Resistive Sensors

We will review resistive sensors and examine:

• The Basic Transduction Mechanism
• Some Example Sensors
• Strain Gage Focus
• Common Signal Conditioning Circuits

Prof. R.G. Longoria
March 30, 2000

Resistive Sensing Mechanism

• The measurand directly or indirectly alters the electrical resistance of a resistive element.
• Electrical resistance is a parameter that we use to relate voltage and current.
• Sensing takes advantage of changes in resistance to infer changes in others physical quantities.
• Keep in mind that: Resistance changes because of material or geometry changes.
Resistive Sensing

- For example, for the simple uniform conductor, 
  \[ R = \frac{\rho L}{A} \]
  with \( \rho \) the resistivity, \( L \) the length and \( A \) the constant cross-sectional area through which current flows. This is only for simple case, but it is helpful in understanding trends.

- **Resistance** is altered either by a geometric \((A, L)\) or material change \((\rho)\) in the resistive element.

- **Resistance** can be directly measured (by an ohmmeter) or through a signal conditioning circuit (e.g., a voltage-divider).

Potentiometric Sensors

- Basic circuit
- Input voltage
- Output voltage
- Resistance wire
- Sliding contact
- \( R = \frac{\rho L}{A} \)
- Angular slider
- Resistor (conductive) element:
  - Wire-wound
  - Cermet
  - Conductive plastic
- \( \Delta x \) defines resolution
Other R-Sensors

- Thermistors (temperature-sensitive), these are semiconductor type devices

- Light-dependent resistors (CdS, CdSe, and CdTe), react to light, increasing charge carriers make effective resistance of device decrease

A Resistive Level Sensor

Signal conditioning: ac -> dc
Piezoresistive Effect

- When the resistive (or conductive) material itself is elongated or compressed due to a mechanical input, there can be changes in the electrical conductive characteristics and this is referred to as a piezoresistive effect.

\[ \sigma \varepsilon = F \]

- Lord Kelvin provided such an insight in 1856 when he showed that the resistance of copper and iron wire change when the wires are subjected to mechanical strain.


\[ \varepsilon \equiv \frac{\Delta l}{l} \]

Strain Gages

Strain gages exhibit piezoresistive behavior, and are one of the most common ways to measure strain.

**Types**

- **unbonded wire** - basically a wire under strain (c. 1940s)
- **foil** - type shown to left (c. 1950s) are most common
- **semiconductor** (c. 1960s)
Piezoresistivity (1)

We know that for a conductor of uniform area, the resistance is given by,

\[ R = \frac{\rho l}{A} \]

where \( \rho \) is the resistivity (cm ohm), \( l \) is the length, and \( A \) is the cross-sectional area.

Under strain, the change in \( R \) is,

\[ dR = \frac{\partial R}{\partial l} dl + \frac{\partial R}{\partial A} dA + \frac{\partial R}{\partial \rho} d\rho \]

which for uniform \( A \) is,

\[ dR = \frac{\rho}{A} dl - \frac{\rho l}{A^2} dA + \frac{l}{A} d\rho \]

For typical conductors, the resistivity values in units of ohm mm\(^2\)/m are: Aluminum 0.0278, Pure Iron 0.1, Constantan 0.48, Copper 0.0172, Gold 0.0222, Tungsten 0.059, Manganese 0.423, Nickel 0.087.

Piezoresistivity (2)

The fractional change of \( R \) is of more interest, so we find,

\[ \frac{dR}{R} = \frac{dl}{l} - \frac{dA}{A} + \frac{d\rho}{\rho} \]

\[ \frac{dl}{l} = \text{fractional change in length} \]

\[ \frac{dA}{A} = \text{fractional change in area} \]

\[ \frac{d\rho}{\rho} = \text{fractional change in resistivity} \]
Piezoresistivity (3)

For a linearly elastic body,

$$\sigma_{xx} = F/A_o = E \cdot \varepsilon_x = E \cdot \frac{dl}{l}$$

where $E$ is the Young’s modulus. Recall

$$\varepsilon_x = \frac{dl}{l}, \quad \varepsilon_y = -\nu \frac{dl}{l}, \quad \varepsilon_z = -\nu \frac{dl}{l}$$

And for an area $A = w t$, the fractional change is,

$$\frac{dA}{A} = \frac{dw}{w} + \frac{dt}{t} = -2\nu \varepsilon_x$$

Recall that $n$ is Poisson’s ratio. Now the fractional change in $R$ is,

$$\frac{dR}{R} = (1 + 2\nu) \varepsilon_x + \frac{d\rho}{\rho} \varepsilon_x$$

Input a strain → Geometric → Material → Output a resistance change

Strain Gage Sensitivity

The Gage Factor, $G$

A measure of the “sensitivity” of a strain gage is given by the gage factor, which is defined as,

$$G = \frac{\text{fractional change in resistance}}{\text{fractional change in strain}}$$

Using the result we just found, we have,

$$G = \frac{1}{\varepsilon} \frac{dR}{R} = (1 + 2\nu) + \frac{1}{\varepsilon} \frac{d\rho}{\rho} \varepsilon_x$$

Typical values:
- 80% Ni, 20% Cr, $G = 2$
- 45% Ni, 55% Cu, $G = 2$
- Platinum, $G = 4.8$
- 95% Pt, 5% Ir, $G = 5.1$
- Semiconductor, $G = 70$ to $135$

“Piezoresistive effect”
More on Gage Types

- Strain gages come in many specialized forms and typically include a calibrated gage factor, G.
- Semiconductor strain gages have the highest values of G. These strain gages can have G values of 70 to 135, and they are typically very small. However, there are some disadvantages which include:
  - output is not linear with strain,
  - very temperature dependent,
  - usually have a much lower strain limit than metallic type,
  - more expensive than metallic type.

Strain Detection
Order of Magnitude Calculation

Consider a situation where the strain is on the order of 1 microstrain.

For a metallic foil strain gage with $G = 2$, $R = 120$ ohm,

$$\Delta R = G \cdot \epsilon \cdot R = 2 \cdot 1 \times 10^{-6} \cdot 120 = 0.0024 \Omega$$

You need to measure a 0.002% change in R!
How would you detect such a change?
Signal Conditioning for R-Sensors

- Direct ohmmeter measurement (circuit not in operation), voltage-divider, or ballast
- Wheatstone bridge
- Other Methods

\[ \text{Signal} \]

\[ \text{Wheatstone Bridge} \]

Signal Conditioning

- Provides a functional transformation needed for accurate and consistent measurement of electrical quantities that have very small changes.
- We will focus on the use of bridge circuits to perform a conversion from an impedance change into a voltage change.
Standard Bridge Configuration

Output DC voltage

\[ V_o = \left( \frac{R_2 R_4 - R_1 R_3}{(R_1 + R_3)(R_2 + R_4)} \right) V_s \]

Null condition is satisfied when:

\[ \frac{R_1}{R_2} = \frac{R_3}{R_4} \]

If all the gages have the same resistance, you can show:

\[ \frac{dv_s}{V_s} = \frac{dR_1 - dR_2 - dR_3 + dR_4}{R} = \frac{G}{4} (\varepsilon_1 - \varepsilon_2 - \varepsilon_3 + \varepsilon_4) \]

This equation can be used to guide placement of gages on a specimen.

Strain Gage Conditioners

Bridge completion must usually be accompanied by additional conditioning circuitry such as filtering and amplification.

There are several suppliers of off-the-shelf conditioners:

- Omega
- Micro Measurements
- Analog Devices
The Basic Strain Gage Measurement Process

The strain gage is part of a multi-stage process that generates a voltage signal proportional to the strain.

\[ \varepsilon \rightarrow G \cdot R \rightarrow \Delta R \rightarrow V_o \rightarrow V_{\text{amplified}} \]

- Sensing Mechanism
- Bridge
- Amplifier

5B38 Isolated, Wide-Bandwidth Strain Gage Input

Analog Devices 5B38