Sensors and Transducers

Avionics and Spacionics

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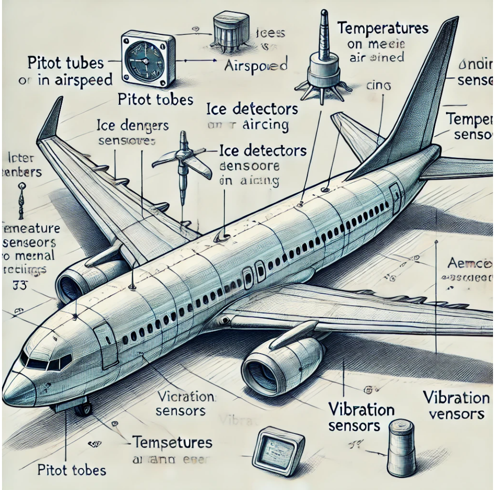
Introduction



Typical airplane sensors

Introduction

In aerospace, sensors and transducers play critical roles in various applications, from monitoring and controlling aircraft systems to ensuring safety and efficiency. Some of the main types include:

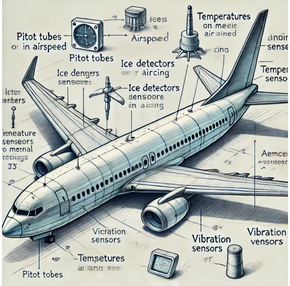
- Pressure: Airspeed, altitude, engine control, ...
- Temperature: mechanical components, fuselage, indoor, atmospheric, ...
- Position/Displacement: position of flight control surfaces and rotating components, ...
- Acceleration/Vibration: measure acceleration forces (crucial for navigation and control systems), engine and airframe vibrations, ...
- Force/Torque Sensors: strain on structural components, torque in drive shafts and other rotating machinery, ...
- Flow Sensors: flow rate of air, fuel, hydraulic system, ...
- Inertial Measurement Units: comprehensive data on the aircraft's orientation, velocity, and acceleration.
- Environmental:parameters in the cabin and other critical areas; detect the formation of ice on critical surfaces.
- And many others!

Introduction

Addressing all these sensors (even briefly) would require a whole semester.

For this reason we will study just a few of the more representative and common:

- Temperature
- Force/Torque Sensors
- Pressure
- Environmental



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Integrated sensor types

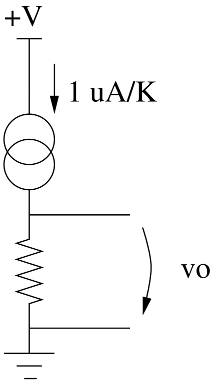


Figure: Current output

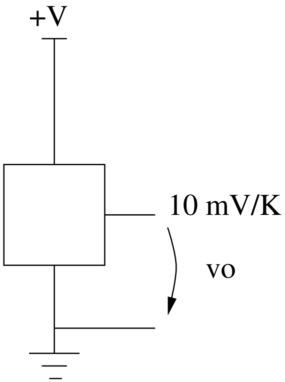


Figure: Voltage output

Integrated temperature sensors: current output

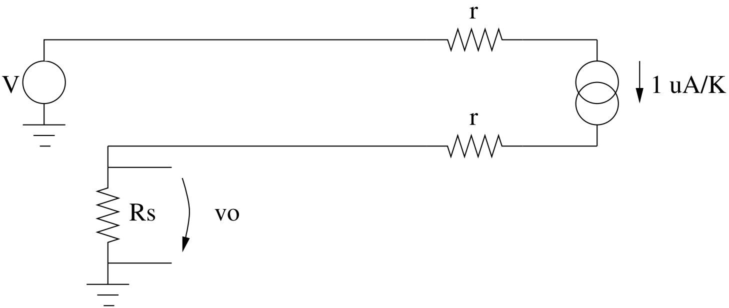


Figure: Reading circuit

How does it compare with a voltage output integrated sensor?

Operation principle

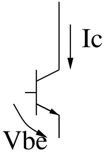


Figure: Reading circuit

Operation principle

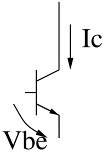
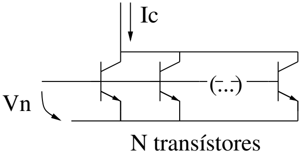


Figure: Reading circuit

$$V_{\mathrm{BE}} = \frac{k\Theta}{q} \ln\left(\frac{I_{\mathrm{C}}}{I_s}\right)$$

k	Boltzmann constant;
Θ	temperature (kelvin);
q	electron charge;
I_s	reverse saturation current, function of geometry and temperature of the transistor

Operation principle



$$V_N = \frac{k\Theta}{q} \ln\left(\frac{I_\mathrm{C}}{NI_s}\right)$$

$$\Delta V_\mathrm{BE} = V_\mathrm{BE} - V_N = \frac{k\Theta}{q} \ln(N)$$

- ΔV_BE is *proportional to absolute temperature* Θ
- Operation principle of the *Brokaw cell (voltage reference, 1.25V)*

Brokaw cell

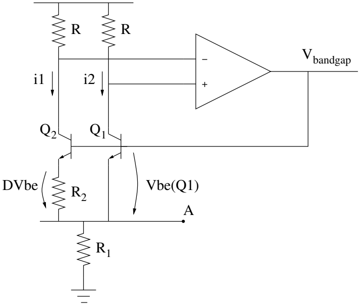


Figure: Brokaw cell: operation principle

$$V_A = \frac{R_1}{R_2} \cdot \frac{k\Theta}{q} \ln(N)$$

Thermistor

- Thermistor = Thermal + Transistor
- Temperature sensors
- NTC: Negative Temperature Coefficient (more common)
- PTC: Positive Temperature Coefficient
- Semiconductors, based on metal oxides

NTC response

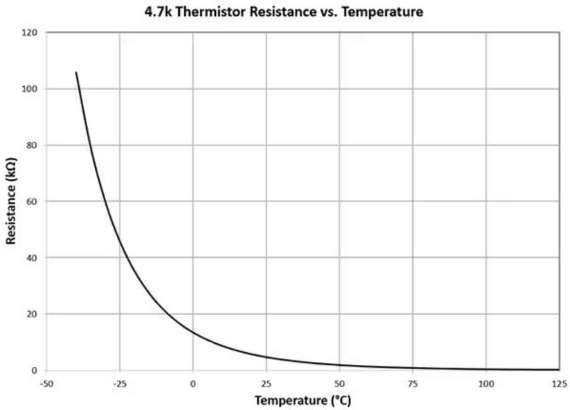
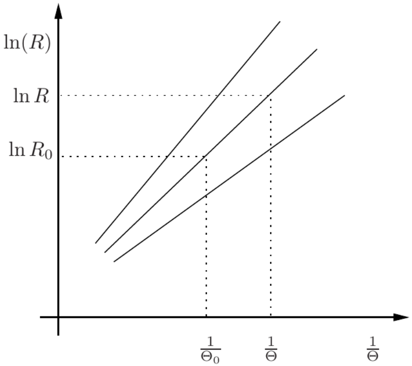


Image source: Bonnie Baker, calculated and drawn based on resistance values from Murata

NTC: Output Linearization



$$\beta = \frac{\ln(R) - ln(R_0)}{\frac{1}{\Theta} - \frac{1}{\Theta_0}}$$

Solving for R results:

$$R = R_0 * e^{\beta\left(\frac{1}{\Theta} - \frac{1}{\Theta_0}\right)}$$

Steinhart and Hart Equation

- Better approximation than linear model
- Originally from -2 to 30 °C
- Allows an accuracy of 0.02°C in a range of 100°C

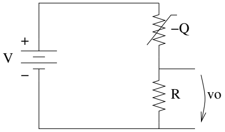
$$\frac{1}{\Theta} = a + b \ln R + c(\ln R)^2 + d(\ln R)^3$$

$$\frac{1}{\Theta} = a + b \ln R + d(\ln R)^3$$

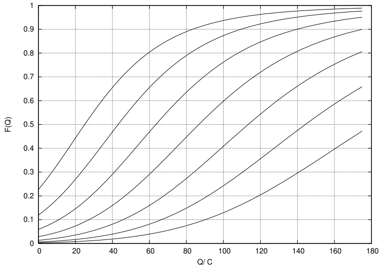
Circuits with thermistors

Goal: improve the output linearity

NTC in series with a resistor R.
There are other circuits ...



$$v_o = V \frac{R}{R+R_\Theta}$$



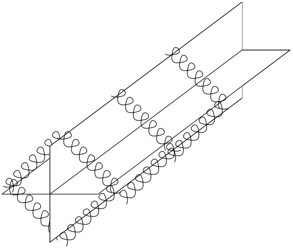
Computing R: Three points method for range $[\Theta_1, \Theta_3]$:

$$R = \frac{RT_2(RT_1+RT_3)-2RT_1RT_3}{RT_1+RT_3-2\cdot RT_2}$$

- RT_1: resist. of therm. for $\Theta = \Theta_1$;
- RT_3: resist. of therm. for $\Theta = \Theta_3$;
- RT_2: resist. of therm. for $\Theta = \Theta_2 = \frac{\Theta_1+\Theta_3}{2}$.

History

- Sir Humphrey David, 1821
- RTD: Resistance Temperature Detector
- 1932: C. H. Meyers



Working principle

Resistance of an electrical conductor:

$$R = R_0[1 + a_1(\Theta - \Theta_0) + a_2(\Theta - \Theta_0)^2 + a_3(\Theta - \Theta_0)^3 + ...]$$

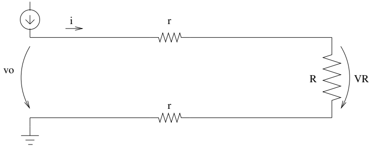
where R_0 is the value of the resistance at temperature Θ_0.
Making $a_1 = \alpha$ and $a_2, a_3, \cdots = 0$:

$$R = R_0[1 + \alpha(\Theta - \Theta_0)]$$

Reading circuits

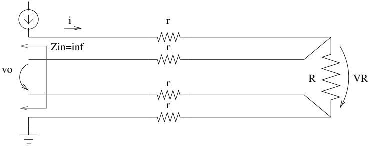
Usually excited with current source. Wire resistance can be important!

2-wire reading circuits



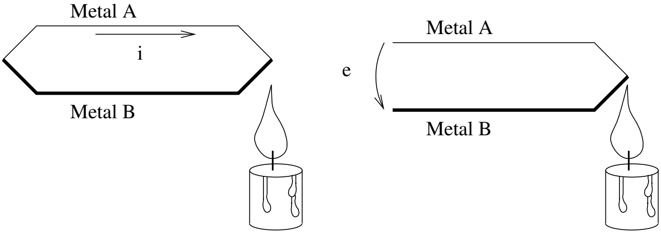
$$v_o = (R+2r)i$$
$$= v_R + 2ri$$

4-wire reading circuits



$$v_o = Ri = v_R$$

Thermocouples: Working Principle



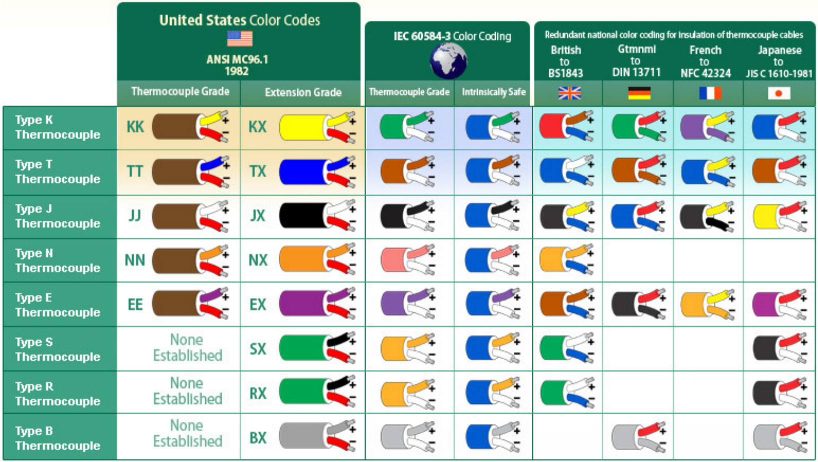
- Open thermoelectric circuit $\Rightarrow$ f.e.m. e_{AB}
- Δe_{AB} is (vaguely) proportional to the variation of the junction temperature.

$$\Delta e_{\mathrm{AB}} \approx \alpha \Delta \Theta$$

Types of Thermocouples

Type	Metals		Seebeck Coef.		Range
	+	-	(μV/K)@T(°C)		°C
B	Pt+30% Rh	Pt + 6% Rh	5.96	600	870-1700
E	Ni+10%Cr	Constantan	58.67	0	0-900
J	Fe	Constantan	50.38	0	0-750
K	Ni+10%Cr	Nickel	39.45	0	0-1250
R	Pt+13%Rh	Pt	11.36	600	0-1450
S	Pt+10%Rh	Pt	10.21	600	0-1450
T	Cu	Constantan	38.75	0	0-350

Color codes


United States Color Codes
ANSI MC96.1
1982
Thermocouple Grade
Extension Grade
IEC 60584-3 Color Coding
Thermocouple Grade
Intrinsically Safe
Redundant national color coding for insulation of thermocouple cables
British to BS1843
Gtmnml to DIN 13711
French to NFC 42324
Japanese to JIS C 1610-1981
Type K Thermocouple
KK
KX
Type T Thermocouple
TT
TX
Type J Thermocouple
JJ
JX
Type N Thermocouple
NN
NX
Type E Thermocouple
EE
EX
Type S Thermocouple
None Established
SX
Type R Thermocouple
None Established
RX
Type B Thermocouple
None Established
BX

Inverse Function Coeficients

$$T_{90} = d_0 + d_1 E + d_2 E^2 + \ldots + d_n E^n$$

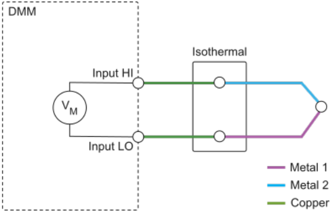
Type	J	
Range	-210 °C to 0 °C	0 °C to 760 °C
Error	±0.05°C	±0.04°C
d_0	0	0
d_1	1.9528268×10^{-2}	1.978425×10^{-2}
d_2	$-1.2286185 \times 10^{-6}$	-2.001204×10^{-7}
d_3	$-1.0752178 \times 10^{-9}$	1.036969×10^{-11}
d_4	$-5.9086933 \times 10^{-13}$	$-2.549687 \times 10^{-16}$
d_5	$-1.7256713 \times 10^{-16}$	3.585153×10^{-21}
d_6	$-2.8131513 \times 10^{-20}$	$-5.3442485 \times 10^{-31}$
d_7	$-2.3963370 \times 10^{-24}$	5.099890×10^{-31}
d_8	$-8.38233321 \times 10^{-29}$	

https://srdata.nist.gov/its90/main/

Often are used tables, particularly with micro-controllers

Cold-junction compensation

- Thermocouples do not measure temperatures - they do measure **temperature differences**!
- Unwanted/parasitic junctions **always** occur in reading circuits!

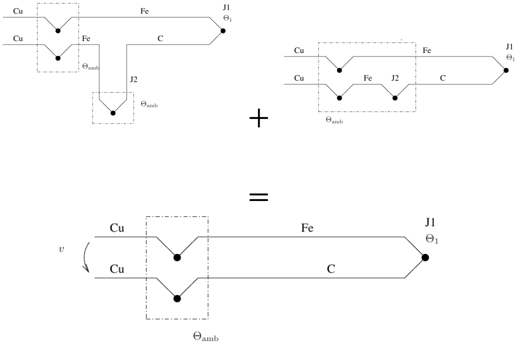


Example: reading the thermoelectric voltage using a digital voltmeter (assumed to be fully made of coper, which is not the case in reality)

Temperature compensation: incorporate the “ambient”/reference temperature in the measurement process

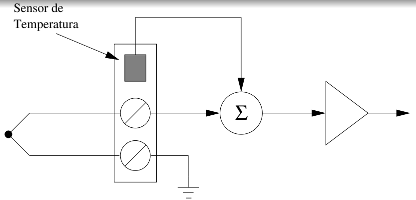
Cold-junction compensation

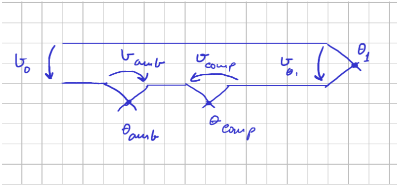
- Assuring that all connections to the measurement side are kept at the same temperature (say θ_{amb})
- Simplifying the circuit and applying the empirical laws



v is given by the DMM (or other method). θ_{amb} is measured with some other sensor (e.g. an integrated sensor). Then, the voltage at θ_1 can be computed.

Hardware Compensation





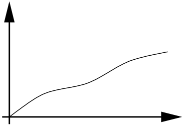
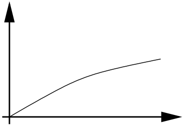
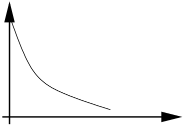
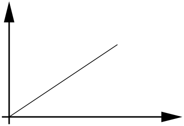
$$v_o = v_{\theta_1} + v_{comp} - v_{amb}$$

$$\text{if } v_{comp} = v_{amb}$$

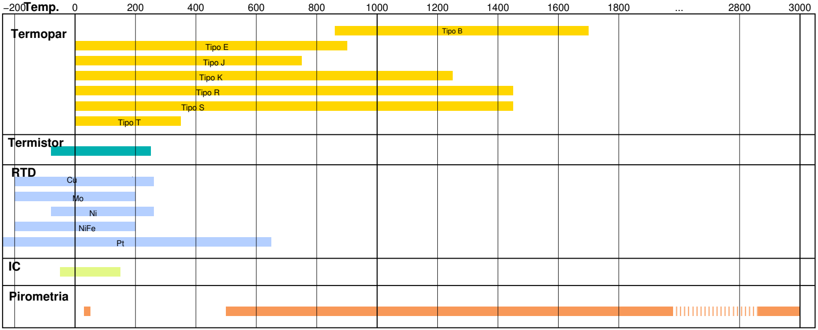
$$v_o = v_{\theta_1} \quad //$$

- If we have a voltage source capable to generate a compensation voltage that matches the parasitic voltage, V_{out} becomes only function of the process temperature.
- Often it is only possible to compensate for variations ($\Delta v_{comp} = \Delta v_{amb}$), resulting on offset error that can be compensated

Temperature Sensor Comparison

Thermocouple	RTD	Thermistor	Integrated
			
Advantages			
Active Simple Robust Cheap Big variety of shapes Big range of temperatures	More stable Exact More linear than thermocouples	Sensitive Quick	The most linear Output range Cheap
Disadvantages			
Non linear Low voltage Cold Junc. comp. Poor stability Low sensitivity	Expensive Slow Requires source of current Small Resist. variation	Non linear Small temp. range Fragile Requires current source Self heating	$\Theta < 250^\circ C$ Needs supply Slow Self heating Limited configurations

Utilization ranges



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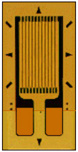
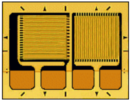
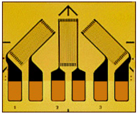
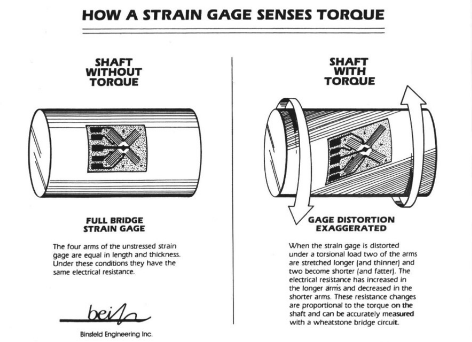
Strain gauges

Used for measuring forces, deformations, vibrations, ...

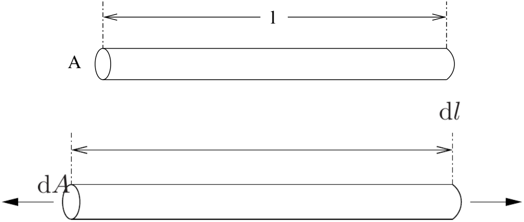








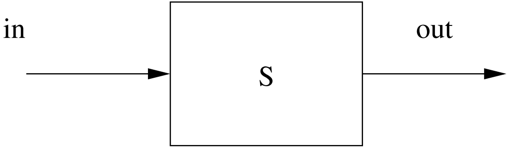
Operating principle



$$R = \rho \frac{l}{A}$$

$$\frac{\delta R}{R} = \frac{\delta \rho}{\rho} + \frac{\delta l}{l} - \frac{\delta A}{A}$$

Strain gauge as a transducer

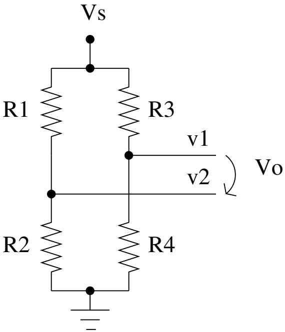


$$S_e = \frac{\Delta R/R}{\Delta l/l} = \frac{\Delta R/R}{\epsilon}$$

The sensitivity of a strain gauge (S_e) is commonly designated as Gauge Factor (GF).

- GF: Gauge Factor (unitless)
- ΔR: Change in resistance of the strain gauge (Ohms)
- R : Nominal (at rest) resistance of the strain gauge (Ohms)
- ϵ: Strain (ratio, dimensionless)

Wheatstone Bridge



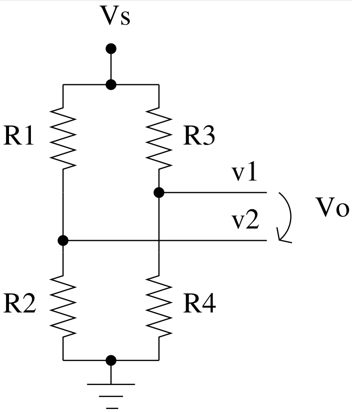
Output V_0 is ...

$$v_o = \frac{R_4 R_1 - R_2 R_3}{(R_1 + R_2)(R_3 + R_4)} v_s$$

$$\beta = \frac{R_1}{R_2} = \frac{R_3}{R_4} \Rightarrow v_o = 0$$

- Wheatstone Bridges provide **High Accuracy for Resistance Measurement**
- Because they rely on achieving a null state, can achieve very precise measurements of unknown resistance compared to simply measuring voltage across a resistor.

Wheatstone bridge: voltage supply



$$R_4 \rightarrow R_4 + \Delta R_4$$

And so ...

$$v_o = \frac{\beta}{(1+\beta)^2} \frac{\Delta R_4}{R_4} v_s$$

Wheatstone bridge: voltage supply

$R_i \rightarrow R_i + \Delta R_i \quad , i = 1, 2, 3, 4$

General equation:

$$v_o = \frac{\beta}{(1+\beta)^2}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} - \frac{\Delta R_3}{R_3} + \frac{\Delta R_4}{R_4}\right) v_s$$

Considering the non-linear terms:

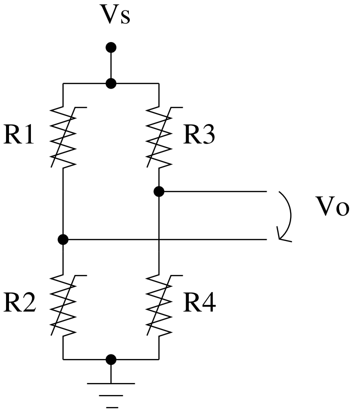
$$v_o = \frac{\beta}{(1+\beta)^2}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} - \frac{\Delta R_3}{R_3} + \frac{\Delta R_4}{R_4}\right)(1-\eta) v_s$$

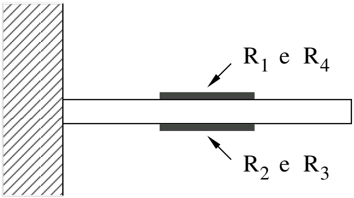
$$\eta = \frac{1}{1 + (1+\beta)\left[\frac{\Delta R_2}{R_2} + \frac{\Delta R_4}{R_4} + \beta\left(\frac{\Delta R_1}{R_1} + \frac{\Delta R_3}{R_3}\right)\right]^{-1}}$$

If $\beta = 1$:

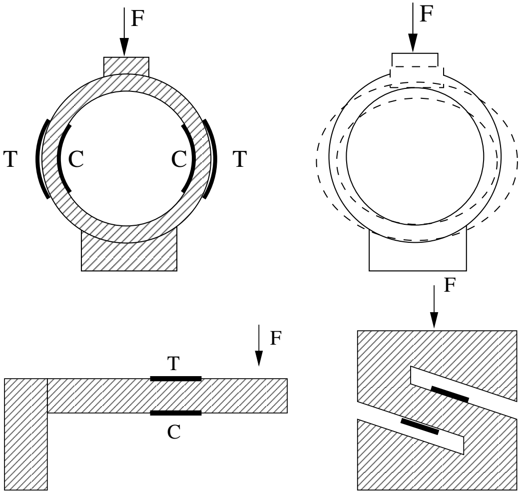
$$\eta = \frac{\sum \frac{\Delta R_i}{R_i}}{\sum \frac{\Delta R_i}{R_i} + 2}$$

Using 4 strain gauge





Load Cells



Load Cells - practical aspects

- Load cell datasheets provide a lot of very important information about its correct use
- These parameters include the range (rated capacity), voltage supply limits, sensitivity, temperature range, etc.
- Sensitivity is usually given in the form of Rated Output as "mV/V @ RC"

V: is the supply voltage

RC: is the Rated Capacity

Exercise

What is the output voltage of a load cell with a rated capacity of 5 kg and a supply voltage of 10 V:
- At rest
- Subject to a weigh of 2.5 kg.

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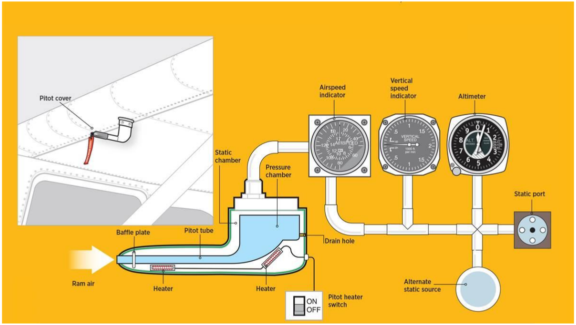
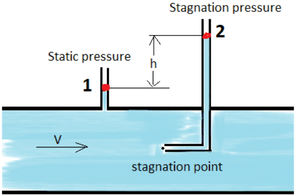
Pitot tube

- Pitot tubes: measures fluid flow velocity.
- Invented by a French engineer, Henri Pitot, in the early 18th century.
- Widely used to measure the airspeed of aircraft, speed of boats and flow velocity of liquids, air and gases in industry.



Source: https://www.aopa.org/news-and-media/all-news/2018/november/flight-training-magazine/how-it-works-pitot-static-system

Pitot tube - principle of operation



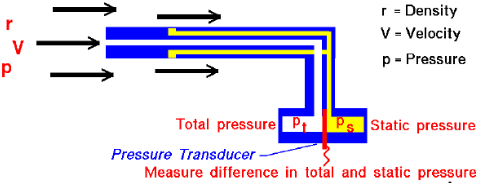
The Bernoulli's: **Stagnation pressure = static pressure + dynamic pressure**

$$p_t = p_s + \frac{\rho \cdot v^2}{2}, \text{ where:}$$

- v: is the flow velocity;
- p_t is the stagnation, total or Pitot pressure;
- p_s is the static pressure;
- ρ is the fluid density.

Solving for v we have: $v = \sqrt{\frac{2 \cdot (p_t - p_s)}{\rho}}$

Pitot tube - principle of operation



Source: https://www.grc.nasa.gov/www/k-12/VirtualAero/BottleRocket/airplane/pitot.html

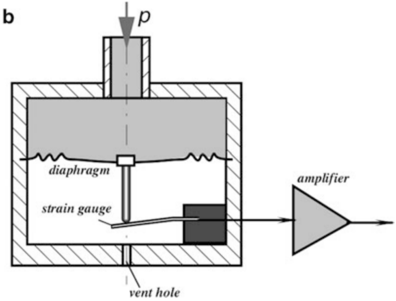
- It is necessary to use a pressure transducer to measure the difference between p_t and p_s
- Typically strain gauges are to this end

Other aspects to consider:

- Does not work for very low speeds. The pressure difference becomes too small to be accurately measured
- If the velocity is very high (supersonic), the assumptions of Bernoulli's equation are violated (corrections for shockwave effects must be applied)

Pressure sensors

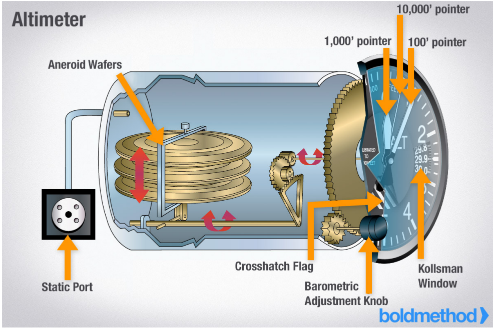
Typical **Pressure Sensors** contain a deformable element whose deformation or movement is measured by a suitable sensor and converted into an electrical signal representative of the pressure value.



Source: Handbook of Modern Sensors

Pressure sensors

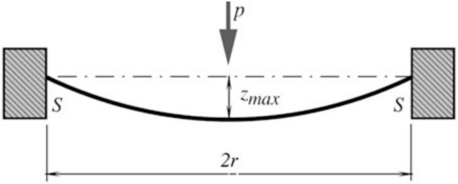
- If the “vent hole” is connected to a known/reference pressure, it becomes possible to measure the pressure difference.
- If such pressure reference is the sea level pressure (1,013.25 hPa or 760.00 mmHg) then we get an altimeter



Source:
https://www.boldmethod.com/learn-to-fly/systems/how-does-an-aircraft-altimeter-work-in-flight/

Pressure sensor

Nowadays most pressure sensors are based on MEMS, using silicon membranes.



Source: Handbook of Modern Sensors

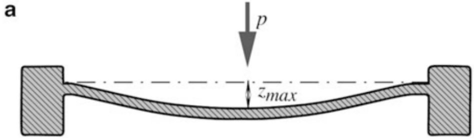
If the thickness of the membrane is $\ll$ than its radius the membrane deforms spherically For low pressure values, differences across the membrane, the center deflection z_{max}, and the stress σ_{max} are quasilinear functions of pressure.

$z_{max} = \frac{r^2 \cdot p}{4 \cdot S}$ and $\sigma_{max} \approx \frac{S}{g}$, where:

- S : radial tension (N/m)
- r : membrane radious
- g : membrane thickness
- z_{max} : maximum deflection
- σ_{max} : stress ($\frac{N}{m^2}$)

Pressure sensor

If thickness of the membrane is not negligibly small (r/g ratio is 100 or less), the membrane is no longer a “membrane” and it is called a thin plate



Source: Handbook of Modern Sensors

In this case we have:

$$z_{max} = \frac{3(1-\nu^2)r^4p}{16Eg^3} \text{ and } \sigma_m \approx \frac{3r^2p}{4g^2}$$

where:

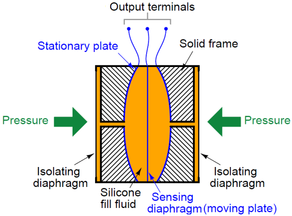
E : Young's modulus ($\frac{N}{m^2}$)

nu : Poisson's ratio

Pressure sensor

There are other types of
pressure sensors that operate over similar principles but use different technologies. These include:

Piezoelectric sensors:
Based on materials
such as quartz crystals or ceramics, which generate a charge when subject to a deformation/pressure. A special
circuit (charge amplifier) is used to converts charge into an output voltage proportional to the pressure.



Source: https://www.ouldsensors.com/what-is-capacitive-pressure-transmitter/

Capacitive sensors:
Consists of two parallel conducting plates separated by a small gap. The Capacitance depends on area, gap size and dielectric properties. One of the plates acts as the diaphragm and is moved by the pressure, changing the capacitance of the circuit.
Capacitance can be measured by means of the resonant frequency of a circuit or by the time taken to charge/discharge the capacitor (more common in digital systems)

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Humidity sensors

A few definitions:

Absolute humidity (or density of water vapor) : the mass (m) of water vapor per unit volume (v) of wet gas: $d_w = \frac{m}{v}$.

Relative humidity (RH) : ratio of the actual vapor pressure of air at any temperature, to the maximum of saturation vapor pressure at the same temperature: $H = 100\frac{P_w}{P_s}$, where P_w is the partial pressure of water vapor and P_s is the pressure of saturated water vapour at a given temperature.

H expresses the vapor content as a percentage of the concentration required to cause the vapor saturation, that is, the formation of water droplets at that temperature.

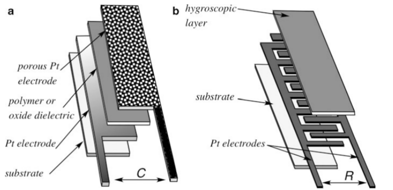
Humidity sensors

Most
humidity probes are composed of two electrodes with a non-conductive polymer film between the electrodes.

The moisture
from the environment affects the electrical characteristics of the film
These changes are measured
and correlated with the humidity

There are three
different types of humidity sensors:

- Capacitive (a)
- Resistive (b)
- Thermal conductivity

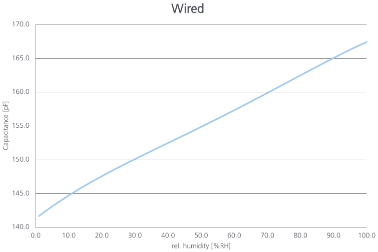


Source: https://www.ouldsensors.com/what-is-capacitive-pressure-transmitter/

Capacitive humidity sensors

With suitable materials and construction techniques it is possible to obtain an approximately linear relation between H and the capacitance. Thus:

$C_h \approx C_0(1 + \alpha_h \cdot H)$, where C_0 is the capacitance at $H = 0$



Source: IST, P14-W Capacitive Humidity Sensor Datasheet

RH depends on temperature. Some sensors compensate for temperature internally, while others require external correction. E.g. for the P14-W sensor, the datasheet indicates:

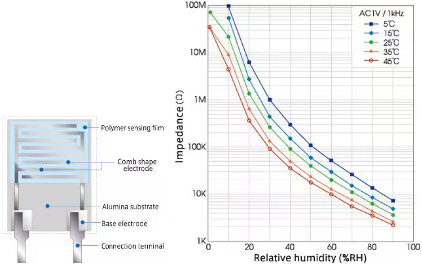
$$\Delta\%RH = (B1 \cdot \%RH + B2) \cdot T + (B3 \cdot \%RH + B4)$$

T is in ^oC and B1, B2, B3 and B4 constants are indicated in the datasheet

Resistive humidity sensors

The resistance of many nonmetal conductors depend on their water content. This is on the basis of resistive humidity sensors, aka hygristor.

E.g. the TDK sensor is made of a ceramic substrate (alumina), which has a relatively low resistivity that changes significantly with humidity conditions



Source: https://product.tdk.com/en/techlibrary/productoverview/numid sensors.html

As for the capacitive sensors, the output signal is strongly influenced by the air temperature, thus requiring proper compensation.

The hygristor's resistance is highly nonlinear, while its conductivity shows a reasonable linearity.

Ice detection sensors

Detect the presence of ice on a surface. Are used to identify the presence of icing conditions and are commonly used in aviation, UAVs, boats, power lines, etc.

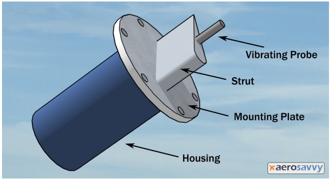
Main ice detector types:

- **Vibrating Probe Type** : The detector has a small probe or sensor that vibrates at a specific frequency. When ice builds up on the probe, the added mass changes the vibration frequency.
- **Optical Ice Detectors** : an optical ice detector directs a light beam (usually infrared or laser) onto a surface of the aircraft. The amount of light reflected back is affected by the presence of ice, as ice alters the way light is reflected compared to water or clear air.
- **Resistive Ice Detectors** : resistive element exposed to the external environment. As ice forms on this element, the electrical resistance changes because ice has different electrical properties than water or air.
- **Ultrasonic Ice Detectors** : The detector emits ultrasonic waves along the surface of a probe. Wave Distortion: Ice alters the propagation of these waves, changing their speed and/or attenuation.

Ice detection sensors - vibrating probe

E.g. the Collins Aerospace vibrating probe ice detector consists of a housing, mounting plate, wing-shaped strut, and a small probe. The device looks simple enough from the outside, but uses some interesting physics to do its job.

- A small wing shape protrudes outside the aircraft about 3 inches. A 2 inch long probe the size of a drinking straw protrudes out the end of the wing and is exposed to airflow.
- An electric current induces the probe to resonate (vibrate) at a specific ultrasonic frequency. Ice accumulation on the probe causes the resonance frequency to decrease.
- The probe has an internal heater to clear ice accumulation.

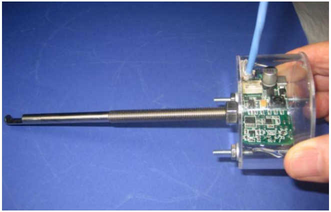


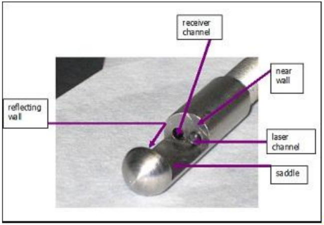
Collins Vibrating Probe Ice Detector, Source: https://aerosavvy.com/ice-detection/

Ice detection sensors - optical

E.g. NewAvionics Corporation Model 9732-STEEL aviation ice detector consists of two light-manipulating windows, an air gap facing the oncoming air stream, and a reflecting wall.

- In-flight ice sensing occurs when molecules of ice appear on the surfaces of either optical window and/or on the reflecting wall of the air gap at the end of the probe.
- Accumulating molecules of ice affect the reflectivity of the airgap wall, attenuate the signal, and trigger an ICE ALERT.





Source: IceMeister Model 9732-STEEL Ice Detecting Sensor for Aircraft Technical Data Sheet

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Accelerometers

Accelerometers are usually used together with gyroscopes in navigation systems, to measure angular velocity and linear acceleration.

These systems typically containing three orthogonal rate-gyroscopes and three orthogonal accelerometers.

The signals generated by these devices allow, after due processing, to track the position and orientation of a moving object.

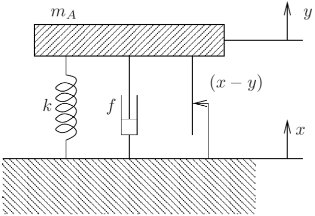
Accelerometers are used for measuring acceleration resulted from subjecting an object to external forces, including gravity.

Enricco Small Size Quartz Accelerometer For Aerospace

Accelerometers

The more common forms of accelerometers are composed of a mass suspended by a spring and damper inside a housing.

A displacement transducer allows to measure the instantaneous position of the mass.



$m_A \cdot \ddot{y} = k \cdot (x - y) + f \cdot (\dot{x} - \dot{y})$
making $z = (x - y)$
$m_A \cdot \ddot{y} = k \cdot (z) + f \cdot (\dot{z})$
in steady state we have: $a = \ddot{y} = \frac{k}{m_A} \cdot z$

- Typical resolution of this type of accelerometer is around 0.1% of full scale with an inaccuracy of 1%.
- Typical range goes from 0.03g 1000g full scale

Accelerometers - example of application

Besides the direct use for **navigation purposes**, accelerometers are also used to **monitor machinery and mechanical structures**, to detect eventual health issues.
Vibrations usually are of the form of linear harmonic motion and can be described by:

$$x = x_0 \cdot sin(\omega \cdot t)$$

Differentiating the equation twice we obtain:

$a = -\omega^2 \cdot x_0 \cdot sin(\omega \cdot t)$, and thus the peak acceleration becomes $a_{peak} = \omega^2 \cdot x_0$.

For example, accelerometer data can be used to obtain both a_{peak} and ω, allowing to obtain the maximum displacement of a structure.

Gyroscopes

Gyroscopes measure **both absolute angular velocity and absolute angular displacement**. This is useful for determining the orientation or rotation of an object.

There are two main technologies: mechanical (spinning wheel) and optical.

Optical gyroscopes have become the dominant technology in modern applications due to:

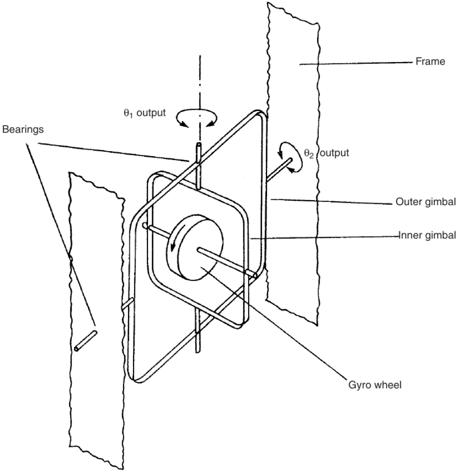
- Higher accuracy
- Smaller size
- No moving parts
- Lower power consumption

Gyroscopes: Free gyroscope structure

- Mechanical gyroscopes consist of “Gyro wheel”, which is a large motor driven wheel, whose angular momentum is such that the axis of rotation tends to remain fixed in space, setting a reference point.

- The gyro frame is attached to the body whose motion is to be measured

- Free gyros measure the absolute angular rotation of a body (there are other types)



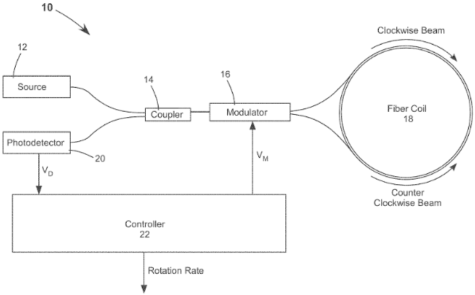
Source: Measurement and Instrumentation Principles

Gyroscopes: Fiber Optic Gyro

Based on the **Sagnac effect**.

The
Sagnac effect is a relativistic phenomenon that occurs when a light beam is split and travels around a closed loop in opposite directions. If there is a rotation, the path length traveled by the two beams will be slightly different, leading to a phase shift between them.

This phase
shift can be measured and used to determine the rate of rotation.



Source: PatentSwarm

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