Voltage, current, or resistance functions. Voltage types (diodes) require excitation current. Current types (AD590) require excitation voltage. Resistive types (bulk silicon) may use either type of excitation.	Many devices are uncalibrated and require significant signal conditioning. AD590 is calibrated, linear, and requires minimal signal conditioning.

FORCE

TYPE	ELECTRICAL I/O CHARACTERISTICS	COMMENTS
Strain gages (metal)	Resistance shifts with applied strain. Almost always used in bridge configuration. Typical impedance levels of 120Ω and 350Ω. Typical change is 0.1% over the whole range.	Resistance change with strain small compared to initial value of device resistance. Requires high-quality low-level signal conditioning.
Strain-gage bridge, load cell	Voltage output with applied strain. Requires excitation potential or current to drive the bridge. Typical excitation is from 5 to 15 volts.	Small voltage outputs require low-drift signal conditioning with good common-mode rejection to achieve any degree degree of precision. Output is linear.
Semiconductor strain gages	Bridge types are assembled from individual gages and have a voltage output. Bridge requires excitation, typically 5V to 15V.	More output than metal strain gages, but with increased non-linearity and sensitivity to temperature.
Piezoelectrics	True charge output device. Modeled as voltage source in series with capacitor. Physical input change produces corresponding charge change. AC and transient response only. Typical upper frequency limit is 20 to 50kHz. Typical output is 10^{-7} coulombs full-scale.	Requires low-bias-current charge amplifier configurations for signal conditioning. Responds to ac signals only.

PRESSURE

TYPE	ELECTRICAL I/O CHARACTERISTICS	COMMENTS
Rheostat/potentiometer	Resistance or ratio-of-resistance output. Requires voltage or current excitation. Typical impedance 500Ω to 5kΩ.	High-level easy-to-condition outputs are typical due to significant resistance or ratio
Strain gage	Resistance shift (single gage) or voltage output (strain-gage bridge). Requires excitation potential or current.	Small resistance change. Low-level signal requires good signal-conditioning amplifiers.
Piezoelectric	Charge output (see FORCE transducer chart).	See FORCE

FLOW

TYPE	ELECTRICAL I/O CHARACTERISTICS	COMMENTS
Pressure-based	See PRESSURE transducers	Pressure types measure flow by measuring ΔP between static and flow-caused pressure, or pressure drop across a constriction. Differential pressure transducers are used to avoid common-mode pressure errors. Response is nonlinear.
Frequency-output types: paddle wheels, rotary types, vortex types	Digital output derived from frequency output are common. Optical or magnetic pickups provide non-invasive measurements. Photocell has 100Ω to 100MΩ on-to-off ratio. Magnetic employs switching or open-collector transistor.	Some types are directly logic-level compatible. Others require impedance and/or voltage amplification, level-shift, and buffering before signal is usable.
Force-based	Typical forms use strain-gage bridges or potentiometer outputs. See PRESSURE and FORCE.	See PRESSURE and FORCE
Thermal	Use active temperature sensors to measure temperature changes caused by flow	See TEMPERATURE

LEVEL

TYPE	ELECTRICAL I/O CHARACTERISTICS	COMMENTS
Float	Resistor or potentiometer output. 100Ω to 2kΩ typical impedance.	Requires excitation (current, voltage) to achieve voltage output. High-level output due to large resistance swings.
Thermal	Resistive. Typical impedances 500Ω to 2kΩ.	Self-heated temperature sensor (thermistor) is used to detect discrete level changes. Abrupt resistance changes occur when liquid level drops to allow thermistor to be uncovered.
Optical	Resistive. Typical on-off impedances 100Ω to 100MΩ.	Optical occlusion or scattering blocks an opto-electronic path.
Pressure	See PRESSURE	Level information obtained by measuring pressure in unoccupied area in top enclosed tank vs. pressure in liquid-covered area.
Load cell	Contents of container measured by weighing	See FORCE