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Sensor-Based Measure Systems

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Outline

- Transduction principles
- Resistive sensors
- Signal conditioning in resistive sensors
- Reactive sensors
- Signal conditioning in reactive sensors
- Digital sensors and smart sensors
- Interference and noise in amplifiers
- Special cases

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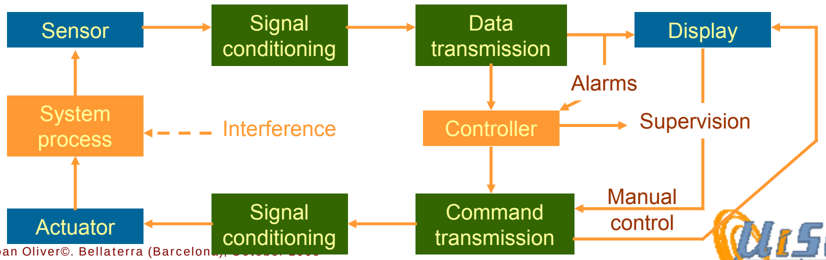
Transduction principles

- **Several terms:**
  - **Measure → Quantification of an object or event. It must be objective and empirical.**
  - **Transduction → Energy transformation of a physical class of energy to another one.**
  - **Sensor → Transductor device which output is an electrical energy class type**
- **Actually, people use the term 'sensor' as a generalised term, independently of the output type**
- **General sensing principles:**



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Sensor classification

	Types	Examples
Power-based	Modulators (passive!) Autogenerators (active!)	Thermistor Thermopar
Output-based	Analogue Digital	Potentiometer Position coder
Operation-based	Deflective Null type	Deflective accelerometer Servo-accelerometer

- **Any energy form can be represented through variables ...**

	Flux		Potential	
Relation	**Estate(y)**	**Rate (y'=dy/dt)**	**Estate(x)**	**Rate (x'=dx/dt)**
Mechanical translation	Momentum	Force	Velocity	Displacement
Mechanical rotation	Angular moment.	Torsion	Angular veloc.	Displacement
Electrical	Charge	Current	Voltage	Flux
Fluidic	Volume	Flux ratio	Pressure	-
Thermic	Heat	Heat variation	Temperature	-

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Static properties of the measure systems

- **Accuracy**
- **Precision: repeatibility + reproductibility**
- **Sensibility:** $S(xa) = \left.\frac{dy}{dx}\right|_{x=xa}$
- **Linearity/accuracy → hysteresis**
- **Systematic errors. The employed method affects the measure**
  - **Example: Measure of the potential decay in a resistance of tolerance 0.1%**

    Method 1: Using a voltmeter of 0.1% lecture accuracy → err = 0.1%

    Method 2: Using an ammeter of 0.1% lecture accuracy:

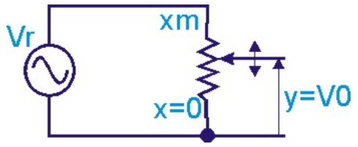
$$\frac{dV}{V} = \frac{R \cdot dI + I \cdot dR}{V} = \frac{dI}{I} + \frac{dR}{R} \Rightarrow \frac{\Delta V}{V} = \frac{\Delta I}{I} + \frac{\Delta R}{R} = \frac{0.1}{100} + \frac{0.1}{100} = 0.2\%$$

- **Random errors → As the number of measures increases it tends to 0**

Dynamic properties of the measure systems (I)

- **Response of the systems in front of input signals**
- **Dynamic error → Difference between the real value and the measured value with static error to 0**
- **Usually measured with transient inputs: impulse, step, ramp, ...**
- **It is necessary to obtain the transfer function to study the dynamic properties.**

- **Zero order systems**
  - **Transfer function: y(t) = k·x(t)**
    - k = static sensibility
    - dynamic errors and null delay are null
    - sensor without energy storage element



$$y = V_r \cdot \frac{x}{x_m} \Rightarrow k = \frac{V_r}{X_m}$$

Dynamic properties of the measure systems (II)

- **First order systems**
  - **Sensors have energy storage and dissipation elements**
  - **Transfer function:** $\frac{Y(s)}{X(s)} = \frac{k}{\tau s + 1}$ (from $a1 \cdot \frac{dy(t)}{dt} + a0 \cdot y(t) = x(t)$)
    - k = 1/a0 = static sensibility
    - τ = a1/a0 = time constant
    - ωc = 1/ τ = cut-off frequency (characterises the dynamic response)
    - Response to a step input(u(t)) → $k \cdot (1 - e^{-t/\tau})$
      with dynamic error: $e_d = y(t) - k \cdot x(t) = 0; \quad delay = \tau$
    - Response to a ramp input (r(t) = R·t) → $R \cdot k \cdot t + R \cdot k \cdot \tau \cdot u(t) + R \cdot k \cdot \tau \cdot e^{-t/\tau}$
      with dynamic error: $R \cdot (t + k \cdot (\tau - t)); \quad with \quad delay = \tau$

Example: Thermometer based on a mass M with specific heat C (J/(Kg·K)), with transmission area = A and heat transfer coefficient h (W/(m²·K))

$$h \cdot A \cdot (Te - Ti) \cdot dt - 0 = M \cdot c \cdot dTi$$

$$\frac{dTi}{dt} = \frac{h \cdot A}{M \cdot c} \cdot (Te - Ti)$$

Dynamic properties of the measure systems (III)

Second order systems

- **Transfer function:**

$$a_2 \cdot \frac{d^2 y(t)}{dt^2} + a_1 \cdot \frac{dy(t)}{dt} + a_0 \cdot y(t) = x(t)$$

$$\frac{Y(s)}{X(s)} = \frac{k \cdot \omega_n^2}{s^2 + 2 \cdot \xi \cdot \omega_n \cdot s + \omega_n^2}$$

  - static sensibility

$$k = 1/a_0$$

  - damping rate

$$\xi = a_1 / 2 \cdot \sqrt{a_2 \cdot a_0}$$

  - natural frequency

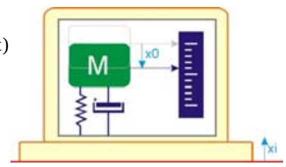
$$w_n = 2 \cdot \pi \cdot f \Rightarrow \omega_n^2 = a_0 / a_2$$

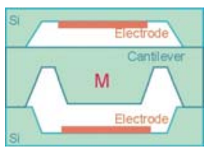
ξ = 1 → critical damping

ξ < 1 → subdamping

ξ > 1 → overdamping

- **Example (accelerometer)**





$$M \cdot (\ddot{x}_i - \ddot{x}_0) = k \cdot x_0 + B \cdot \dot{x}_0$$

Acceleration measure

$$\frac{X_0(s)}{\ddot{X}_i(s)} = \frac{X0(s)}{s^2 \cdot X_i(s)} = \frac{M}{K} \cdot \frac{K/M}{s^2 + s \cdot B/M + K/M} \rightarrow \begin{cases} k = M/K \\ \xi = B / 2 \cdot \sqrt{K \cdot M} \\ \omega n = \sqrt{K/M} \end{cases}$$

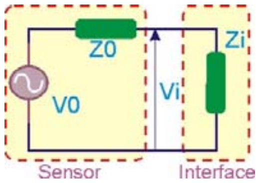
Displacement measure

$$\frac{X_0(s)}{X_i(s)} = \frac{M}{K} \cdot \frac{K/M \cdot s^2}{s^2 + s \cdot B/M + K/M}$$

Input and output impedances

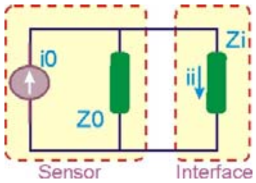
- **Sensor output impedance determines the measuring input circuit impedance:**
  - **An output in voltage demands a high input impedance in order to transport the sensor output voltage.**

$$Vi = \frac{Zi}{Zi + Zo} \cdot Vo$$



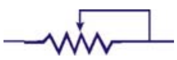
  - **An output in current demands a low input impedance in order to transport the sensor output current.**

$$Ii = \frac{Zo}{Zi + Zo} \cdot Io$$

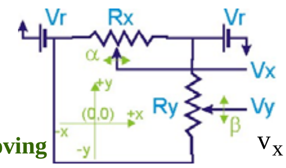


Resistive sensors (I)

- **Sensors based in the resistance variation. Several examples**
- **Potentiometers**

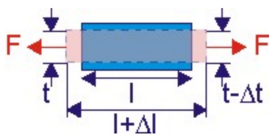


  - **Example: Joystick: two potentiometers moving in four quadrants: situation of a point in a plane**



$$v_x = V_r \cdot (1 - 2 \cdot \alpha)$$
$$v_y = V_r \cdot (1 - 2 \cdot \beta)$$

- **Strain gauges**



  - **Piezoresistive materials: Resistance variation of a conductor or semiconductors due to mechanical stress**

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

  - **In isotropic and elastic materials it is found (G=gauge factor, e=elastic deformation unit)**

$$\frac{dR}{R} = G \cdot \frac{dl}{l} = G \cdot \varepsilon$$

  - **If variations are small,** $R \cong R_0 \cdot \left(1 + G \cdot \frac{dl}{l}\right) = R_0 \cdot (1 + x)$

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Resistive sensors (II)

- **RTD's (Resistive Temperature Detectors)**
  - **Temperature detection by resistance variation**
  - **Example: Platinum temperature detectors (PTD)**

$$R = R_0 \cdot [1 + \alpha_1 \cdot (T - T_0) + \alpha_2 \cdot (T - T_0)^2 + \cdots + \alpha_n \cdot (T - T_0)^n]$$

R0 → Reference temperature resistance

α1, α2, αn → Coefficient measured at reference temperatures (0ºC, 100ºC, ...)

  - **Example: Metals used as RTD in lineal range**

$$R = R_0 \cdot [1 + \alpha_1 \cdot (T - T_0)], \quad \alpha = \frac{R_{100} - R_0}{(100^\circ C) \cdot R_0}$$

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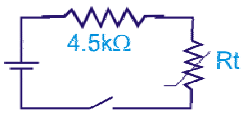
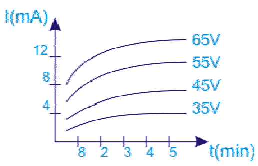
Resistive sensors (III)

- **Thermistor (Thermally Sensitive Resistor)**
  - **Resistance temperature dependent semiconductors**
  - **They could be positive temperature coefficient (PTC) or negative temperature coefficient (NTC) thermistors**
  - **Several models**
    - Two parameters (±0.3ºC on 50ºC range)
      $$R_T = R_0 \cdot e^{\beta \cdot \left(\frac{1}{T} - \frac{1}{T_0} \right)}$$
    - Three parameters (±0.01ºC on 100ºC range)
      $$R_T = R_0 \cdot e^{A + \frac{B}{T} + \frac{C}{T^3}}$$
  - **Input voltage (current) thermistors with constant heating dissipation are specially used in control circuits**

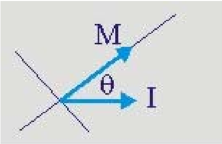


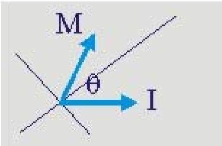


Resistive sensors (IV)

- **Magnetoresistive**
  - **Magnetoresistive effect: A magnetic field H applied to a conductor in conduction creates a Lorentz force F = e·v x H over the e^-, that alters the course of the e^-. When the relaxation time is short, the e^- displacement provokes a transversal electrical field (opposed to the e^- movement – Hall effect). The magnetoresistive effect appears at larger relaxation times, when the resistance increases.**
  - **The magnetoresistive effect is lower than the Hall effect in the major part of the conductors. However, in anisotropic materials (f.e., in ferromagnetics), resistance is given by** $R = R_{min} + (R_{max} - R_{min}) \cdot \cos^2\theta$ **with Rmin appearing when the current is transversal to the magnetic field and Rmax when the current is parallel to the magnetic field.**
  - **An external magnetic field provokes a rotation in the magnetisation axe so that**

$$R = R_{min} + (R_{max} - R_{min}) \cdot \left(1 - \left(\frac{H}{H_s}\right)^2\right)$$





Resistive sensors (V)

- **LDRs – Light Dependent Resistors**
  - **The semiconductor resistance is a function of the received light**
  - **Radiation sensitive from 1mm to 10nm**
  - **Photonic energy is a function of the ratiation frequency**

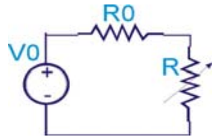
$$E = h \cdot f, \left(\lambda = \frac{c \cdot h}{E}\right), h = 6.62 \cdot 10^{-34} J \text{ (Plank constant)}$$

  - **Photoconductor resistance is a non linear relationship with the received illumination (Ev) (A and α are photoresistor dependent parameters)**

$$R = A \cdot E_v^{-\alpha}$$

Signal conditioning in resistive sensors (I)

- **Environment conditions**
  - **Resistance as a parameter dependent function: R = R0·f(x), f(0)=1**
  - **Linear case: R = R0·(1+x)**
  - **Wide x range:**
    - from 10^{-12} to 10^{-5} in strain gauges
    - passing through 0 to -1 in linear potentiometers
    - to > 10000 in LDRs
  - **Furthermore, sensors need power and are temperature dependent**
- **Measure of the resistance can be produced by 2-wire or 4-wire methods**
- **Measure can be deflective or null (bridges)**
- **Equivalent Thévenin of the resistive sensor:**

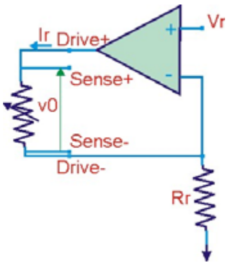


$$P = \left(\frac{V_0}{R_0 + R}\right)^2 \cdot R$$

$$P\max(\text{at } R = R_0) = \frac{{V_0}^2}{4 \cdot R_0}$$

Conditioning in resistive sensors (II)

- **Deflective simple method: to provide current and voltage measurement or to provide voltage and current measurement**
- **Example: NTC (negative temperature coefficient thermistor) sensor powered by constant current (voltage measurement)**

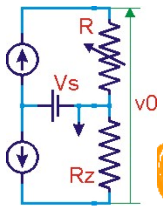


$$v_o = I_r \cdot R = \frac{V_r}{R_r} \cdot R_o \cdot (1 + x)$$

$$\text{Small signal analysis} \Rightarrow v_s = v_o - I_r \cdot R_r \xrightarrow{R_r = R_o} = V_r \cdot (1 + x) - V_r = V_r \cdot x$$

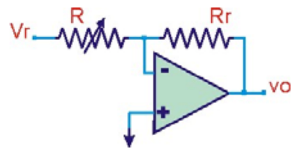
A second approach

$$v_o = I \cdot (R - R_z) \xrightarrow{R_z = R_o} = I \cdot R_z \cdot x$$

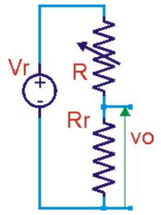


Voltage dividers (I)

- It can be used in sensors with great resistance range and in non-linear sensors, where the vo-R non-linearity allows the linearization
- Vr and Rr must be chosen as a function of the desired operational range

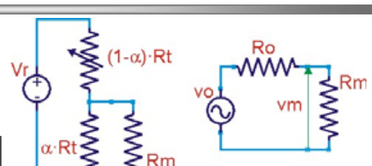


$$v_o = \frac{V_r}{R_r + R} \cdot R_r \qquad R = \frac{v_o}{V_r - v_o} \cdot R_r \;\rightarrow\; v_o = -Vr \cdot \frac{Rr}{R}$$



Voltage dividers (II)

- Using potentiometers
  - Simplest method (Rm = voltmeter resistance)

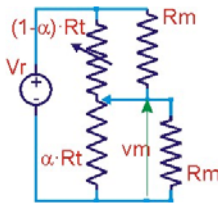


$$v_m = \frac{v_o}{R_o + R_m} \cdot R_m \xrightarrow{k = R_m / R_t} = \frac{V_r \cdot \alpha}{1 + \frac{\alpha \cdot (1-\alpha)}{k}} \;\rightarrow\; err = \varepsilon = \frac{v_m - v_o}{v_o} = \frac{-\alpha \cdot (1-\alpha)}{k + \alpha \cdot (1-\alpha)}$$

linear output for $k >> 1$. Ideally $v_o = V_r \cdot \alpha$

  - The maximum error is produced in the middle of the potentiometer (α=0.5).
  - The following circuit forces a null error in the middle of the potentiometer

$$v_m = V_r \cdot \frac{\alpha \cdot (k + 1 - \alpha)}{2 \cdot \alpha \cdot (1-\alpha) + k}$$



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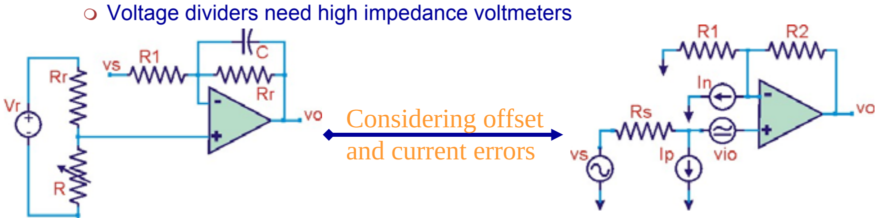
Voltage dividers (III)

- **Amplifiers for voltage dividers**
  - Voltage dividers need high impedance voltmeters



  - It has high impedance input with gain 1+R2/R1
  - Gain bandwidth limited by capacitance C
  - Output has offset and noise

$$v_o = v_s \cdot \left(1+\frac{R_2}{R_1}\right) + v_{io} \cdot \left(1+\frac{R_2}{R_1}\right) - I_p \cdot R_s \cdot \left(1+\frac{R_2}{R_1}\right) + I_n \cdot R_2,$$

$$\text{where } v_s = V_r \cdot \frac{R}{R+R_r} \text{ and } R_s = \frac{R \cdot R_r}{R+R_r}$$

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Wheastone bridges (I)

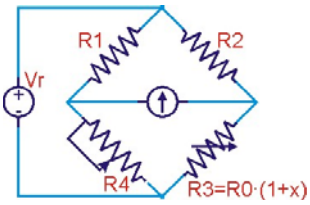
- **Resistance value adjustment using feedback**
- **Under balanced condition it results**

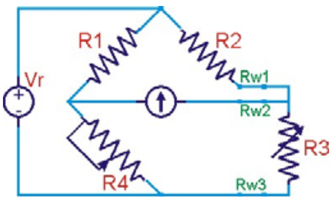
  R3 = R4·R2 / R1

- **Wire resistance could be important when the sensors are connected far from the measuring circuit. Siemens three wire method could be used in this case:**

  Rw3 and Rw1 support the same variations
  (Rw2 is not important here)

$$\varepsilon = \frac{R_4 \cdot R_2 / R_1 - R_3}{R_3} = \frac{R_w}{R_3} \cdot \left(1 - \frac{R_4}{R_1}\right)$$

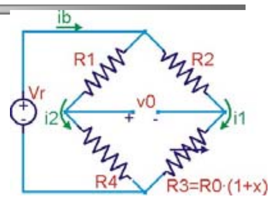




Wheastone bridges (II)

- **Deflective measurements**
  - Voltage (or current) measure between dividers
  - Balanced bridge with x=0 ➔ k = R1 / R4 = R2 / R0 ➔

$$v_0 = V_r\cdot\left(\frac{R_3}{R_2+R_3}-\frac{R_4}{R_1+R_4}\right) = V_r\cdot\frac{k\cdot x}{(k+1)(k+1+x)}$$

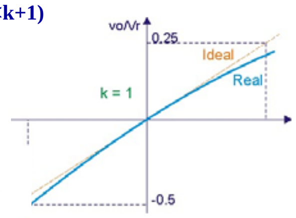


- **Sensitivity is a function of x**

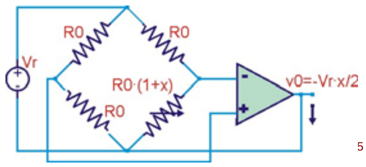
The output is proportional to R3 changes (only when x<<k+1)

$$S_0 = \left.\frac{dv_0}{d(x\cdot R_0)}\right|_{x=0} = \frac{V_r\cdot k}{R_0}\cdot\frac{1}{(k+1)^2}$$

Maximum sensitivity occurs at k = 1



- **Wheatstone bridge linearization**



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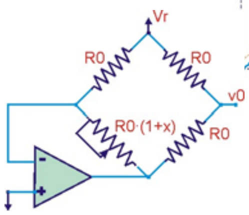
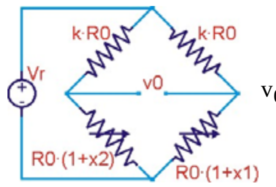


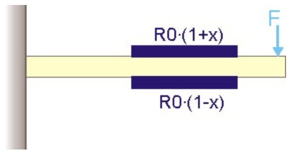
Wheastone bridges (III)

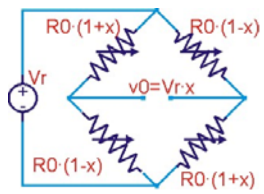
- **Differential measurements**



$$v_0 = V_r\cdot\frac{k\cdot(x_1-x_2)}{(k+1+x_1)(k+1+x_2)} \xrightarrow{x_1,x_2<<k+1} = V_r\cdot\frac{k\cdot(x_1-x_2)}{(k+1)(k+1)}$$

Example





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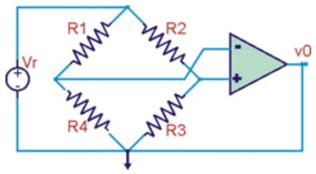
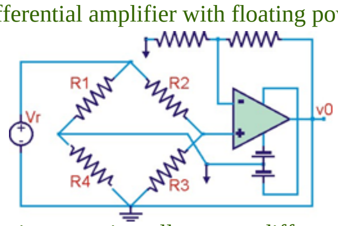
Detection systems using Wheatstone bridge

- **Application commands detection circuitry. Usually the signal must be ranged (using an opamp) before entering the ADC**

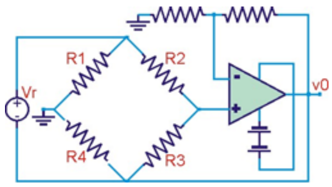
Grounded bridge differential amplifier



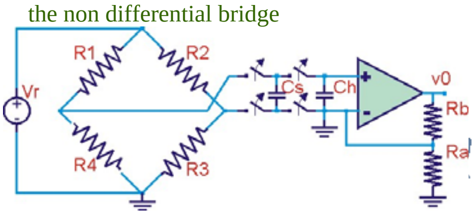
Non differential amplifier with floating power



Floating bridge with non diferential amplification



A floating capacitor allows non differential amplification with differential conversion from the non differential bridge



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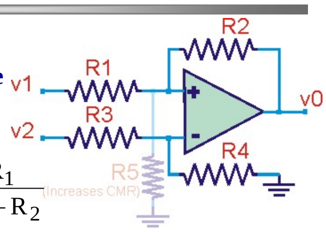
Differential amplifiers (I)

- **Amplification proportional to the inputs difference**
- **Useful in resistive bridges with non connected to ground outputs**



$$v_0 = \frac{1}{1+ {}^{1}\!/\!_{A_d \cdot \beta}}\left[v_2 \cdot \frac{R_4}{R_3+R_4}\cdot\left(1+\frac{R_2}{R_1}\right) - v_1 \cdot \frac{R_2}{R_1}\right],\ \beta = \frac{R_1}{R_1+R_2}$$

$$\text{If}\ \begin{cases} v_d = v_2 - v_1 \\ v_c = \dfrac{v_2+v_1}{2}\end{cases} \rightarrow v_0 = \frac{1}{1+{}^{1}\!/\!_{A_d \cdot \beta}}\left[v_d \cdot \frac{1}{2}\cdot\left\{\frac{R_4}{R_3+R_4}\cdot\left(1+\frac{R_2}{R_1}\right)+\frac{R_2}{R_1}\right\} + v_c \cdot \frac{R_4 R_1 - R_2 R_3}{R_4 \cdot (R_3+R_4)}\right]$$

$$\left.\begin{aligned} &\text{Diferential amplification}: G_d = \left.\frac{v_o}{v_d}\right|_{v_c=0} \\ &\text{Common mode}: G_c = \left.\frac{v_o}{v_c}\right|_{v_d=0}\end{aligned}\right\} \left\{\begin{aligned} &\text{For great } G_d \text{ and small } G_c \Rightarrow \\ &\frac{R_4}{R_3} = \frac{R_2}{R_1} = k \Rightarrow G_d = \frac{k}{1+\dfrac{k+1}{A_d}} \xrightarrow{\text{Great } A_d} \cong k\end{aligned}\right.$$

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Differential amplifiers (II)

- **Gc = 0 is difficult to achieve: Common Mode Rejection Ratio**

$$CMRR = \frac{G_d}{G_c} = \frac{1}{2} \cdot \frac{R_1 \cdot R_4 + R_2 \cdot R_3 + 2 \cdot R_2 \cdot R_4}{R_1 \cdot R_4 - R_2 \cdot R_3} \cong \frac{k+1}{4 \cdot t_r}$$

t_r = resistace tolerance

- **Input impedance must be considered**

$$z_{i1} = \frac{v_1}{\frac{v_1 - v_n}{R_1}} = \frac{R_1}{1 - \frac{v_2}{v_1} \cdot \frac{R_4}{R_3 + R_4}}$$

$$z_{i2} = \frac{v_2}{\frac{v_2 - v_p}{R_3}} = R_3 + R_4$$

differential mode ($v_c = 0, v_2 = -v_1$) $\rightarrow$ $z_{i1} = \frac{(k+1) \cdot R1}{2 \cdot k + 1}$, $z_{i2} = R_3 + R_4$

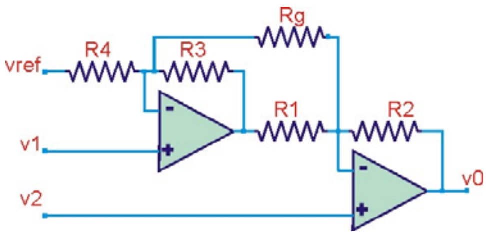
common mode ($v_d = 0, v_1 = v_2$) $\rightarrow$ $z_{i1} = (k+1) \cdot R1$, $z_{i2} = R_3 + R_4$

Instrumentation amplifiers (I)

- **Two op-amp based**

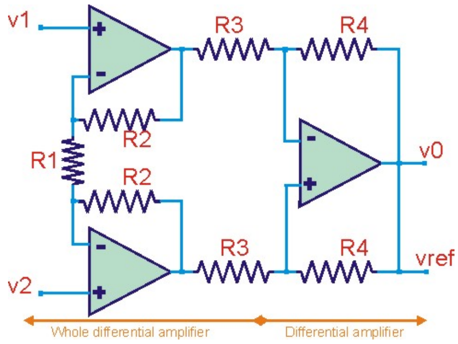
  Differential amplifier with high gain and high input adjustable impedance (Rg) and low output impedance and offset

$$v_o = v_d \cdot \left(1 + k + \frac{R_2 + R_4}{R_g}\right) + V_{ref}$$



Instrumentation amplifiers (II)

- **Three op-amp based**
  - Adjustable gain using R1
  - Input stage should be gain stage



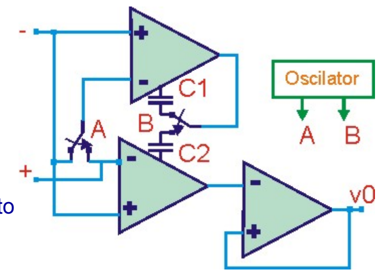
$$\left.\begin{array}{l} v_a = v_1\cdot\left(1+\frac{R_2}{R_1}\right) - v_2\cdot\frac{R_2}{R_1} \\ v_b = v_2\cdot\left(1+\frac{R_2}{R_1}\right) - v_1\cdot\frac{R_2}{R_1} \end{array}\right\}$$

$$\left.\begin{array}{l} \text{with } v_2 = v_1 \Rightarrow A_c = 1 \\ v_o - v_{ref} = (1+G)\cdot k\cdot(v_2 - v_1), G = 2\cdot\frac{R_2}{R_1}, k = \frac{R_4}{R_3} \end{array}\right\}$$

High performance amplifier: chopper differential opamp

- **Used in low drift applications**
- **Stable and autozeroing amplifier using offset capacitors**
- **Typical drift in the range ~0.3µV/ºC and 1µV/month**

- **Functioning**
  - A switch connects input amplifier to C1, charging the capacitor until offset value
  - Once A is opened, B transports charge to C2, in that a way that the offset is compensated by subtracting it from the output.



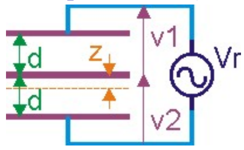
Reactant (capacitive) sensors

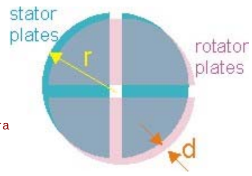
- **Based on variable capacitance**
  - **They can be linear or non-linear**
  - **Used for measuring linear or rotational displacements, pressure, strain, ...**

$$C \cong \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{d} \cdot (n-1),\ \varepsilon_0 = 8.85\,pF/m,\ \varepsilon_r \cong 1,\ n\ \text{identical layers}$$

- **Based on differential capacitance**
  - **Used for displacement measures (ranging from 0.1pm to 10mm)**

$$\left.\begin{aligned} C1 &= \frac{\varepsilon \cdot A}{d+z} \\ C1 &= \frac{\varepsilon \cdot A}{d-z} \end{aligned}\right\} \left.\begin{aligned} v_1 &= V_r \cdot \frac{C2}{C1+C2} \\ v_2 &= V_r \cdot \frac{C1}{C1+C2} \end{aligned}\right\} v_1 - v_2 = Vr \cdot \frac{z}{d}$$





$$C1 = C3 = \frac{\varepsilon_0 \cdot \pi \cdot R^2}{4 \cdot d} \cdot \left(1 + \frac{2 \cdot \theta}{\pi}\right)$$

$$C2 = C4 = \frac{\varepsilon_0 \cdot \pi \cdot R^2}{4 \cdot d} \cdot \left(1 - \frac{2 \cdot \theta}{\pi}\right)$$

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Reactant (inductive) sensors

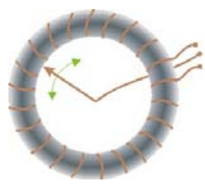
- **Reluctant-inductive sensors**
  - **Reluctance → Magnetic flux quantity due to electric current**

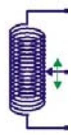
L → Inductance, M → Mutual inductance, R → Magnetic reluctance

$$L = n \cdot \frac{\phi}{i} = n \cdot \frac{Fm/\Re}{i} = n \cdot \frac{n \cdot i/\Re}{i} = \frac{n^2}{\Re}$$

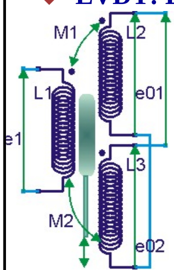
For a spiral of l length and A section
(used as a metal detector)

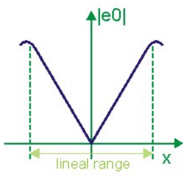
$$\Re \cong \frac{1}{\mu_0 \cdot \mu_r} \cdot \frac{l}{A}$$





- **LVDT: Linear Voltage Dependent Transformer**





Mutual inductance variation between primary and secondary

Used in displacement, speed, acceleration, ...measurements

$$e_0 = i_2 \cdot R_L = \frac{s \cdot (M_1 - M_2) \cdot e_1 \cdot R_L}{2 \cdot s^2 \cdot L_1 L_2 + s \cdot (R_2 \cdot L_1 + 2 \cdot R_1 \cdot L2) + R_1 \cdot R_2}$$

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Other sensors

- Magnetic sensors
  - Ac tachometers
  - Hall effect sensors
  - Synchros, resolvers, inductosyn
  - Magnetoelastic and magnetoresistive
  - Pulse-wire sensors and wiegand sensors
  - Flux-gate
  - SQUID → Superconducting Quantum Interference Device's
- Thermopar autogenerator sensors
- Pyroelectric autogenerator sensors
- Photovoltaic sensors

Conditioning in capacitive sensors (I)

- Sensor reactance measurement
  - Usually implies the measure of low capacitances with great stray capacitances
  - Two main circuits for
    - Sensors with linear admitance change

      For example: layer displacement capacitance (in a capacitor) sensor

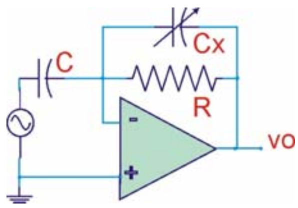
      Constant current is applied to the sensor

      R polarises the sensor, and it must be much greater than sensor impedance

$$C_x = \varepsilon \cdot \frac{A}{d \cdot (1+x)} = \frac{C_o}{1+x}$$

Considering that R does not influence the measure

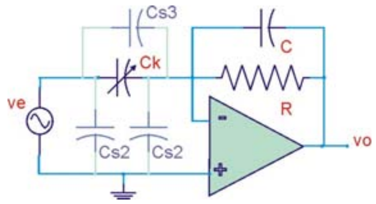
$$v_o = -v_e \cdot \frac{Z_x}{Z} = -ve \cdot \frac{C}{C_o} \cdot (1+x)$$



Conditioning in capacitive sensors (II)

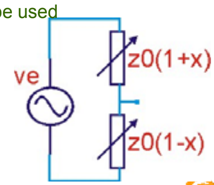
- Sensors with linear impedance change
  - Constant voltage is applied to the sensor
  - Usually charge amplifier is used.

$$v_o = -v_e \cdot \frac{C_x}{C}$$



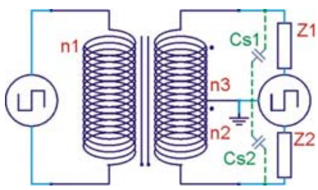
- In the case of differential sensors voltage dividers can be used
  - The constant term dominates when x<<1
  - Interference errors in both sensors are canceled

$$v_o = v_e \cdot \frac{z_o \cdot (1+x)}{z_o \cdot (1-x) + z_o \cdot (1+x)} = v_e \cdot \frac{1+x}{2}$$



ac bridges

- As in voltage dividers,
  - Bridges with unique sensor → Non linear output
  - Differential bridges → linear output and cancellation of coincident errors in both sensors
- **Bridges in inductive sensors**
  - Similar as in resistance bridge sensors
- **Bridges in capacitive sensors**
  - It is recommended do not use resistances because the parasitic impedances in capacitors can be as large as those and, thus, provoking important errors.
  - use of Blumblein bridges or transformers
    - Cs1 and Cs2 with small influence
    - N2 and N3 determine the voltage rate between z1 and Z2
    - 0.1pF over 50pF values with 1nF stray capacitances can be detected
    - With values z1=z0·(1-x) and z2=z0·(1+x) , and big detector input impedance, vd=vs=v2·x/2



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Capacitive bridge analog linearization (pseudobridges)

- Used in non differential capacitive sensor measurements
- Simpler than transformers

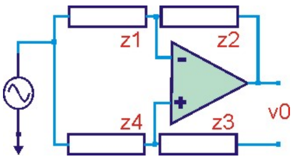
Non differential

Layer separation dependent sensor are placed in Z2. If it is permitivity dependent, then in Z1.

Z1 and Z2 can be capacitors (fix one + sensor)

Z3 and Z4 could be resistances → lineal output

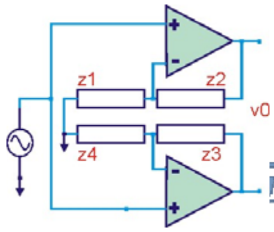
$$v_o = v_e \cdot \frac{z_3/z_4 - z_2/z_1}{1 + z_3/z_4}$$



Differential

In dielectric or area dependent sensors, Z1 and Z4 forms the differential capacitor. In layer dependent, they are placed in z2 and Z3

$$v_o = v_e \cdot \left(z_2/z_1 - z_3/z_4 \right)$$



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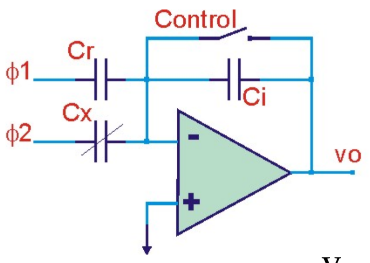
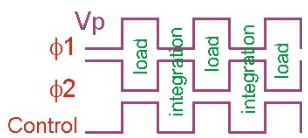
Specific circuitry for capacitive sensors (I)

- **Commuted capacitors allows the realisation of monolythic circuitry for signal conditioning in capacitive sensors**
- **Charge integration**

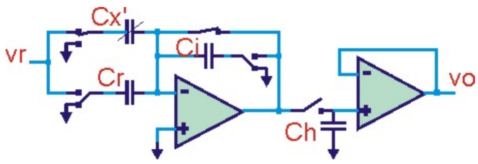




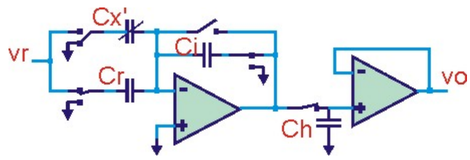
$$v_o = v_p \cdot \frac{C_x - C_r}{C_i}$$

Specific circuitry for capacitive sensors (II)

- **Charge redistribution method**
  - Autozeroing phase: an unknown capacitor is charged to a reference voltage. Then, integration Ci and the reference Cr capacitors are discharged

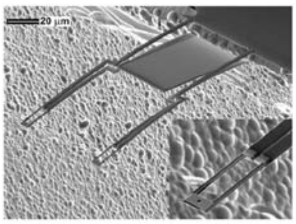


  - Measure phase: Cx is grounded, Cr connects to Vr and the feedback loop is closed through the OpAmp. Cx signal is integrated
    - If Cx=Cr, Cx charge is redistributed between Cx and Cr, and the opamp output continues to 0
    - If Cx ≠Cr, a net flux through Ci exists and then the opamp output voltage is proportional to Cx-Cr

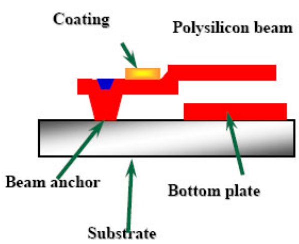


Example: Microsensor array platform (ESTD)

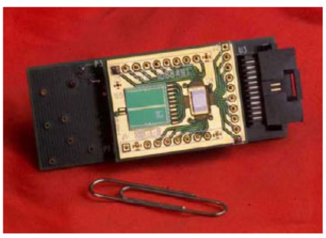
- **A low-cost very low power (5mW in continuous) sensor array platform for physical and chemical parameters measurement**
- **Based on microfabricated catilever arrays**
- **Readouts based on capacitance changes**
- **Sensitivity of 0.1nm bending**



IR Sensitive MicroCantilever



Microfabricated Cantilever



10-Cantilever Array with Readout Electronics
(Latest version needs less than one milliwatt.)

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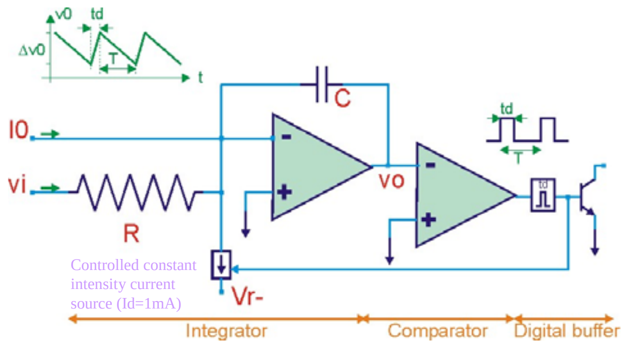
Towards digital processing (I)

- **Voltage-to-frequency conversion (VFC's)**



$$I \cdot T = Id \cdot Td$$

$$f = \frac{1}{T} = \frac{I}{Id \cdot Td}$$

- **Highly linear, great resolution and good noise immunity. Accuracy dependent on the component errors**
- **A bit slow conversion**

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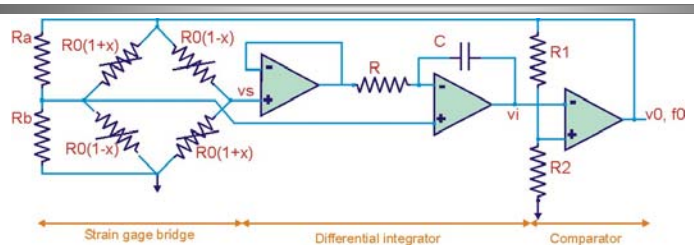
Quantity-to-frequency direct conversion (I)



$$\text{Comparator at low level} \rightarrow \overline{V_0} \Rightarrow v_s = \overline{V_0} \cdot x$$

$$\text{Comparator at high level} \rightarrow V_0 \Rightarrow v_s = V_0 \cdot x$$

$$t = t0 \, (\text{and } t_{\uparrow}) : v_i(t) = \frac{V_0 \cdot x}{R \cdot C} \cdot t + V_i(0)$$

$$t = T_1 \, (\text{comparator commutes}) : v_i(T_1) = \frac{V_0 \cdot x}{R \cdot C} \cdot T_1 + V_i(0) = V_0 \cdot \frac{R2}{R1 + R2}$$

$$\text{From } T_1 : v_i(t) = \frac{\overline{V_0} \cdot x}{R \cdot C} \cdot (t - T_1) + V_0 \cdot \frac{R2}{R1 + R2}$$

$$t = T_2 : v_i(T_2) = \frac{\overline{V_0} \cdot x}{R \cdot C} \cdot (T_2 - T_1) + V_0 \cdot \frac{R2}{R1 + R2} = \overline{V_0} \cdot \frac{R2}{R1 + R2} \Rightarrow V_i(0) = \overline{V_0} \cdot \frac{R2}{R1 + R2}$$

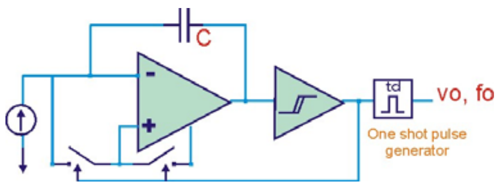
Quantity-to-frequency direct conversion (II)

$$\text{Thus}: T_1 = \left(V_0 - \overline{V_0}\right)\frac{R_2}{R_1+R_2}\cdot\frac{R\cdot C}{V_0\cdot x}$$

$$T_2 = \left(V_0 - \overline{V_0}\right)\frac{R_2}{R_1+R_2}\cdot\frac{R\cdot C}{x}\cdot\left(\frac{1}{V_0}-\frac{1}{\overline{V_0}}\right)$$

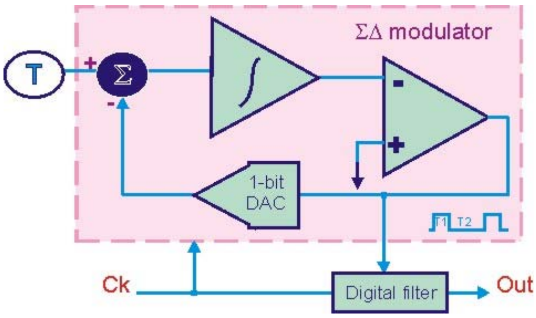
$$\text{So}: \quad f0 = \frac{x}{R\cdot C}\cdot\frac{R_1+R_2}{R_2}\cdot\frac{-V_0\cdot\overline{V_0}}{\left(V_0-\overline{V_0}\right)^2} \xrightarrow{\text{if } V_0=-\overline{V_0}} f0 = \frac{x}{R\cdot C}\cdot\frac{R_1+R_2}{4\cdot R_2}$$

- **Thus, the solution is voltage independent.**
- **Current output sensors have easy frequency conversion using direct current integration. For example, TSL220 (TI) integrated circuit performs the conversion light-to-current. The output integration time is proportional to photodiode current.**



Quantity-to-frequency direct conversion (III)

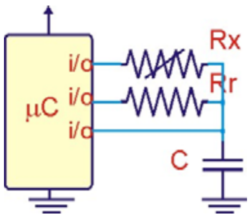
- **The TMP03(ºC)/TMP04(ºF) integrated circuits (Analog Devices) have a Σ–Δ modulator to perform the temperature conversion to digital output**
- **Accuracy is a function of the clock frequency and counter resolution.**



$$T(^{o}C) = 235 - \frac{400\cdot T_1}{T_2}$$

Quantity-time direct conversion (I)

- The comparison of an unknown resistance to a known one is a simple measuring technique. This can be done using the load/unload capacitance time, and it can be done using a uC.
- Care must be taken with the I/O port finite resistance
- C determines the resolution and must be chosen depending on the expected counting.

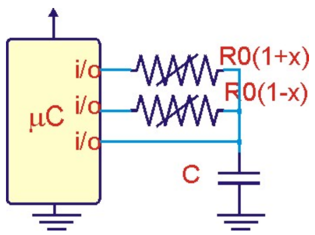


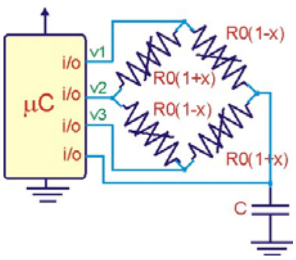
$$\left.\begin{aligned}(t_{load}\,R_x) &\rightarrow t_x = -R_x \cdot C \cdot \ln\left(1-\frac{V_{th}}{V_{oh}}\right)\\ (t_{load}\,R_r) &\rightarrow t_r = -R_r \cdot C \cdot \ln\left(1-\frac{V_{th}}{V_{oh}}\right)\end{aligned}\right\} \Rightarrow R_x = R_r \cdot \frac{t_x}{t_r}$$

Quantity-time direct conversion (II)

- Other possibilities

$$x = \frac{t1-t2}{t1+t2}, \quad \left|\begin{aligned} t_1 &= -R_0 \cdot (1+x) \cdot C \cdot \ln\left(1-\frac{V_{th}}{V_{oh}}\right)\\ t_2 &= -R_0 \cdot (1-x) \cdot C \cdot \ln\left(1-\frac{V_{th}}{V_{oh}}\right)\end{aligned}\right.$$





$$x = \frac{t1-t3}{t2} = \frac{R_0 \cdot (1+x) \cdot (3-x) - R_0 \cdot (1-x) \cdot (3+x)}{4 \cdot R_0}$$

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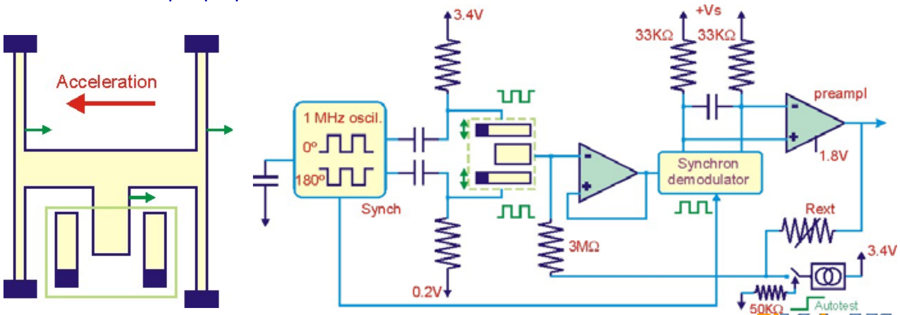
Examples

- **Accelerometer**
  - Sensor, conditioning on the same circuit
  - Balanced ac excitation on the sensor (at null acceleration, null output)
  - Feedback applies an electrostatic force to the sensor that opposes to acceleration
  - Output proportional to the acceleration force



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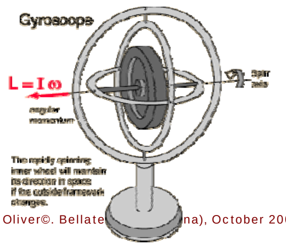
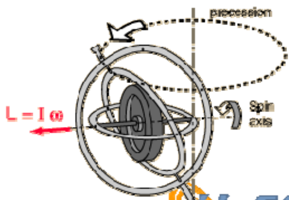
Gyros: definition (from www.enciclopedia.com)

Symmetrical mass, usually a wheel, mounted so that it can spin about an axis in any direction. When spinning, the gyroscope has special properties. (...) Once a gyroscope starts to spin, it will resist changes in the orientation of its spin axis. For example, a spinning top resists toppling over, thus keeping its spin axis vertical. If a torque, or twisting force, is applied to the spin axis, the axis will not turn in the direction of the torque, but will instead move in a direction perpendicular to it. This motion is called precession. (...) The modern gyroscope was developed in the first half of the 19th cent. by the french physicist Jean B. L. Foucault, and its first notable use was in a visual demonstration of the earth's rotation. In the second half of the 19th cent., with the invention of the electrically driven rotor, its uses multiplied. It became possible to rotate the gyroscope's wheel at desired speeds without interfering with the precession. (...) The gyroscope is the nucleus of most automatic steering systems, such as those used in airplanes, missiles, and torpedoes. It is also used in the gyrocompass, a directional instrument used on ships. Unaffected by magnetic variations, its spinning axis, when brought in line with the north-south axis of the earth, provides an accurate line of reference for navigation.





Gyros: math equations (I)
(From Engineering Mechanics - Statics and Dynamics, R. C. Hibbeler)

1. Newton's Law states that the sum of the *external* forces acting on a particle equals the particle's mass times its acceleration. Actually, Newton's original formulation related the external forces to the particle's *linear momentum*. (1)
2. If we chose a reference point O and **r** *is a position vector to the particle*, we can take the cross product of both sides of this equation to get an expression that relates the *moment of the forces* (**M**o) acting on the particle to the *angular momentum* (**H**o) of the particle with respect to the reference point O. (2)
3. After several equalities, it is found that, given a moving particle, the Sum of the Moments about a point O is equal to the time rate of change of the particle's angular momentum. (3)

$$\sum \vec{F} = m \cdot \vec{a} = m \cdot \vec{v}' \qquad (1)$$
$$\sum \vec{M}_O = \vec{r} \times \sum \vec{F} = \vec{r} \times m \cdot \vec{v}' \qquad (2)$$
$$\sum \vec{M}_O = \vec{H}'_O \qquad (3)$$

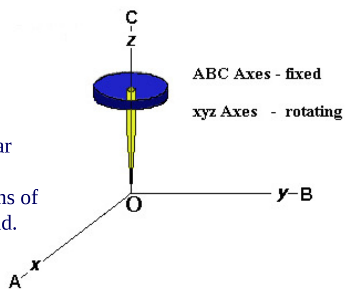
This equation (derived for a particle) is also valid for a system of particles. That is, the Sum of the Moments about point O due to the external forces acting on a system of particles is equal to the time rate of change of the angular momentum of the system of particles about this same reference point O.

So, this equation applies to the analysis of a gyroscope.

Gyros: math equations (II)

4. Now, we need an expression for the angular momentum **H**o or its time derivative **H**'o with attributes that can be physically measured such as mass, radius, angular velocity, and angular acceleration.
   Equation (4) gives Δ**H**o for a particle in the body having an incremental mass Δm and an *angular velocity* **ω**.
5. Summing for all the particles of the body, we obtain equation (5)
6. And, solving it in the case of a *principal axes of inertia* (a particular case where the coordinate system has at least two of the three orthogonal planes defined by the coordinate system as axes of symmetry of the body) , we obtain equation (6).

$$\left[\Delta \vec{H}_O\right]_j = \vec{r} \times \Delta m_j \cdot \vec{v}_j = \vec{r} \times \left(\vec{w} \times \vec{r}\right)_j \cdot \Delta m_j \qquad (4)$$
$$\vec{H}_O = \int_{\vec{H}_O} d\vec{H}_O = \sum \left[\Delta \vec{H}_O\right]_j = \int_m \vec{r} \times \left(\vec{w} \times \vec{r}\right) dm \qquad (5)$$
$$\vec{H} = \vec{I} \cdot \vec{w}, \quad \vec{I} = \left(I_{xx}, I_{yy}, I_{zz}\right) \qquad (6)$$



Angular momentum **H**o can now be calculated since the angular velocity can be measured and the *moments of inertia* (I), which depend only upon the mass and physical dimensions of the body, can be looked up in a table or calculated by hand.

Gyros: math equations (III)

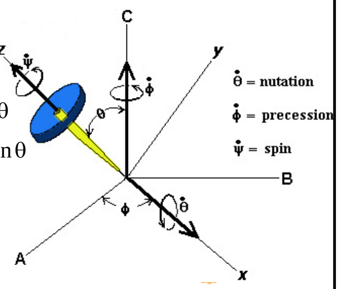
7. Analytical gyroscope results can be obtained choosing a coordinate system such that at least two of the three orthogonal planes defined by the coordinate system are axes of symmetry for the gyroscope. Then all the products of inertia will become zero, and we only have to include moments of inertia in our calculations. To accomplish this, we will use a *rotating coordinate system* with origin at the pivot point of the gyro. The rotating coordinate system will follow the gyro's nutation and precession but not its spin. We will call the angular velocity of the rotating reference $\boldsymbol{\Omega}$ = nutation + precession = $\theta' + \phi'$ and label the rotating axes as the xyz axes. We will also have a fixed reference coordinate system which will also have its origin at the pivot point of the gyro and we will call this the ABC axes. The angular velocity of the gyro with respect to the fixed ABC axes will be $\boldsymbol{\omega}$ = nutation + precession + spin = $\theta' + \phi' + \psi'$. The angles θ, ϕ and ψ are called *Euler angles*

8. So, $H_o \rightarrow H_o' \rightarrow \Sigma M$ can be calculated:

$$\sum M_x = I_x \cdot \theta'' - I_y \cdot (\phi')^2 \cdot \cos\theta \cdot \sin\theta + I_z \cdot \phi' \cdot \sin\theta \cdot (\phi' \cdot \cos\theta + \psi')$$

$$\sum M_y = I_y \cdot (\phi' \cdot \theta' \cdot \cos\theta + \phi'' \cdot \sin\theta) - I_z \cdot \theta' \cdot (\phi' \cdot \cos\theta + \psi') + I_x \cdot \phi' \cdot \theta' \cdot \cos\theta$$

$$\sum M_z = I_z \cdot (-\phi' \cdot \theta' \cdot \sin\theta + \phi'' \cdot \cos\theta + \psi'') - I_x \cdot \phi' \cdot \theta' \cdot \sin\theta + I_y \cdot \theta' \phi' \cdot \theta' \cdot \sin\theta$$



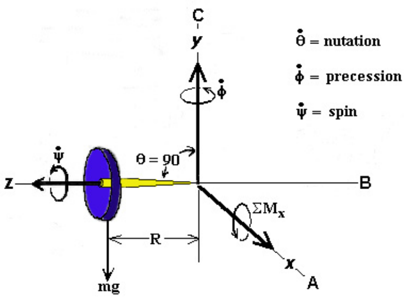
In general, it would be very hard to arrive at a solution that satisfies these equations, however ...

Gyros: math equations (IV)

7. ...in the specific case where the precession ϕ' is constant, the spin ψ' is constant, and the nutation angle $\theta = 90^o$ is a constant 90 degrees as shown in figure below, the solution becomes quite easy:

$$\left.\begin{array}{l}\theta' = 0\\ \phi'' = 0\\ \psi'' = 0\end{array}\right\} \rightarrow \begin{array}{l}\sum M_x = I_z \cdot \phi' \cdot \psi'\\ \sum M_y = 0\\ \sum M_z = 0\end{array}$$

8. So the only moment in this case is the moment about the x-axis. There are no negative signs in this equation and we consistently use the *right-hand-rule* in expressing all vector quantities, therefore, all of the vectors - the sum of the moments about the x-axis (ΣMx), the precession of the gyro about the y-axis (ϕ'), and the spin of the flywheel about the z-axis (ψ') all act along their respective positive axes as indicated in the figure.



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Gyros: math equations (V)

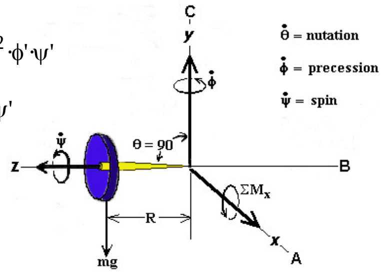
9. As the only moment about the x-axis is the moment resulting from the weight of the flywheel, and if the flywheel is at a distance R from the pivot point (origin O), and recalling that Iz = Izz, we have:

$$m \cdot g \cdot R = I_{zz} \cdot \phi' \psi'$$

10. This equation tells us that if the flywheel is lying at 90º at a distance R from the pivot point and the flywheel is spinning at a constant angular velocity y', then the gyro will not topple over as might be expected, but instead, it will precess about the positive y-axis at a constant angular velocity of ϕ'.

$$\text{For a solid circular disc } (I_{zz} = \frac{1}{2} m \cdot r^2): \quad m \cdot g \cdot R = \frac{1}{2} m \cdot r^2 \cdot \phi' \psi'$$

$$\text{For a solid circular ring } (I_{zz} = m \cdot r^2): \quad m \cdot g \cdot R = m \cdot r^2 \cdot \phi' \psi'$$



To counter the moment m·g·R, a gyro that uses a solid circular disk as the flywheel will precess twice as fast as a gyro that uses a thin circular ring (assuming both flywheels have the same mass m and radius r).

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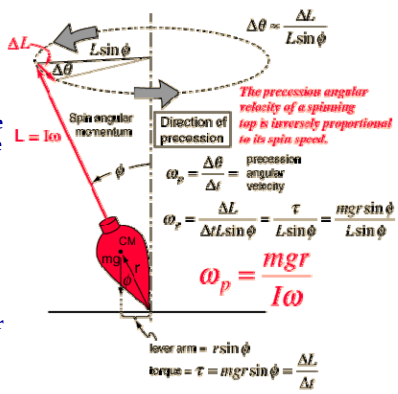
Gyros: precession spinning top

A rapidly spinning top will precces in a direction determined by the torque exerted by its weight. The precession angular velocity is inversely proportional to the spin angular velocity, so that the precession is faster and more pronounced as the top slows down This process involves a considerable number of physical and mathematical concepts. The angular momentum of the spinning top is given by its moment of inertia times its spin speed but this exercise requires an understanding of it's vector nature. A torque is exerted about an axis through the top's supporting point by the weight of the top acting on its center of mass with a lever arm with respect to that support point. Since torque is equal to the rate of change of angular momentum, this gives a way to relate the torque to the precession process. From the definition of the angle of precession, the rate of change of the precession angle q can be expressed in terms of the rate of change of angular momentum and hence in terms of the torque.

The expression for precession angular velocity is valid only under the conditions where the spin angular velocity w is much greater than the precession angular velocity wP. When the top slows down, the top begins to wobble, an indication that more complicated types of motion are coming into play.



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Gyros: the earth

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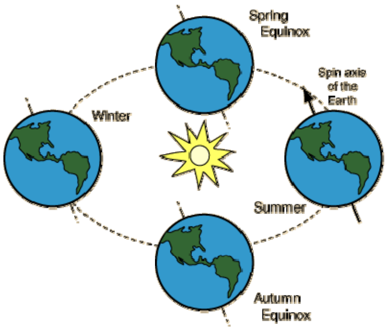
The Earth acts like a gyroscope in its orbit around the sun in that it maintains the direction of its spin axis in space. The implication of the conservation angular momentum is that the angular momentum of the rotor maintains not only its magnitude, but also its direction in space in the absence of external torque. Thus the axis and the northern hemisphere will be tipped toward the sun for part of the year (summer) and away from it at another time of year (winter). This is the cause of the seasons of the Earth.



Micromechanised gyros (I)

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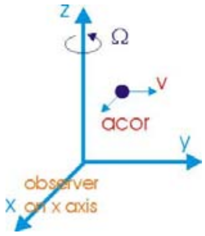
- **Micromechanised gyros sense rotation from Coriolis effect**
- **Coriolis effect**
  - **Apparent acceleration of a mobile in a rotation system**
    - When the coordinate system (including the observer) rotates with Ω angular velocity in the z axis, observer 'sees' the particle to move towards x axis with acceleration

$$\vec{a}_{coriolis} = 2 \cdot \vec{\Omega} \times \vec{v}$$

    - So, when a mechanical element (disc, plate, ... waves (using an external force) and it is placed in a rotational reference system, then Coriolis force produces a secondary oscillation perpendicular to the primary oscillation movement
    - This systems usually uses a quartz resonator



Joan Oliver©. Bellaterra (Barcelona), October 2005

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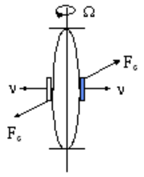
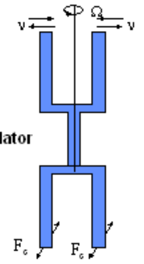
Micromechanised gyros (II)

- **Giring (from http://www.siliconsensing.com)**
  - GYRING© is Silicon Sensing's patented technology for accurate and robust angular rate sensing. Solid State gyros all work by detecting Coriolis forces, these are forces which can be observed whenever linear motion occurs in a rotating frame.
  - The simplest form of Coriolis gyro, the simple oscillator, uses a single 'beam' of material (usually quartz or ceramic), which is vibrated to create a standing wave along its length. When subjected to rotation, this standing wave moves around the beam, causing it to vibrate in a new direction, this change in vibration position is proportional to the rate of rotation the gyro has been subjected to. This type of gyro is highly susceptible to external shocks and vibration, and depending on the type of material used, errors over life can change substantially and individual gyros can show sudden, unexplained & irregular bias shifts.





$$\vec{F} = 2 \cdot m \cdot \vec{\Omega} \times \vec{v}_r$$

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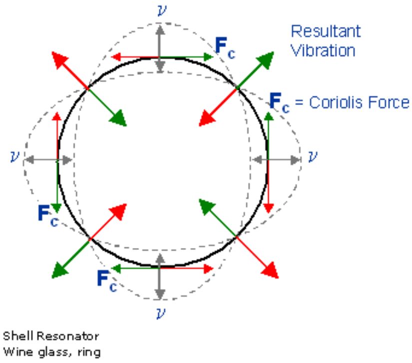
Micromechanised gyros (III)

- To try and achieve more consistent results, the single vibrating beam gyro concept was developed to contain more than one beam, the balanced oscillator, typically in a 'Tuning Fork' configuration. However this design is still highly sensitive to external shocks & vibration.
- This sensitivity to shock & vibration was not acceptable to the aerospace, automotive or defence markets. We therefore took the concept a stage further, and designed a 3D tuning fork or 'Wine Glass' configuration with a cos2θ standing wave around the rim, creating the shell resonator.
- Like the single beam and tuning fork gyro configurations, this vibration pattern moves around the resonator when the gyro is subjected to rotation and the detection of this change in vibration allows the rate of rotation to be calculated.



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Micromechanised gyros (IV)

- **Single-Axis Gyro - CRS05**
  - **A robust and affordable mass-produced gyroscope for automotive and commercial customers. Angular rate sensors are used wherever rate of turn sensing is required without a fixed point of reference. The sensor will output a DC voltage proportional to the rate of turn and input voltage**

Specification (Typical Data)	-01	-02	-75
Rate Range	±50°/s	±200°/s	±75°/s
Output	Analogue voltage (ratiometric)		
Scale Factor			
Nominal	40mV/°/s	10mV/°/s	27mV/°/s
Variation over temperature range	< ±3%		
Non Linearity	< ±1.0% of full scale		
Bias			
Setting tolerance	< ±1.5°/s		
Variation over temperature range	< ±3°/s		
Ratiometric error	< ±1°/s		
Drift vs. Time	< ±0.5°/s		
g Sensitivity	< ±0.025°/s/g on any axis		
Bandwidth (-90° Phase)	80Hz	30Hz	40Hz
Quiescent Noise	< 85mV rms	< 4mV rms	< 8mV rms
Environment			
Temperature	−40°C to +100°C		
Linear acceleration	< 100g		
Shock	200g (1ms, 1/2 sine)		
Vibration	2g rms (20Hz to 2kHz, random)		
Cross axis sensitivity	< 5%		
Mass	<11 gram		
Electrical			
Voltage (supply)	+4.75V to +5.25V		
Current (supply)	< 35mA (running)		
Noise and Ripple	< 10mV rms (up to 10kHz)		
Ready Time	< 0.5s		

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Gyros (... pure technology)

- iBOT™
  - The Johnson & Johnson iBOT™ Mobility System provides new levels of personal freedom and accessibility for people with disabilities, it is a unique gyro-balanced mobility device that can operate on either four or two wheels, stabilising the user by automatically adjusting and balancing itself.
  - Allows you to climb up and down stairs with or without assistance, allowing you to gain access to previously difficult places to reach.
  - It can climb curbs as high as 4 inches and travel over grass, gravel, sand and other forms of uneven terrain.

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References

- http://hyperphysics.phy-astr.gsu.edu

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Thank you for your attention

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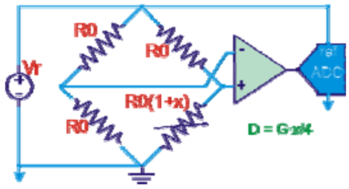
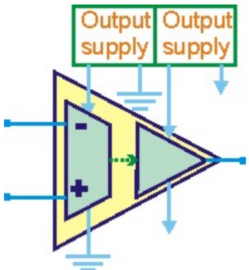
Power supply in Wheastone bridges

- **DC power in Wheastone bridges must be taken into account:** $\frac{dv_0}{v_0} = \frac{dV_r}{V_r}$
- **Precision measurements require minimisation of power supply errors**
- **Several options:**
  - Making an output rate proportional between output and power supply
  - Using opamp with high PSRR
  - Power supply regulators in the bridge power supply could afford good solutions in applications with high input power supply (10V, for example) and low measurement urrents (< 20mA), as in gauge bridges.



Isolation amplifier

- **Used in highly noisy environments**
- **Optocoupler based amplifier**



Electromagnetic sensors

- **Based on Faraday law** $E = -n \cdot \frac{d\phi}{dt}$
  - Example: ac tachometer: a n spiral circuit that generates a voltage when subject a magnetic field, with output voltage and frequency variable.

$$E = -n \cdot \frac{d\phi}{dt} = -n \cdot \frac{d(B.A.\cos\theta)}{dt} = n \cdot B \cdot A \cdot \sin\theta \cdot \frac{d\theta}{dt}$$

$$\omega = 2 \cdot \pi \cdot n = \frac{d\theta}{dt}$$

$$\rightarrow e = n \cdot B \cdot A \cdot \omega \cdot \sin \int \omega \cdot d\omega$$

$$e = n \cdot B \cdot A \cdot 2 \cdot \pi \cdot n \cdot \sin(2 \cdot \pi \cdot n \cdot t)$$

- **Hall effect sensors**
  - Differential of potential generation in a semiconductor into a magnetic field and with a current that crosses the semiconductor perpendicular to the magnetic field
  - Coefficient Hall is given by $A_H = \frac{V_H \cdot t}{I \cdot B}$
  - Used as a distance and speed detectors