SECTION 4
STRAIN, FORCE, PRESSURE, AND FLOW MEASUREMENTS
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STRAIN GAGES

The most popular electrical elements used in force measurements include the resistance strain gage, the semiconductor strain gage, and piezoelectric transducers. The strain gage measures force indirectly by measuring the deflection it produces in a calibrated carrier. Pressure can be converted into a force using an appropriate transducer, and strain gage techniques can then be used to measure pressure. Flow rates can be measured using differential pressure measurements which also make use of strain gage technology.

Figure 4.1

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 as shown in Figure 4.2. Force acting on the wire (area = A, length = L, resistivity = ρ) will cause the wire to elongate or shorten, which will cause the resistance to increase or decrease proportionally according to:

$$R = \rho L/A$$

and

$$\Delta R/R = GF \cdot \Delta L/L,$$

where GF = Gage factor (2.0 to 4.5 for metals, and more than 150 for semiconductors).

The dimensionless quantity $\Delta L/L$ is a measure of the force applied to the wire and is expressed in *microstrains* ($1\mu\varepsilon = 10^{-6}$ cm/cm) which is the same as parts-per-million (ppm). From this equation, note that larger gage factors result in proportionally larger resistance changes, hence, more sensitivity.

Figure 4.2

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

Figure 4.3

Perhaps the most popular version 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. (see Figure 4.4). 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 and 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.

Figure 4.4

Semiconductor strain gages make use of the piezoresistive effect in certain semiconductor materials such as silicon and germanium in order to obtain greater sensitivity and higher-level output. Semiconductor gages can be produced to have either positive or negative changes when strained. They can be made physically small while still maintaining a high nominal resistance. Semiconductor strain gage bridges may have 30 times the sensitivity of bridges employing metal films, but are temperature sensitive and difficult to compensate. Their change in resistance with strain is also nonlinear. They are not in as widespread use as the more stable metal-film devices for precision work; however, where sensitivity is important and temperature variations are small, 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.

Figure 4.5

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 that changes in charge are produced in certain materials when they are subjected to physical stress. In fact, piezoelectric transducers are *displacement* transducers with quite large charge outputs for very small displacements, but they are invariably used as force transducers on the assumption that in an elastic material, displacement is proportional to force. 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. Conditioning a piezoelectric sensor output is discussed in further detail in Section 5.

Strain gages can be used to measure force, as in Figure 4.6 where a cantilever beam is slightly deflected by the applied force. Four strain gages are used to measure the flex of the beam, two on the top side, and two on the bottom side. The gages are connected in an all-element bridge configuration. Recall from Section 2 that this configuration gives maximum sensitivity and is inherently linear. This configuration also offers first-order correction for temperature drift in the individual strain gages.

Figure 4.6

Strain gages are low-impedance devices; they require significant excitation power to obtain reasonable levels of output voltage. A typical strain-gage based load cell bridge will have (typically) a 350Ω impedance and is specified as having a sensitivity in terms of millivolts full scale per volt of excitation. The load cell is composed of four individual strain gages arranged as a bridge as shown in Figure 4.7. For a 10V bridge excitation voltage 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. Many load cells have "sense" connections to allow the signal conditioning electronics to compensate for DC drops in the wires. Some load cells have additional internal resistors which are selected for temperature compensation.

Figure 4.7

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, or displacement, and to measure pressure changes by the motion produced. The output of this mechanical interface is then applied to an electrical converter such as a strain gage or piezoelectric transducer. Unlike strain gages, piezoelectric pressure transducers are typically used for high-frequency pressure measurements (such as sonar applications or crystal microphones).

Figure 4.8

There are many ways of defining flow (mass flow, volume flow, laminar flow, turbulent flow). Usually the *amount* of a substance flowing (mass flow) is the most important, and if the fluid's density is constant, a volume flow measurement is a useful substitute that is generally easier to perform. 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* are one form of device used to perform this function. The flow rate is obtained by measuring the differential pressure with standard pressure transducers as shown in Figure 4.9. Differential pressure can also be used to measure flow rate using the *venturi* effect by placing a restriction in the flow as shown in Figure 4.10. Figure 4.11 shows a bending vane with an attached strain gage placed in the flow to measure flow rate.

Figure 4.9

Figure 4.10

Figure 4.11

BRIDGE SIGNAL CONDITIONING CIRCUITS

An example of an all-element varying bridge circuit is a fatigue monitoring strain sensing circuit as shown in Figure 4.12. The full bridge is an integrated unit that can be attached to the surface on which the strain or flex is to be measured. In order to facilitate remote sensing, current excitation is used. The OP177 servos the bridge current to 10mA around a reference voltage of 1.235V. The strain gauge produces an output of 10.25mV/1000με. The signal is amplified by the AD620 instrumentation amplifier which is configured for a gain of 100. Full-scale strain voltage may be set by adjusting the 100Ω gain potentiometer such that, for a strain of –3500με, the output reads –3.500V; and for a strain of +5000με, the output registers a +5.000V. The measurement may then be digitized with an ADC which has a 10V fullscale input range. The 0.1µF capacitor across the AD620 input pins serves as an EMI/RFI filter in conjunction with the bridge resistance of 1kΩ. The corner frequency of the filter is approximately 1.6kHz.

Figure 4.12

Another example is a load cell amplifier circuit shown in Figure 4.13. A typical load cell has a bridge resistance of 350Ω. A 10.000V bridge excitation is derived from an AD588 precision voltage reference with an OP177 and 2N2219A used as a buffer. The 2N2219A is within the OP177 feedback loop and supplies the necessary bridge drive current (28.57mA). To ensure this linearity is preserved, an instrumentation amplifier is used. This design has a minimum number of critical resistors and amplifiers, making the entire implementation accurate, stable, and cost effective. The only requirement is that the 475Ω resistor and the 100Ω potentiometer have low temperature coefficients so that the amplifier gain does not drift over temperature.

Figure 4.13

As has been previously shown, a precision load cell is usually configured as a 350Ω bridge. Figure 4.14 shows a precision load-cell amplifier that is powered from a single supply. The excitation voltage to the bridge must be precise and stable, otherwise it introduces an error in the measurement. In this circuit, a precision REF195 5V reference is used as the bridge drive. The REF195 reference can supply more than 30mA to a load, so it can drive the 350Ω bridge without the need of a buffer. The dual OP213 is configured as a two op amp in-amp with a gain of 100. The resistor network sets the gain according to the formula:

$$G = 1 + \frac{10\text{k}\Omega}{1\text{k}\Omega} + \frac{20\text{k}\Omega}{196\Omega + 28.7\Omega} = 100\ .$$

For optimum common-mode rejection, the resistor ratios must be precise. High tolerance resistors (±0.5% or better) should be used.

For a zero volt bridge output signal, the amplifier will swing to within 2.5mV of 0V. This is the minimum output limit of the OP213. Therefore, if an offset adjustment is required, the adjustment should start from a positive voltage at V_{REF} and adjust V_{REF} downward until the output (V_{OUT}) stops changing. This is the point where the amplifier limits the swing. Because of the single supply design, the amplifier cannot sense signals which have negative polarity. If linearity at zero volts input is required, or if negative polarity signals must be processed, the V_{REF} connection can be connected to a voltage which is mid-supply (2.5V) rather than ground. Note that when V_{REF} is not at ground, the output must be referenced to V_{REF}.

Figure 4.14

The AD7730 24-bit sigma-delta ADC is ideal for direct conditioning of bridge outputs and requires no interface circuitry. The simplified connection diagram is shown in Figure 4.15. The entire circuit operates on a single +5V supply which also serves as the bridge excitation voltage. Note that the measurement is ratiometric because the sensed bridge excitation voltage is also used as the ADC reference. Variations in the +5V supply do not affect the accuracy of the measurement.

The AD7730 has an internal programmable gain amplifier which allows a fullscale bridge output of ±10mV to be digitized to 16-bit accuracy. The AD7730 has self and system calibration features which allow offset and gain errors to be minimized with periodic recalibrations. A "chop" mode option minimizes the offset voltage and drift and operates similarly to a chopper-stabilized amplifier. The effective input voltage noise RTI is approximately 40nV rms, or 264nV peak-to-peak. This corresponds to a resolution of 13 ppm, or approximately 16.5-bits . Gain linearity is also approximately 16-bits. Further discussion of this type of ADC can be found in Section 8.

Figure 4.15

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