IDMIL - Input Devices and Music Interaction Laboratory
McGill University

Introduction to Strain Gage (SG) Technology

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About this talk

objective: present the essential theory about strain gages and some application aspects

topics:

- stress and strain analysis;
- strain gages technology (types, features);
- application aspects (applying SG, circuits, signals).

Strain Gage definition

Pallas-Areny, R and Wenster, J.G., 2001 say that

"Strain gages are based on the variation of resistance of a conductor or semiconductor when subjected to a mechanical stress"

Stress and strain analysis
Approaches

- **simulation/mathematic analysis:**
  - mainly numerical analysis, analytical analysis is limited;
  - high computational power required;
- **experimental:**
  - consists on applying a given load and then measure the strain, where:
  - load cells controls/measures the amount of force applied;
  - sensors experience the strain in a particular place;
  - both simultaneous data generate the stress strain curve.

Stress and Strain Analysis

Relationship

1. force is applied to a body:
   stress $\Rightarrow \tau = F/A$
2. the body deforms:
   strain $\Rightarrow \epsilon = \Delta L/L$

Modulus of Elasticity (Young)

relates strain and stress

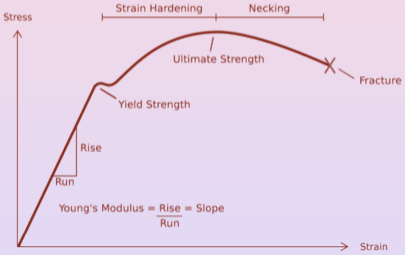

Figure: Stress-strain curve

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Poisson

negative ratio that relates the strain in the transverse direction to the strain in the longitudinal direction (force's direction)

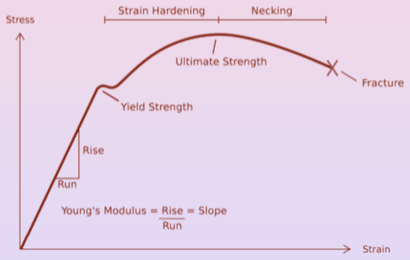

Figure: Stress-strain curve

Most common sensors to measure strain

piezoresistive SG: resistance changes related to strain

- conductive material: metallic SG;
- semiconductive material: mostly silicon;

piezoelectric SG: voltage generation when stressed (active sensor). Mainly used for dynamic applications;

vibrating wire: mechanical waves phenomenon (changes on vibration frequency according to the length of a stressed wire);

optical fiber: force/pressure cause micro-deformations on the fiber changing the light reflection. Good for high electromagnetic field environments.

Piezoelectric SG's Characteristics

Measuring principle

- "Electrical resistance changes when the material is mechanically deformed" (Fraden, J.,2004) ⇒ piezoresistive effect;
- Materials deform, elastically or plastically, when submitted to stress ⇒ mechanical property;
- Materials experience changes in size and shape due to temperature ⇒ temperature effect.

Metallic SG's Characteristics

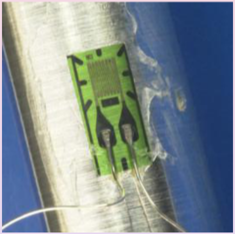

Figure: Metallic strain gage

Constructive aspects

- wire grid with several longitudinal segments and a large cross section;
- can be deposit over a foil that provides compensation for a given material (similar coefficient of thermal expansion).

Metallic SG's Characteristics

An electrical resistance of a conductor having length l, area A and resistivity ρ is:

$$R = \frac{\rho * l}{A} \tag{1}$$

If the wire experience a longitudinal load, both its dimensions, l and A, and resistivity ρ will change:

$$\frac{dR}{R} = \frac{d\rho}{\rho} + \frac{dl}{l} - \frac{dA}{A} \tag{2}$$

The dimensional variation, within the elastic limit obey the Hooke's Law ($\tau = E * \epsilon$):

$$\tau = \frac{F}{A} = E * \epsilon = E * \frac{dl}{l} \tag{3}$$

where τ is the mechanical stress, E the Young's Modulus, ϵ the strain.

Metallic SG's Characteristics

Also, according to Poisson, the transversal dimension t also changes according to the longitudinal load. Then:

$$\nu = -\frac{dt/t}{dl/l} \tag{4}$$

From this equation, one can calculate the partial differential for the area ($A = \pi * D^2/4$):

$$\frac{dA}{A} = \frac{2 * dD}{D} = -\frac{2 * \nu * dl}{l} \tag{5}$$

The applied stress also causes a variation on the vibration intensity in the metal lattice, which reduces the electron mobility. In metals, the Bridgmann's constant (C) relate the amount of variation of resistivity with the amount of variation of the volume.

$$\frac{d\rho}{\rho} = C * \frac{dV}{V} \tag{6}$$

According to (Pallas, 2004), for a conductor, isotropic, within the elastic limit, the amount of resistance variation is

$$\frac{dR}{R} = \frac{dl}{l} * [1 + 2\nu + C * (1 - 2\nu)] = GF * \frac{dl}{l} = GF * \epsilon$$

Semiconductor SG's Characteristics

- very small size and extremely delicate;
- due to the small dimension, the dimensional changes are negligible (l and A);
- instead, the semiconductor properties change (like number of carriers and average mobility), varying the resistivity;
- in opposite to metallic SG, the resistivity changes in semiconductor SG are greater than dimensional changes;
- the temperature plays an important role on changing the resistivity.

Semiconductor and Metallic SGs

Qualitatively Comparison

Gage Factor

Metallic: low, sensor should be applied next to the study point (more vulnerable to rupture);

Semiconductor: high, the application can be far from the possible rupture point (greater life cycle);

Application

Metallic: relatively easy to apply, depends on the size and foil layer presence;

Semiconductor: difficult, requires good quality tools, trained technician, time, patience and care;

Linearity

Metallic and Semiconductor: equivalent linearity, good for small strain (up to 10 $\mu m/m$);

Hysteresis

Metallic: worse, larger area to deform and larger adhesive area;

Semiconductor: better, because it's small and it has no base material;

Semiconductor and Metallic SGs

Qualitatively Comparison: Temperature

Temperature: the key question

Metallic: better, temperature varies the resistance of the sensor;

Semiconductor: worse, temperature varies both resistance and also gage factor of the sensor;

both: all of them require some kind of temperature compensation:

- thermal expansion coefficient (foil strain gages);
- *dummy* SG technique;
- full-bridge technique;
- controlled and stable temperature (impossible on real time applications).

Semiconductor and Metallic SGs

Quantitatively Comparison

Table: Typical characteristics of metallic and semiconductor strain gages (Pallas, 2004)

Parameter	Metallic	Semiconductor
Measurement range	0,1 μm/m a 50000 μm/m	0,001 μm/m a 3000 μm/m
Gage Factor	1,8 a 4,5	40 a 200
Nominal resistance (Ω)	120, 250, 350, 600, ..., 5000	1000 a 5000
Resistance tolerance	0.1% to 0.35 %	1 % to 2 %
Active grid length (mm)	0,4 a 150 (standard: 3 a 5)	1 a 5

General signal characteristics (metallic SG)

- maximum strain, in average: 4 $\mu\epsilon$ or 4 $\%_0$;
- considering no other influence, it's possible to predict that the resistance will have the same variation range;
- this small variation is not measurable by most of the multimeters, scopes and for take advantage of analog to digital converters full range (computer as HMI);

Conclusion

it's essential to have amplification and filtering circuits (conditioning circuits)

Wheatstone Bridge

- two voltage dividers in parallel;
- useful for (un)balance circuits;
- useful for measure relative quantities instead of absolute;
- there are four different topologies for WB:
  - quarter bridge: one variable element (SG) and three fixed resistances;
  - half bridge: two variable elements (SG) and two fixed resistances (two possible topologies);
  - full bridge: four variable elements (SG).

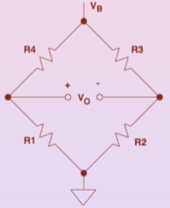

Figure: Wheatstone Bridge

Anderson's Loop

NASA's Wheatstone Bridge Alternative (www.vm-usa.com)

- it's a six-terminal dual-differential subtractor;
- subtractor's output is uninfluenced by any voltage that may exist between each differential input terminal pair ('n' individual circuits);
- equations are fundamentally linear for any change in circuit elements;
- wire voltage drops are simply ignored, not somehow compensated for by depending on actual wires to behave exactly alike in the measurement environment.
- Multiple sensing elements can be observed with respect to one or more reference elements by using multiple subtractors;
- once one sensor open, all output won't work properly;
- it's not that easy to design a good current power source.

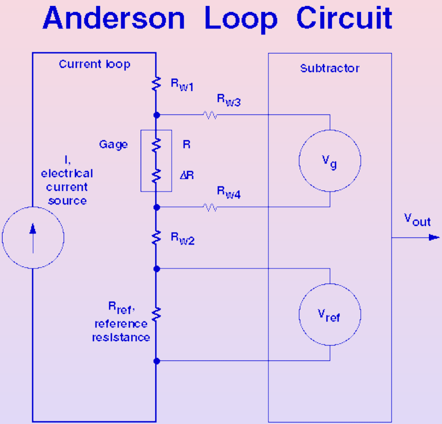

Figure: Anderson Loop Circuit

$$
\begin{aligned}
V_{out} &= V_g - V_{ref} \\
&= I * R_g - I * R_{ref} \\
&= I * (R + \Delta R) - I * R_{ref} \\
&= I * (R + \Delta R) - I * R \\
&= I * (R - R + \Delta R) \\
&= I * \Delta R
\end{aligned}
\tag{8}
$$

Compensations

Temperature, Wires and Remote Measurements

Temperature:
- self-compensating bridge topologies;
- dummy technique;

Wires:
- length (remote measurements);
- electromagnetic interference:
  - twisted pairs;
  - shielded cables;
- temperature: white cable;

Remote Measurements:
- amplification near the measurement point;
- (4 to 20) mA current transmission;

Other advanced techniques and features

- concentrate the stress in the measurement area;
- zero adjustment (adjust);
- optimal bridge excitation (avoiding self-heating and extreme power dissipation);
- errors and uncertainty analysis.

Quick reference guide

- Sensor and signal conditioning (Pallas, 2004);
- Unified Approach to the Engineering of Measurement Systems (Stein, P.K.)
- Introduction to Instrumentation and Measurements;
- Electronic Measurement and Instrumentation;
- Introduction to Mechatronics and Measurement Systems;
- Mechanical Measurements;
- Instrumentation and Control;
- Handbook of Transducers for Electronic Measuring Systems;
- Instrumentation for Engineering Measurements;
- Measurement Systems
- Measurement, Instrumentation, and Sensors Handbook;
- Your Successor to the Wheatstone Bridge? NASAs Anderson Loop.

Thank you for attending this talk

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acknowledge

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