Basics of signal processing, design of specimens, system acquisition

Basic of Sensor and Transducers

Dr. Simone Peloso

General principles

Meaningful interpretation of the model tests is not possible unless proper instrumentation is used for measuring the many important quantities related to the behaviour of the structure.

The instrumentation process includes:

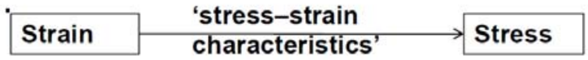
- Careful identification of the quantities to be measured;
- Selection of the appropriate sensors and the auxiliary equipment;
- Installation of the sensors on the completed model;
- Calibration of sensors;
- Checkout of equipment prior to the model test;
- Acquisition of data;
- Reduction of data into meaningful stresses, forces, and force–deformation relationships.

General principles

The behaviour of a structure is reflected in the forces and deformations that result from subjecting it to the different loading conditions.

In general the following quantities need measurement:

1. Strain*:* Strain may be measured in concrete, either by instrumenting the surface *or* by suitably embedding gages inside, or on the steel reinforcement and the prestressing strands.



2. Deflection*:* Its distribution along the structure and its variation with the applied load and magnitude in a structure or a constituent element. (Deflection measurements are needed to define the load–deformation characteristics and can be helpful in determining the limits of elastic behavior, curvature, and changes in curvature.)

Quantities to be measured

3. Cracks*:* Their locations, patterns, and widths related to the loading. (This information is used to determine satisfactory service load conditions and also to obtain the ultimate or limit load stress conditions.)

4. Forces*:* Their magnitudes and nature in the concrete or the steel reinforcement, at the boundary supports, and sometimes at loading points. (Knowledge of these internal forces, which are in equilibrium with the applied forces is especially useful in the study of indeterminate structures.)

5. Temperature: Its distribution within the mass of concrete, where the structure is subjected to differential temperature conditions.

6. Creep and shrinkage: Their measurements in a structure subjected to sustained loading. (These are similar to item 1 above, but care must be exercised to ensure that the instrumentation is stable over the entire period of measurement.

7. Properties of materials: They must be determined in order to translate other measurements (such as strains) into overall structural behaviour, and to correlate test results with theory. (Measurement of properties of concrete are particularly important since they are subject to variations from environmental conditions, such as relative humidity and temperature.)

Quantities to be measured

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8. Dynamic response*:* Various types of responses of a structure when subjected to dynamic loads (e.g. impact, blast, seismic, fatigue and repeated loadings). Accelerations, velocities, and displacements are measured.

NOTES:

- The equipment to measure the above quantities varies from simple hand instruments to the more-sophisticated electronic devices.
- The readout instruments accompanying these measuring devices also vary from hand-operated to continuous scanning, recording, and monitoring systems
- The outcome of any experimental program depends significantly on the accuracy and reliability of measurements. (In the case of small-scale models, the quantities to be measured are much smaller in magnitude, based on the principles of similitude thus magnifying the error possibility and the associated need for accuracy)

Perofrmance specification

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Proper selection and integration of sensors and transducers are crucial in "instrumenting" a vibrating system.

A measuring device passes through two stages in making a measurement.

The measurand is sensed

Sensor stage ↓

The measured signal is transduced (i.e. converted) into an electrical signal

Transducer stage ↓

Signal conditioning, Processing, or Recording

It is common practice to identify the combined sensor– transducer unit as either a sensor or a transducer

Performance specification

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In most applications, the following variables are particularly useful in determining the response and structural integrity of a vibrating system

Response Variable	Measuring Devices
Displacement	Potentiometer or LVDT
Velocity	Tachometer or Geophones
Acceleration	Accelerometer
Stress and Strain	Strain gauge

Transducers are divided into two broad categories:

Passive transducers do not require an external electric source for activation: electromagnetic, piezoelectric and photovoltaic transducers

Active transducers do not possess self-contained energy sources and thus need external activation: resistive transducers such as potentiometers

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Performance specification

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Transducers

Generally speaking, a **transducer** is a device that converts one type of energy to another.

Transducers are the input element in a measurement system.

The transducer is the device sensing the physical quantity that is to be measured and producing an electrical output.

A transducer may contain one or more sensors which transmit a signal to a measurement unit producing the electrical output.

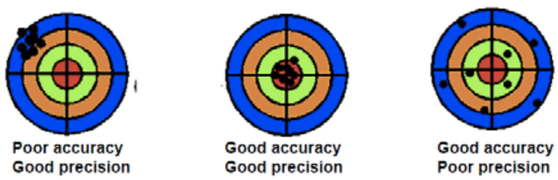
Accuracy and Precision

The measurement accuracy determines the closeness of the measured value to the true value.

$$\text{Error} = \frac{(\text{MeasuredValue}) - (\text{TrueValue})}{(\text{TrueValue})}\,\%$$

The measurement error may be represented by a random variable using its mean value and its standard deviation

The precision of an instrument is determined by the standard deviation of error in the instrument response.



Sensitivity and Resolution

The sensitivity of a transducer is defined as

$$\text{sensitivity} = \frac{\text{change in electrical quantity}}{\text{change in physical quantity}}$$

The sensitivity may be computed from the input-output relationship as the derivative dy/dx.

When the relationship is linear, the sensitivity is the angular coefficient of the straight line *a*.

The resolution of a sensor is the smallest change it can detect in the quantity that it is measuring.

Input-Output relationship

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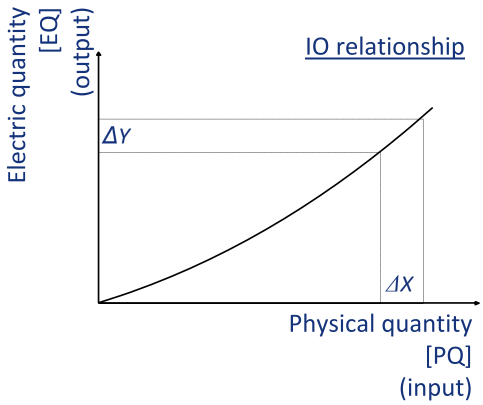
In static conditions, the behaviour of a transducer may be described by different parameters that can be deduced from the input-output relationship of the device.



The transducer is linear if its input-output relationship may be described by a straight line, i.e. in the form $y=ax+b$

Threshold and Range

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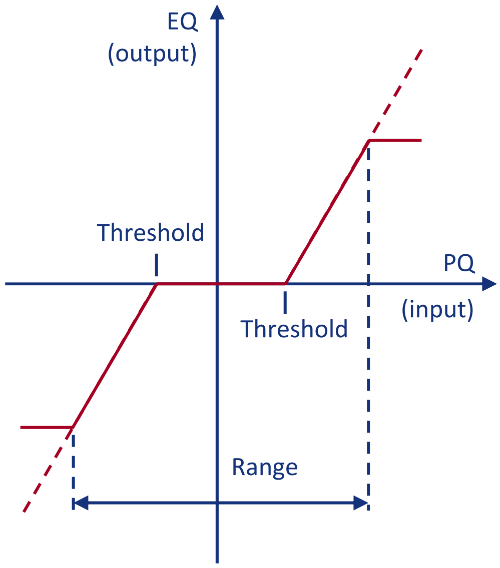
The threshold is the minimum input value for the physical quantity to produce a non zero output of the transducer.

The range is the interval of the physical quantity's values that the transducer is able to measure, defined by its inferior and superior limits.



Hysteresis and Errors

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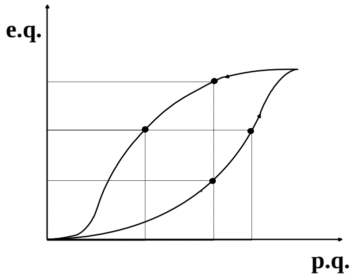
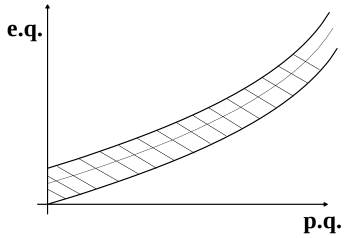
Hysteresis is the maximum difference between the increase and decrease paths of the transducer output during a cycle extending to the range limits.

A load curve and an unload curve must be used to infer the proper measurement.





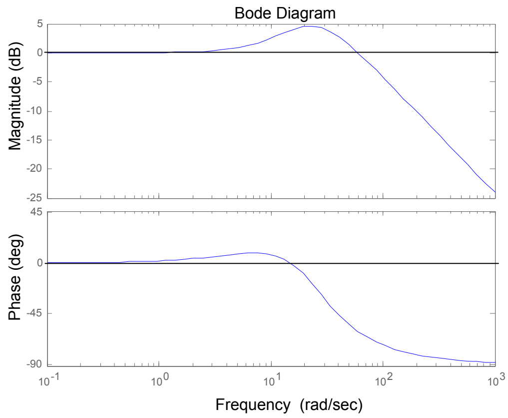
The error of a transducer is the difference between the real and the ideal transducer behavior.

The error band is the area around the input-output curve that covers the worse measurement error.

Dynamic behavior

When the physical quantities to be measured may vary rapidly in time, as in the case of dynamic tests, one needs to ensure that the transducers may be able to follow its changes without altering the measurement.

This may be accomplished by studying the sensitivity of the transducer as a function of frequency, i.e. the bode diagram of the transfer function of the transducer.



Instrument ratings

In selecting a particular transducer (measuring device) for a specific vibration application, special attention should be give to its ratings, which usually are provided by the manufacturer, and the required performance specifications as provided by the customer (or developed by the system designer).

Typical rating parameters supplied by instrument manufacturers are:

Sensitivity of a transducer is measured by the magnitude (peak, root-mean-square [RMS] value, etc.) of the output signals corresponding to a unit input of the measurand. This may be expressed as the ratio of (incremental output)/(incremental input) or, analytically, as the corresponding partial derivative. In the case of vectorial or tensorial signals (e.g., displacement, velocity, acceleration, strain, force), the direction of sensitivity should be specified.

Cross-sensitivity is the sensitivity along directions that are orthogonal to the direction of primary sensitivity; it is expressed as a percentage of the direct sensitivity. High sensitivity and low cross sensitivity are desirable for measuring instruments. Sensitivity to parameter changes, disturbances, and noise has to be small in any device, however; this is an indication of its robustness. Often, sensitivity and robustness are conflicting requirements

Instrument ratings

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Dynamic range of an instrument is determined by the allowed lower and upper limits of its input or output (response) so as to maintain a required level of measurement accuracy. This range is usually expressed as a ratio, in decibels. In many situations, the lower limit of the dynamic range is equal to the resolution of the device. Hence, the dynamic range is usually expressed as the ratio (range of operation)/(resolution), in decibels.

Linearity is determined by the calibration curve of an instrument. The curve of output amplitude vs. input amplitude under static conditions within the dynamic range of an instrument is known as the static calibration curve. Its closeness to a straight line measures the degree of linearity. Manufacturers provide this information either as the maximum deviation of the calibration curve from the least squares straight-line fit of the calibration curve or from some other reference straight line. If the least squares fit is used as the reference straight line, the maximum deviation is called independent nonlinearity, Nonlinearity may be expressed as a percentage of either the actual reading at an operating point or the full-scale reading.

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Instrument ratings

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Zero drift is defined as the drift from the null reading of the instrument when the measurand is maintained steady for a long period. Note that in this case, the measurand is kept at zero or any other level that corresponds to null reading of the instrument.

Usual causes of drift include:

- instrument instability
- ambient changes (e.g., changes in temperature, pressure, humidity, and vibration level)
- changes in power supply (e.g., changes in reference DC voltage or AC line voltage),
- parameter changes in an instrument (due to aging, nonlinearities, etc.).

Bandwidth of an instrument determines the maximum speed or frequency at which the instrument is capable of operating. High bandwidth implies faster speed of response. Bandwidth is determined by the dominant natural frequency of the transducer. Instrument bandwidth must be several times greater than the maximum frequency of interest in the measured signal. The bandwidth of a measuring device is important, particularly when measuring transient signals. Note that the bandwidth is directly related to the useful frequency range.

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Instrument ratings

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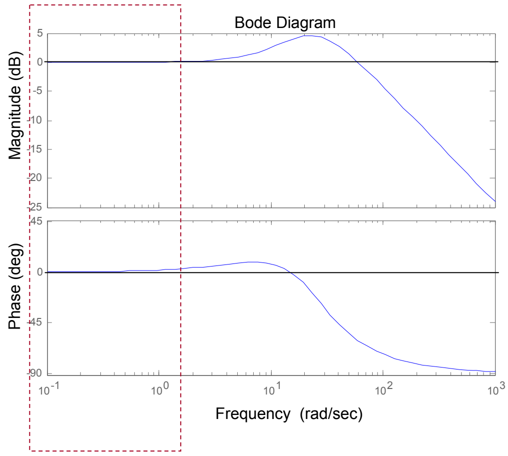
Useful frequency range
corresponds to the interval of both flat gain and zero phase in the frequency response characteristics of an instrument. The maximum frequency in this band is typically less than half the dominant resonant frequency of the instrument.



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Instrument ratings

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Examples of rating parameters of several sensors and transducers

Transducer	Measurand	Accuracy	Typical Resolution	Sensitivity
Potentiometer	Displacement	0.1%	0.1 mm	200 mV/mm
LVDT	Displacement	0.3%	0.001 mm or less	50 mV/mm
Resolver	Angular displacement	0.2%	2 min	10 mV/deg
Tachometer	Velocity	0.5%	0.2 mm/sec	5 mV/mm/sec; 75 mV/rad/sec
Eddy current proximity sensor	Displacement	0.5%	0.001 mm 0.05% full scale	5 V/mm
Piezoelectric accelerometer	Acceleration (and velocity, etc.)	1%	1 mm/sec^2	0.5 mV/m/sec^2
Semiconductor strain gage	Strain (displacement, acceleration, etc.)	1%	1 to 10 μsec(1 μsec = 10^{-6} unity strain)	1 V/ε, 2000 μsec max
Loadcell	Force (10–1000 N)	0.05%	0.01 N	1 mV/N
Laser	Displacement/shape	0.5%	1.0 μm	1 V/mm
Optical encoder	Motion	± 1/2 bit	10 bit	10^4/rev

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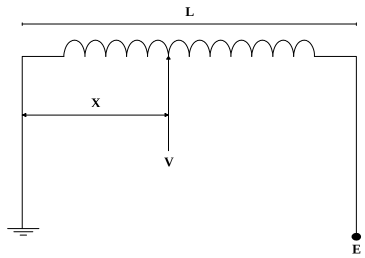
Linear position transducers

Linear potentiometers are devices allowing to transduce linear displacements.

They have three connectors: ground, V_{cc} (supply) and V (output connector).

Resistance-based potentiometers may use a wire winding around cylindrical core or a thin carbon layer as resistors.

The output connector may translate and is rigidly attached to the object whose displacement we want to measure. The displacement of the object of interest therefore causes a displacement of the cursor on the resistor (X), which causes a change in the output voltage of the pot.



$$\frac{X}{L} = \frac{V}{E}$$

If the resistance has uniform resistivity

$$V = \frac{XE}{L}$$

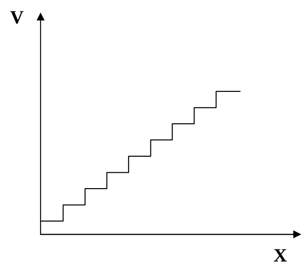
Wire vs Carbon

A common drawback of the wrapped wire potentiometer is the resulting discrete resolution of its input-output relationship: each wrapping (coil) produces a step in the output function.

The life span of these transducers is limited by the wearing of the resistance due to mechanical friction.

The force necessary to overcome the friction of the cursor alters the measurement.

A conditioning circuit to filter out the high frequency noise related to cursor displacement is usually necessary

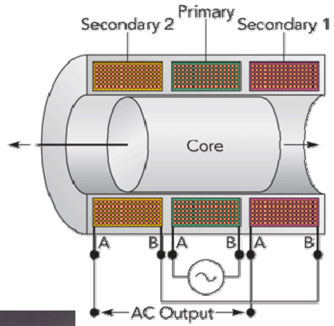


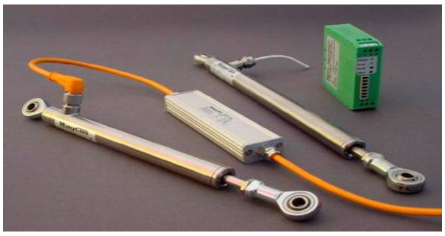
Potentiometers based on a carbon film overcome the resolution limitation of wired pots, yet they tend to be less linear and wear down faster.

Linear Variable Differential Transformer (LVDT)

The operation of the LVTD is based on the principle of variable mutual inductance.

The transducer consists of one primary coil and two secondary coils which are coupled through a moving core whose position is tied to the displacement to be measured.



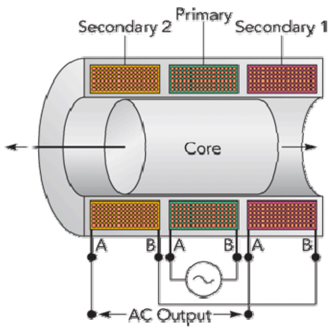


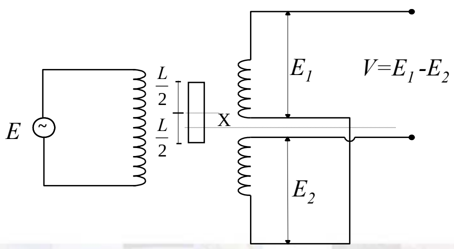
Linear Variable Differential Transformer (LVDT)

An alternating current is driven through the primary, causing a voltage to be induced in each secondary proportional to its mutual inductance with the primary.

As the core moves, these mutual inductances change, causing the voltages induced in the two secondary to change.

The coils are connected in reverse series, so that the output voltage is the difference between the two secondary voltages.





Linear Variable Differential Transformer (LVDT)

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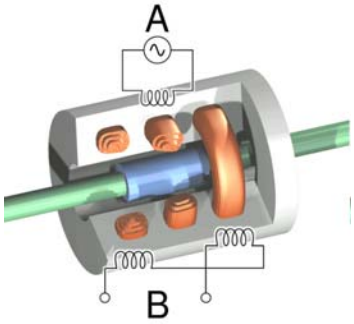
When the core is in its central position equal but opposite voltages are induced in the two secondary coils and the output voltage is zero.

When the core is displaced in one direction, the voltage in one coil increases as the other decreases, causing the output voltage to increase from zero to a maximum, corresponding to the flux concatenating only the first coil.



The magnitude of the output voltage is proportional to the distance moved by the core, making it a linear transducer.

Linear Variable Differential Transformer (LVDT)

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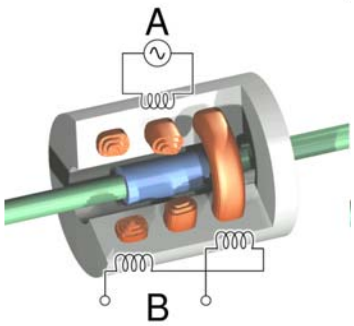
When the core is displaced in one direction, the voltage in one coil increases as the other decreases, causing the output voltage to increase from zero to a maximum, corresponding to the flux concatenating only the first coil.

This voltage is in phase with the primary voltage.

When the core moves in the other direction, the opposite occurs and the phase of the output voltage is opposite to that of the primary.



The phase of the voltage indicates the direction of the displacement.

LVDT principles

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The magnetic flux for each coil facing the core will be $\Phi = BS$

Thus if N1 and N2 are the coils facing the core, the flux concatenating with the secondary windings becomes:

$$\Phi_1 = \Phi N_1(X)$$
$$\Phi_2 = \Phi N_2(X)$$

Thus the electromotive force induced in each secondary is:

$$E_1 = j\,\omega\,\Phi_1$$
$$E_2 = j\,\omega\,\Phi_2$$

And therefore the differential output voltage will be:

$$V = E_1 - E_2 = j\omega\Phi\left[N_1(X) - N_2(X)\right]$$

Considering that n indicates the number of coils per unit displacement in the two secondary windings, the output voltage is related to the core displacement X by:

$$V = j\omega\Phi 2nX$$

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Linear Variable Differential Transformer (LVDT)

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The secondary output signal is then processed by a phase-sensitive demodulator which is switched at the same frequency as the primary energy supply.

This results in a final output which, after rectification and filtering, gives D.C. output proportional to the core movement and also indicates its direction, positive or negative from the central zero point.

Because the sliding core does not touch the inside of the tube, it can move without friction, making the LVDT a highly reliable device.

The absence of any sliding or rotating contacts allows the LVDT to be completely sealed against the environment.

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Linear Variable Differential Transformer (LVDT)

LVDTs are commonly used for position feedback in servomechanisms, and for automated measurement in machine tools and many other industrial and scientific applications.

Instruments: Objectives

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Measurement of the quantities of interest:

Deformations

Local information:
- **Element curvatures in the critical sections**
- **Steel strain across the plastic hinges**

Displacements

Damage related quantities:
- **Floor displacements and rotations**
- **Interstorey drifts**
- **Shear deformation of infill panels**

Accelerations

Global quantities:
- **Floor accelerations (dynamic amplification of motion)**
- **Proportions between the accelerations at different points across the structure (dynamic identification)**

Instruments: Objectives

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Measurement of the quantities of interest:

Deformations

Direct Measure:
- **Strain Gauges**

Derived Measure:
- **Rectilinear Displacement Transducers**

Displacements
- **Video acquisition with High Definition Cameras**

Accelerations
- **Accelerometer**

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Instruments

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Rectilinear Displacement Transducers

Direct measure:
- **Relative displacements between the two ends of the instruments.**

Derived measure:
- **Average deformation along the instrument length;**
- **Average curvature (with more than one instrument)**

Useful stroke from 25 to 250 mm

Infinite resolution

Displacement speed up to 10 m/s

Displacement force < 0.5 N

Electric output 0÷10 V

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Instruments

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Rectilinear Displacement Transducers

Derived measure:

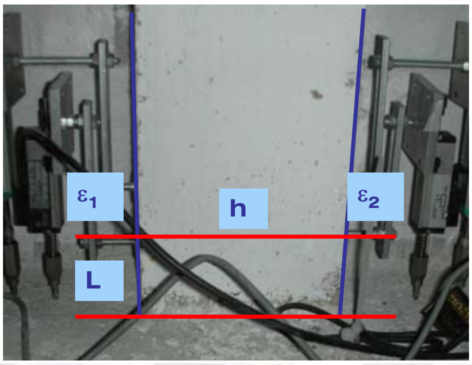
Average deformation

Average curvature

$$\varepsilon_1 = \frac{\Delta_1}{L}$$

$$\varepsilon_2 = \frac{\Delta_2}{L}$$

$$\chi = \frac{\varepsilon_1 - \varepsilon_2}{h}$$



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Instruments

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Rectilinear Displacement Transducers

Derived measure:

Shear deformation of infill panels

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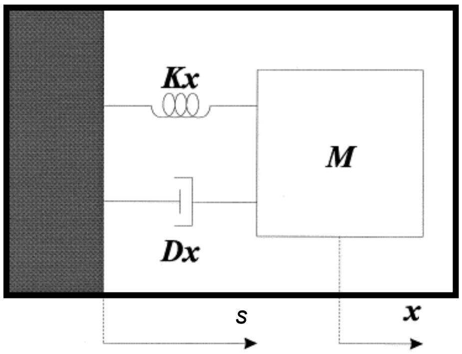
Accelerometers

An accelerometer is a transducer measuring proper acceleration (i.e. relative to free fall, or an inertial frame).

The most common accelerometer consists in a box containing a known mass which can move on a linear path and is held by a spring attached to the box.

The mass is also attached to a damper, introducing a viscous term in the equilibrium equation and reducing the oscillations which would result from step displacements.

The displacement of the mass is then transduced by a linear potentiometer (friction less).



$$-M\,(\ddot{x}+\ddot{s})-D\,\dot{x}-K\,x=0$$

Mass Spring Damper Accelerometer

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When the accelerometer experiences an acceleration, the mass is displaced to the point that the spring is able to accelerate the mass at the same rate as the casing. The displacement is then measured to give the acceleration.

$$-s^2 M\,x(s)-Ma-D\,s\,x(s)-K\,x(s)=0$$

$$s^2 M\,x(s)-D\,s\,x(s)+K\,x(s)=-M\,a(s)$$

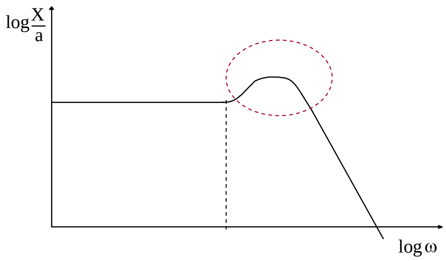
$$\frac{x(s)}{a(s)}=-\frac{1}{s^2+D/M\;s+K/M}$$

Frequency response

The dynamic response of the mass-spring-damper accelerometer typically resembles the one shown in figure.

At low frequencies, the relationship $X = -M/K \cdot a$ holds, while at relatively high frequencies there is a peak of resonance followed by a rapid gain decrease.

The applicability of these transducers therefore ranges between 0 rad/s and the resonance frequency ω_{res}



$$\omega_{res} = \sqrt{K/M}$$

MEMS accelerometers

Modern accelerometers take advantage of current manufacturing technologies allowing the miniaturization of devices and their implementation as *micro electro-mechanical systems* (MEMS).

These often measure the deflection of a heated gas bubble from the center of the device.

The square in the middle of the chip is a resistor that heats up a gas bubble. As the device is moved, surrounding thermal couples sense the location of the bubble.

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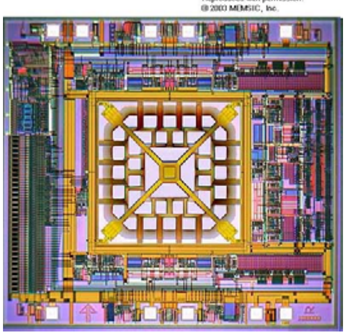

MEMS accelerometers

Modern accelerometers take advantage of current manufacturing technologies allowing the miniaturization of devices and their implementation as *micro electro-mechanical systems* (MEMS).

Most MEMS work in-plane: they are designed to be sensitive only to a one or two directions in the plane of the circuit. By adding an additional *out-of-plane* device three axes can be measured.

This solution always has a much lower misalignment error than three discrete devices combined.

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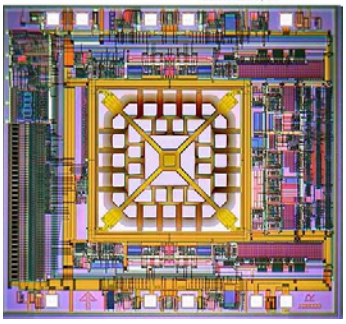
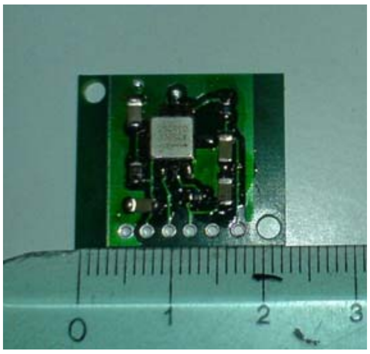


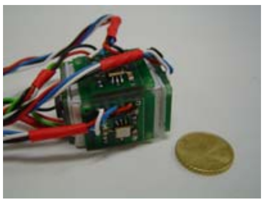
MEMS accelerometers

Typical MEMS accelerometers exhibit a ±1 g to ±10 g range.

Sensitivity is often ratiometric (i.e. the output of the instrument is directly proportional to the input), for a 5 V power supply these may be 25 to 500 mV/g, depending on the range of the device.

Manufacturers:
- Analog Devices;
- ST microelectronics;
- Memsic;
- …





Piezoelectric accelerometers

A piezoelectric accelerometer that utilizes the piezoelectric effect of certain materials to measure accelerations.

As with all transducers, piezoelectric accelerometers convert one form of energy into another, specifically they provide an electrical signal in response to the acceleration being measured.

Piezoelectric materials used for the purpose of accelerometers can also fall into two categories.

The first, and more widely used, is single-crystal materials (usually quartz).

PRO: long life span in terms of sensitivity;

CON: less sensitive than some piezoelectric ceramic.

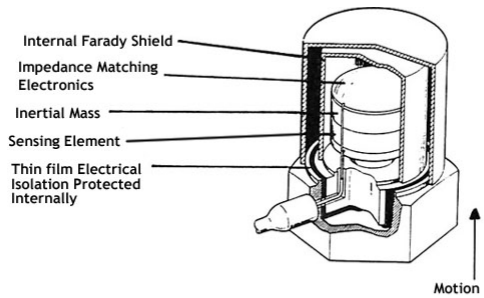
The second is piezoelectric ceramic materials.

PRO: higher piezoelectric constant (sensitivity); lower production costs;

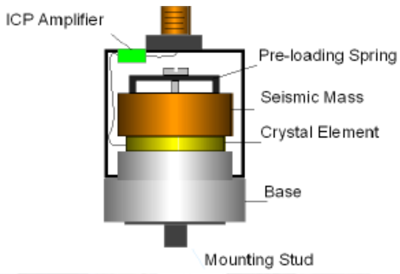
CON: their sensitivity degrades with time (shorter life span)

Piezoelectric accelerometers

Using the general sensing method upon which all accelerometers are based, acceleration acts upon a seismic mass that is restrained by a spring or suspended on a cantilever beam, and converts a physical force into an electrical signal.

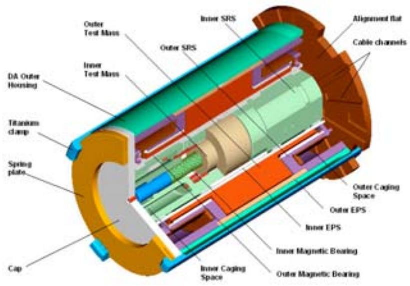


Before the acceleration can be converted into an electrical quantity it must first be converted into either a force or displacement. This conversion is done via the mass spring system shown in the figure.



Piezoelectric accelerometers

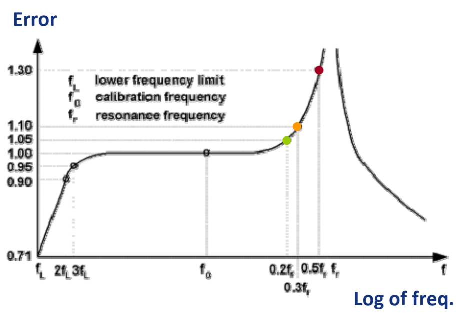
The seismic mass and the piezoceramics (plus other "flexible" components) form a spring mass system. It shows the typical resonance behavior and defines the upper frequency limit of an accelerometer. In order to achieve a wider operating frequency range the resonance frequency should be increased. This is usually done by reducing the seismic mass. However, the lower the seismic mass, the lower the sensitivity. Therefore, an accelerometer with high resonance frequency, for example a shock accelerometer, will be less sensitive whereas a seismic accelerometer with high sensitivity has a low resonance frequency.



Piezoelectric accelerometers

Figure shows a typical frequency response curve of an accelerometer when it is excited by a constant acceleration. Several useful frequency ranges can be derived from this curve:

- At approximately 1/5 the resonance frequency (0.2 f_r) the response of the sensor is 1.05. This means that the measured error compared to lower frequencies is 5 %.
- At approximately 1/3 the resonance frequency (0.3 f_r) the error is 10 %. For this reason the "linear" frequency range should be considered limited to 1/3 the resonance frequency.
- The 3 dB limit with approximately 30 % error is obtained at approximately one half times the resonance frequency.



Piezo-electric accelerometers

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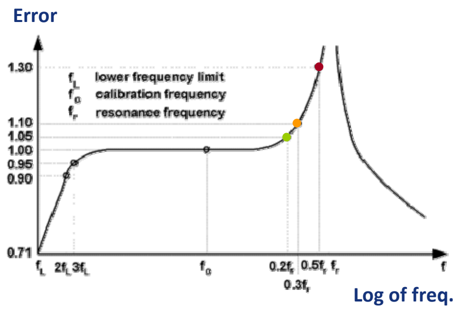
Figure shows a typical frequency response curve of an accelerometer when it is excited by a constant acceleration. Several useful frequency ranges can be derived from this curve:

The lower frequency limit mainly depends on the chosen preamplifier. Often it can be adjusted. With voltage amplifiers, the low frequency limit is a function of the RC time constant formed by accelerometer, cable, and amplifier input capacitance together with the amplifier input resistance.



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Positioning example

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Accelerometers

Direct measure:

•Single axis acceleration

Derived measure:

•Floor acceleration

•Floor displacement and rotation

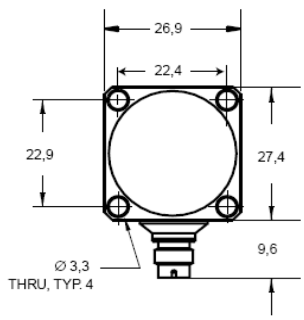
•Modal quantities

Acceleration range: ± 2.5 g

Resolution: 0.8 μg @ < 1Hz

Resonant frequency: 5000 Hz

Weight 28 grams



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Positioning example

Accelerometers

Direct measure:
•Single axis acceleration

Derived measure:
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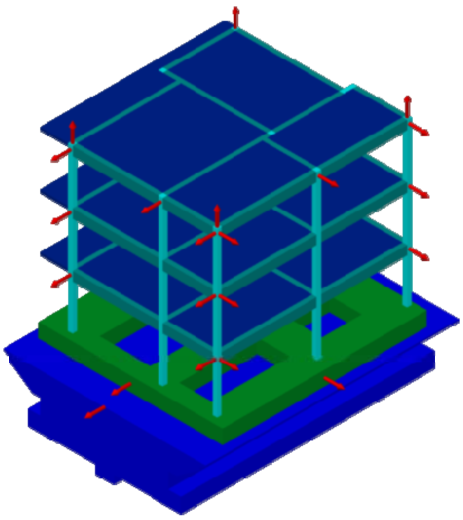
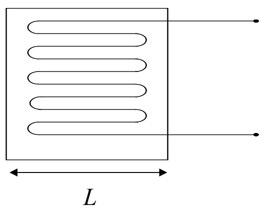


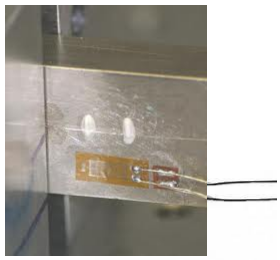
Strain gauge

A strain gauge is a device that measures the strain of an object by measuring the resulting deformation.

The most common type of strain gauge consists of an insulating flexible backing which supports a metallic foil pattern. In a typical strain gauge, a long, thin conductive strip is arranged in a zig-zag pattern of lines parallel to the direction of the measurement.

The gauge is attached to the object by a suitable adhesive. As the object is deformed, the foil is deformed, causing its electrical resistance to change. This resistance change, usually measured using a Wheatstone bridge, is related to the strain by a quantity known as the gauge factor.





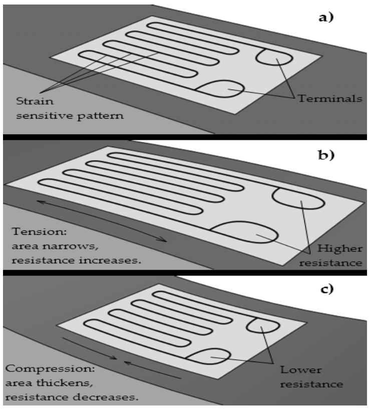
Strain gauge

A strain gauge is based on the property that electrical conductance (G=1/R) does not depend only on the conductivity of a conductor (a property of its material), but it depends also on its geometry.

When an electrical conductor is stretched it will become narrower and longer, thus increasing its electrical resistance end-to-end.

Conversely, when a conductor is compressed it will broaden and shorten, changes that decrease its electrical resistance end-to-end.

From the measured electrical resistance of the strain gauge, the amount of strain may be inferred and eventually the stress can be derived.



Gauge factor

The gauge is attached to the object with adhesive and, as the object is deformed, the gauge is deformed causing a change of its conductance. The sensitivity of the device is measured by the gauge factor:

$$g = \frac{\Delta R / R}{\Delta L / L}$$

Recall that the resistance of a conductor is related to its physical properties by

$$R = \rho \frac{L}{S}$$

Differentiating, the gage factor may be expressed as $g = 1 + \alpha + \frac{d\rho / \rho}{dL / L}$

Where $0<\alpha<1$

Typical g values for metallic gauges is above 2. For nickel-copper alloys it is 2, nickel-iron-chrome reaches 3.5 and pure nickel slightly above 12.

Higher g values may be obtained using superconductor materials, but their un-deformed resistance is then temperature dependent.

Strain gauge circuits

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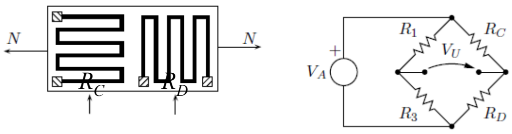
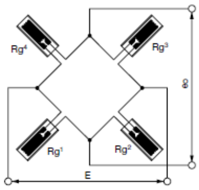
To compensate for the temperature influence on the resting resistance two identical strain gauges orthogonal to each other and connected as one leg of a Wheatstone bridge.



$$\Delta V_U = \frac{V_A}{4} g \frac{\Delta L}{L}$$

For two dimensional measurements, four strain gauges are typically used together building a full Wheatstone Bridge

Strain is defined as $\varepsilon = \frac{\Delta L}{L}$ and is therefore unit less



Applications

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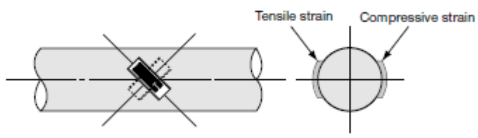
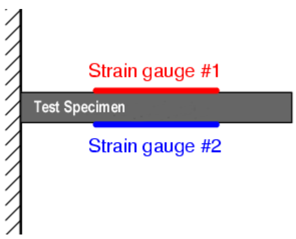
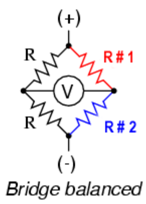
Strain gauges are the building component of other types of transducers for measuring forces (if applied to a test material of known properties), torques (using a pair of strain gauges measuring the torsional deformation of a rod) and pressures.







$$\Delta V = \frac{V_A}{2} g \frac{\Delta L}{L}$$

Strain gauge

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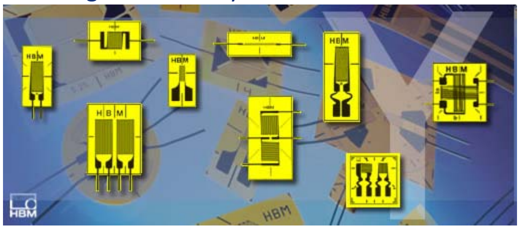
Strain gauges come in a variety of sizes and shapes.

Linear displacement transducers based on strain gages typically have a full measurement range between 5 and 100 mm. Typical crack detection gauges range 10 mm to 50 mm in strand length.

Strain measures are usually very small and are usually expressed in $\mu\varepsilon$.

Measuring strain requires accurate measurement of very small changes in resistance. For example, suppose a test specimen undergoes a substantial strain of 500 $\mu\varepsilon$. A strain gauge with a gauge factor g = 2 will exhibit a change in electrical resistance of only 2·(500 ´ 10^{-6}) = 0.1%. For a 200 Ω resistance the change will be only 2 Ω



Positioning example

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Strain Gauges

Direct measure:

- Deformation of steel bars across the plastic hinges

<u>Note</u>: the strain gauge has to be applied to the steel bar PRIOR to the concrete casting.

Seismometer

The seismometer is the transducer of ground movements and is used to record seismic waves during earthquakes. The seismograph additionally includes a recording device. Seismometers may record ground displacement, velocity or acceleration vs. time.

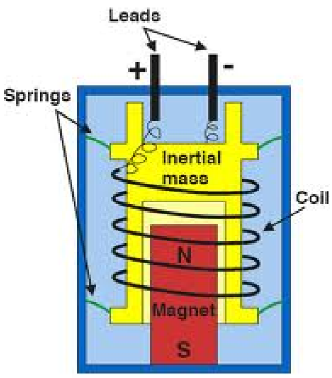
The working principle of the traditional seismometer is similar to that of the mass-spring accelerometer: a mass is free to move with respect to its casing while held to it by a spring-damper system. When the ground moves, the mass tends to remain motionless in space while the frame moves with the ground. The movement of the internal mass relative to the frame is measured.

A replica of an ancient Chinese Siesmograph from Eastern Han Dynasty (25-220 CE)

Seismometer

Geophones use a magnetic mass moving within a wire coil, producing an electrical signal which is proportional to ground velocity. Their frequency response is that of a harmonic oscillator, with corner frequency typically around 10Hz.

$$\omega_{res} = \sqrt{K/M}$$



Teleseismometers

Modern broadband seismometers allow the measurement of movements at frequencies between close to 0.001 Hz to 30 Hz.

These instruments use a negative feedback loop to hold the mass still in space with respect to the frame using an electromagnetic field. The force used to hold the mass steady is measured and ground acceleration is inferred. Devices may be multiple axis by using separate masses.

Movements of the internal mass is measured using a LVDT and represent the error which the negative feedback control loop attempts to drive to zero by varying the current driving the electromagnetic field. The latter is a precise measurement of the force needed to hold the mass steady and its acceleration can therefore be inferred as $a=F/m$.

Data may be digitally recorded using an A/D converter and stored or periodically transmitted automatically.

Special care must be used for long term monitoring instruments being exposed to large temperature excursions and weather agents.

Force Measurement

Various types of instrumentation are available for directly measuring different forces, such as compression or tension.

- Load cells: for measuring reactions and external forces (strain gauge load cells are the most common)

- Embedded stress plugs or meters: for measuring stresses and strains inside a concrete structure

- Stress sensitive paints: between washers to measure forces by the electrical resistance of these paints

Although most of these are available commercially, often their use is precluded because of economic factors and the nature of the experiment; e.g., a load cell required for measuring reactions in a small-scale beam test may not be available in that small size or else may not fit in the available space for the measurement.

In such a case, laboratory available equipment can be easily used to fabricate the required load cell.

Load cells

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A load cell is an electronic device (transducer) that is used to convert a force into an electrical signal.

This conversion is indirect and happens in two stages:

1) Through a mechanical arrangement, the force being sensed deforms a strain gauge.

2) The strain gauge converts the deformation (strain) to electrical signals.

A load cell usually consists of four strain gauges in a Wheatstone bridge configuration.

The electrical signal output is typically in the order of a few millivolts and requires amplification by an instrumentation amplifier before it can be used.

The output of the transducer is plugged into an algorithm to calculate the force applied to the transducer

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Load cells: Wheatstone bridge

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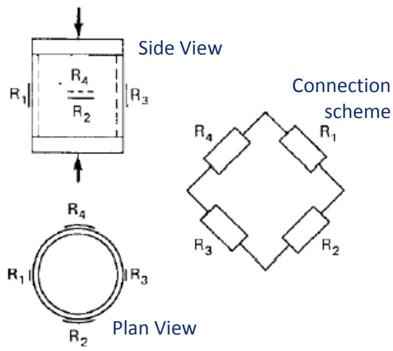
A basic load cell of any of these kinds consists of a complete strain gage bridge

The strain gages 1, 2, 3, and 4 are arranged so as to eliminate the effect of the undesired stress components. From bridge theory, the output of the bridge may be expressed as:

$$\varepsilon_0 = -\varepsilon_1 + \varepsilon_2 - \varepsilon_3 + \varepsilon_4$$



If the strain gages reading strains ε_2 and ε_4 are placed in the load cell so as to read strains opposite in sign to strains ε_1 and ε_3 , the sensitivity and accuracy of the load cell improves.

This is accomplished by placing R_1 and R_3 in the direction of the applied force and R_2 and R_4 in the transverse direction

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Load cells

Thus $\varepsilon_0 = K\,\varepsilon_1$ where K = brdge multiplication factor (K = 2.6 if Poisson's ration is 0.3).

Sensitivity of a load cell may be expressed in units of strain per unit load. Thus, it is directly proportional to the maximum stress used in the design of the cell and inversely proportional to its maximum load capacity.

$$\varepsilon_0 = K\,\varepsilon_1 = K\,\frac{\text{design stress}}{E}$$

$$\text{Sensitivity} = \frac{\varepsilon_0}{\text{design load}} = \frac{\text{design stress}}{\text{design load}}\,\frac{K}{E}$$

For a give design stress and design load, the optimum sensitivity will result from a maximum value of K and a minimum value of E

Typical load cells

Load cells are used for measuring loads and reactions and other forces and can be classified into categories, depending on the type of loading.

Compression Load Cells
Compression load cells often have an integral button design. They are ideal for mounting where space is restricted. They offer excellent long term stability.

Compression/Tension Load Cells
Compression/tension load cells can be used for applications where the load may go from tension to compression and vice versa. They are ideal for space restricted environments. Threaded ends facilitate easy installation.

S-Beam Load Cells
S-Beam load cells get their name from their S shape. S-Beam load cells can provide an output if under tension or compression. Applications include tank level, hoppers and truck scales. They provide superior side load rejection.

Bending Beam Load Cells
Used in multiple load cell applications, tank weighing and industrial process control. They feature low profile construction for integration into restricted areas.

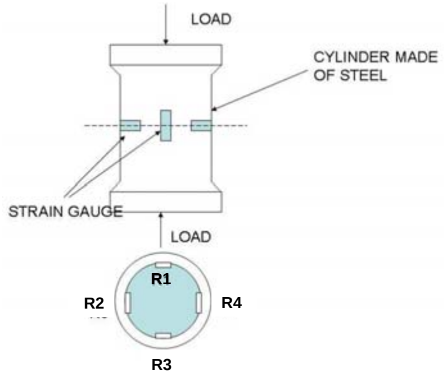
Platform and Single Point Load Cells
Platform and single point load cells are used to commercial and industrial weighing systems. They provide accurate readings regardless of the position of the load on the platform.

Canister Load Cells
Canister load cells are used for single and multi-weighing applications. Many feature an all stainless steel design and are hermetically sealed for washdown and wet areas.

Load cells

A vast number of load cell types have developed over the years:

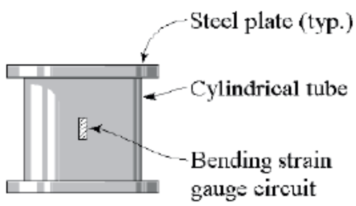
The first designs simply use a strain gauge to measure the direct stress which is introduced into a metal element when it is subjected to a tensile or compressive force

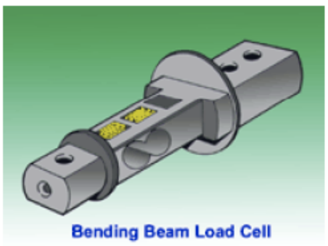


Bending load cells

A bending beam type design uses strain gauges to monitor the stress in the sensing element when subjected to a bending force.

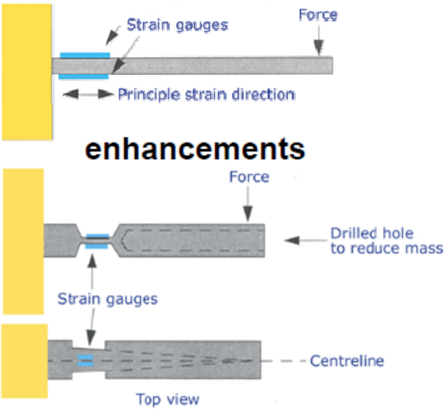
The strain gauges are bonded on the flat upper and lower sections of the cell at points of maximum strain. This load cell type is used for low capacities and performs with good linearity. Its disadvantage is that it must be load correctly to obtain consistent results.





Bending load cells

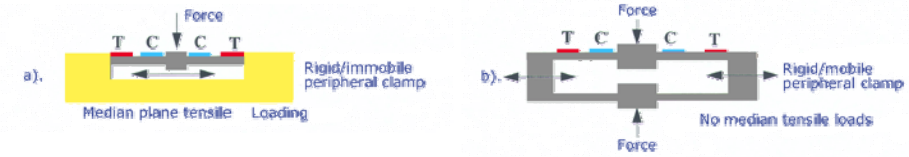
Since the majority of the beam length serves only to increase the moment at the rigid clamp, various modifications of the simple beam are used to reduce the beam mass in the interest of maintaining a high natural frequency or to concentrate the strain at the strain gauge locations.



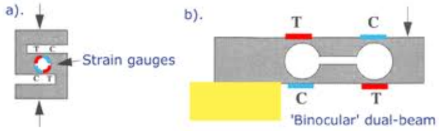
A review of beam bending characteristics reveals that the surface strain present in the beam surface linearly varies from the point of force application to the clamp. This implies that the strain gauges will experience a strain gradient and provide an output equating to the average strain. Constant stress beam sections can be fabricated by tapering the edges of the beam such that the tapered edges projected intersect at the point of load application to the beam

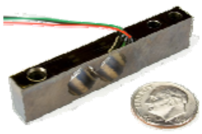
Bending load cells

Multiple cantilever structures produce a "multiple bending" where tension and compression strain fields exist on the same surface of the beam.



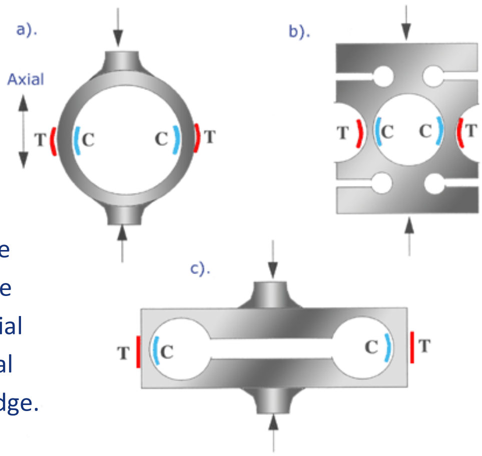
Coupled dual-beam load cell configurations conveniently produce equal and opposite axial loads within each of the beams in response to extraneous couples. Since the strain gauges can be wired to cancel the effects of axial loads, the result is a load cell structure largely insensitive to the point of load application. The sensitivity of the load cell to off-axis loads is minimized.





Bending Ring (Morehouse proving ring)

Both axial and bending occur within the transduction zone of the sensor characterizes ring-style load cells.

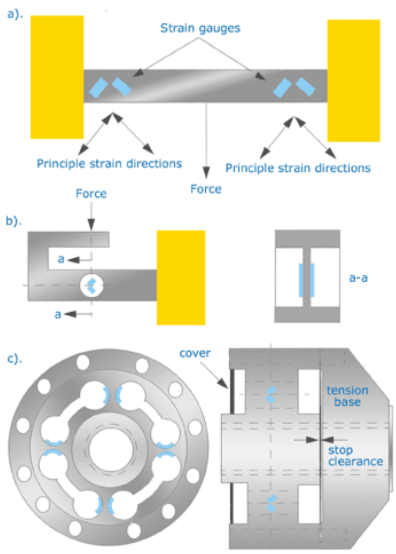


The beauty of the proving ring with strain gauges installed as shown is the fact that all gauges of the Wheatstone bridge ideally experience identical axial strain, resulting in cancellation of axial strain effects in the output of the bridge.

Shear load cells

Strain gauge-based load cell structures, configured to operate based upon the measurement of shear strain, provide high capacity and low compliance in a compact and low profile geometry.

It is a more efficient method of load determination as it is less dependent on the way and direction in which the force is applied to the load cell.



Shear load cells

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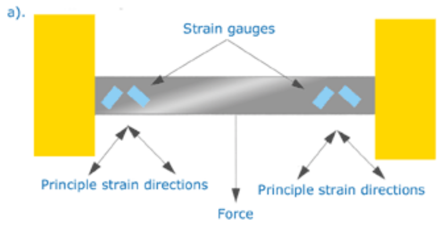
Strain gauges measuring shear are oriented at 45 degrees to the neutral axis in bending and are mounted to straddle the neutral axis. Bending stresses are, by definition, equal to zero at the neutral axis in bending. Although the strain gauge must possess some finite physical dimensions, by equally straddling the neutral axis in bending, half of each strain gauge will experience some bending strain while the other half will experience the same strain in the opposite direction thereby largely cancelling bending in the output of the sensor. Practically, the shear patterns cannot be positioned with absolute perfection and shear webs cannot be fabricated with absolute symmetry resulting in less than perfect cancellation of bending strains.



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Load cells errors

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Excitation voltage

Higher excitation voltage increases the temperature gradient from the gages to the material

e.g. Interface cells operates at 10 VDC. Increasing the excitation voltage to 20 VDC would decrease sensitivity by 0.07%

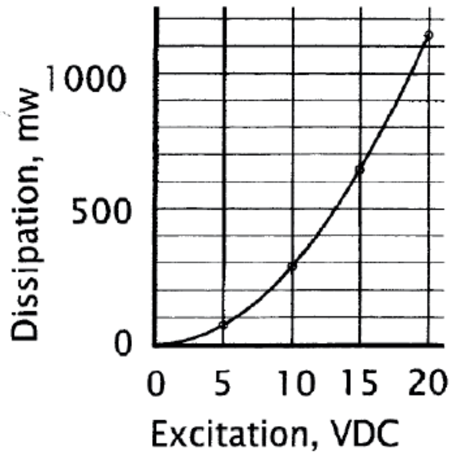

Figure 2. Dissipation versus Excitation Voltage (350 ohm Bridge)

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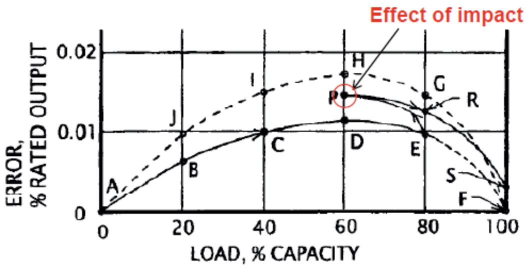
Load cells errors

Hysteresis

The difference between load cell output readings for the same applied load, one reading obtained by increasing the load from minimum load and the other by decreasing the load from maximum load.

This could be minimized by "conditioning" the load cell. Three cycles from zero to 130-140% max load



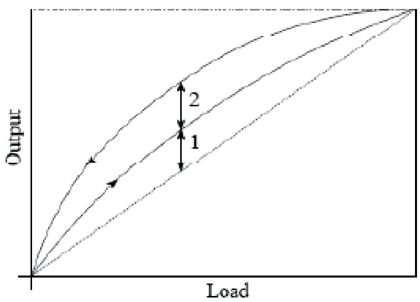
Output Errors With Different Loading Sequences

Load cells errors

Non linearity

The deviation of the increasing load cell calibration curve from either:
1) a straight line which passes through minimum load output and the load cell output at 75% of the measuring range;
2) a straight line connecting the zero load and the rated load output values;
3) the best straight line fitted to output values by the least squares method, through zero load output.

All measurements at a stable ambient Temperature of 20°C or 68°F.



Non-linearity (1) and Hysteresis (2).

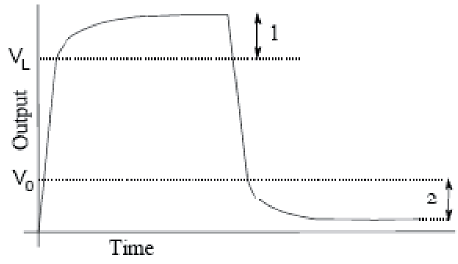
Load cells errors

Creep

The change in load cell output occurring with time while under constant load (>90% of the load cell capacity) and with all environmental conditions and other variables remaining constant.

Minimum Dead Load Output Return (MDLOR)

The difference in load cell output at minimum dead load, measured before and after a 30 minute load application of at least 90% of the cell's rated capacity



Creep (1) and MDLOR (2)

Load cells errors

When we consider resolution, repeatability and reproducibility of load cell we need to consider the above performances in terms of the systems were the load cell are used.

The limiting factors are generally not associated with the load cell:
- proper application of the load cell
- loading systems and mechanical fixtures used to apply the loads
- electrical equipment used to measure the load cell output.

Difficult problems to solve:
- temperature variations
- forces such as air motion and building vibration
- inability of hydraulic systems to maintain a stable pressure

Load cells errors

Repeatability is affected by any one of these factors:
- tightness of the mechanical connections of fixtures
- rigidity of the load frame or force application system
- repeatability of the hydraulic forcing system itself
- application of a dead weight load too quickly (impact)
- poor control of reading times introducing creep into data
- unstable electronics due to temperature drift, power line susceptibility, noise, etc.

Reproducibility?

The load cell is calibrated at one location and then used to measure forces at another location.

Computer Vision System for High Precision Displacement Measurements

A number of applications prevents the use of traditional acquisition instruments and system.

Application of fast or impulsive loads, large displacements tests, experimental activities possibly inducing partial or total collapse of the specimens are just some examples of tests for which normal transducers can not be used.

The main reasons are:
- limited reliability of the acquired signals (related to the high loading rate);
- high risk of breaking transducers (high cost).

In these cases, particularly to avoid damages or loss of instrumentations, contact-less transducers are an effective solution.

At Eucentre, we have developed a machine vision system: an optical acquisition system based on high definition cameras, retro-reflective markers and infra-red illumination.

High definition digital cameras

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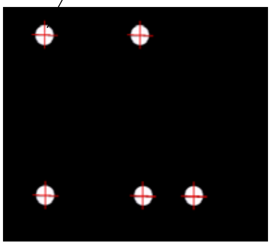
Measure positions of markers acquiring and analysing a series of digital images

Marker placed on the specimen

Digital camera

Pixel position →
World coordinate (mm):
[150;50]px → [240;80] mm



Markers identification
performed on acquired images

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Hardware (Acquisition Unit)

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Each acquisition unit is composed by:

- PC with UPS device in a ruggedized case

- *X64 Xcelera CL-PX4 frame grabber, plugged into the PCI express 4x socket*

- PT–40–04M60 (Pantera) high definition digital camera (Dalsa) with NIR filter and Illuminator

  Camera resolution: 2352x1728 (8bpp) at 60Hz, scalable up to 2352x864 at 120Hz

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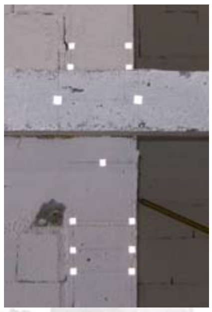
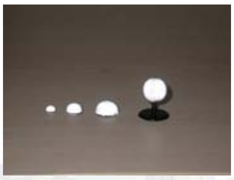
Hardware (Overall System)

- 10 ports KVM Switch for remote management of acquisition units

- ISO Tech Signal generator for a triggered synchronized acquisition



- 3M® Reflective markers (rounded and flat shaped)



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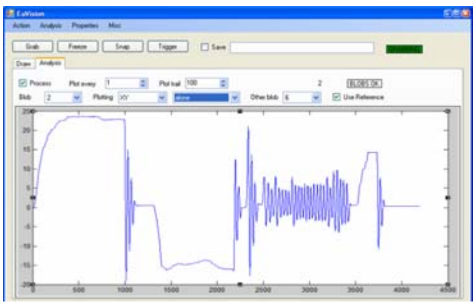
Software (Acquisition Unit)

Multi layered software solution: EuVision (lower to higher abstraction level)

- Dalsa Drivers (Sapera LT SDK) – interface to frame grabber
- C++ / Assembly core analysis module – image compression / markers detection
- OpenCV C++ higher level frame and signals filtering management
- C++/CLI .NET front-end (User Interface)
- WCF / Remoting service - listening for remote automation



- Performs the image acquisition
- Detects and tracks blobs in the frame
- Converts pixel coordinates into world physical units
- Stores data in local or remote database
- Exposes measures to remote users

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Software (Overall System)

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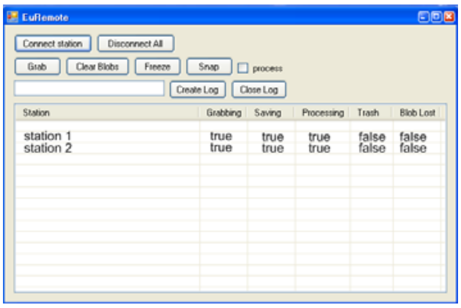
Remote Controller Application (EuRemote)

• Polls each connected unit state
• Remotely sets acquisition and storing parameters
• Remotely controls the acquisition (start/stop/pause)
• Detects blobs identification issues and frames loss

.NET Remoting full duplex application, written in C#

• Optimized binary TCP/IP secure communication
• Synchronized start/stop with < 8ms max phase error between acquisition units
• Virtually unlimited number of stations connected



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Blob Detection

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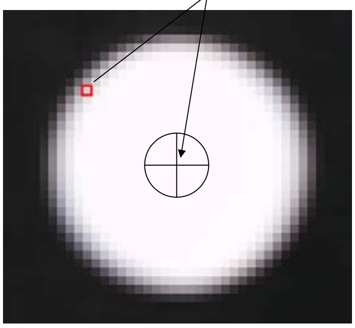
IR filter lenses make only the reflective markers visible in the scene when NIR lighting is on.

Blob identification (recognition of a contiguous set of pixels after the application of a B/W threshold) in the scene

Calculation of the centroid for each blob, using colour intensity as weight parameter



Precise up to 1/10 - 1/50 sub-pixel, using colour transitions

(depending on the threshold value and environmental lighting conditions)

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Blob Tracking (sequence)

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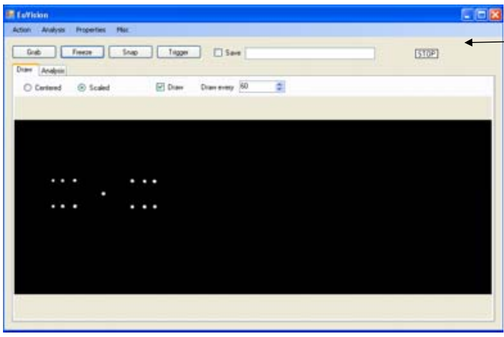

A first image is acquired

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Blob Tracking (sequence)

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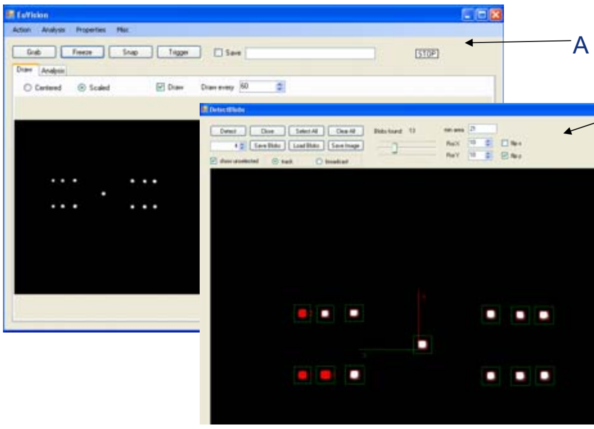

A first image is acquired

The user can select and number the blobs to track

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Blob Tracking (sequence)

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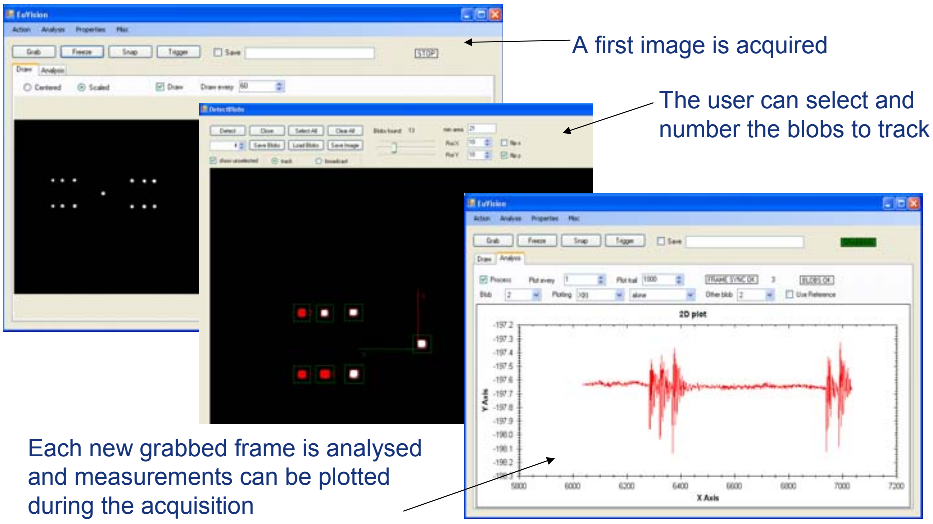

A first image is acquired

The user can select and number the blobs to track

Each new grabbed frame is analysed and measurements can be plotted during the acquisition

Calibration
(1 – parameters identification)

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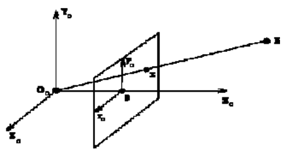
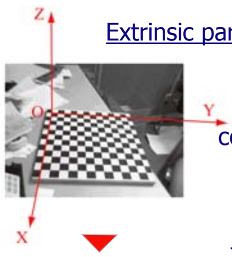
Pin-hole camera model

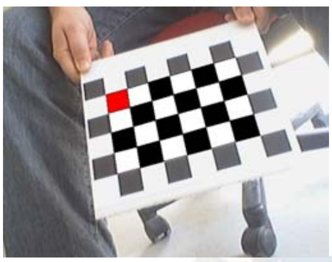


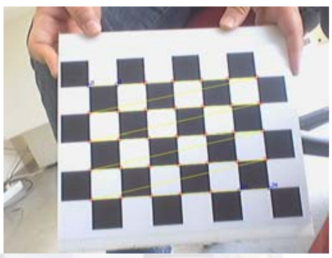


Extrinsic parameters (relative roto-translation between the two coordinate systems – camera & target)

Calibration result (calibration pattern is reconstructed in the image)

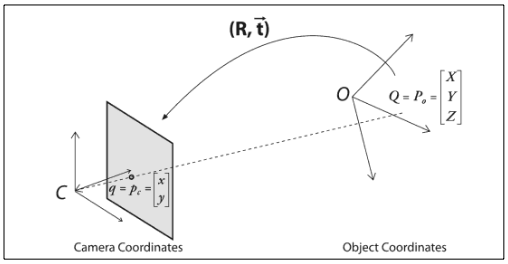
Intrinsic parameters





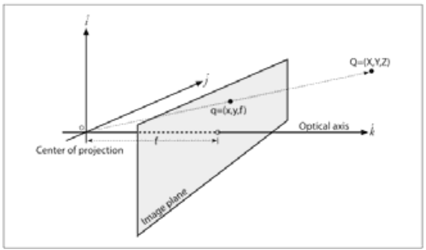
Camera sensor and lens distortion (focus and lens non-linearities)

Calibration
(2 – real world coordinates computation)

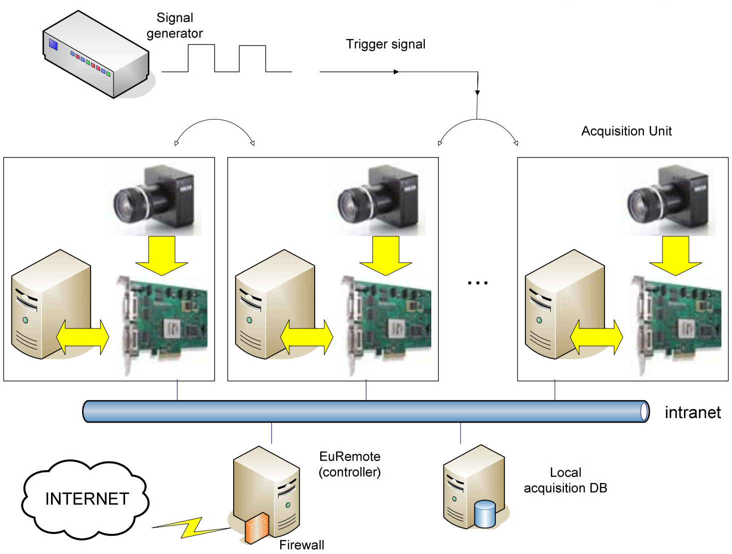


Knowing the roto-translation matrix allows for inverse computation of points lying on the calibration plane

On-line algorithm projects the optical ray of each blob center (in pixels coordinates) into the calibration image plane (in physical length units [mm])



System Synchronization



Telepresence / remote visualization

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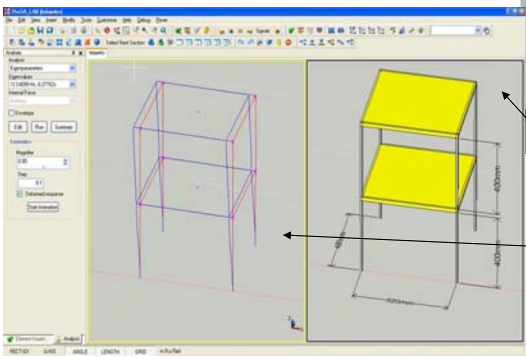
- Blobs can be selected for on-line data transmission to the remote database
- Database allows concurrent transactional data access
- Remote applications can show live measurements during the test



3D geometry model

F.E.M. model with live displacements plotted

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SERIES-POLYMAST Experiment

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- 10 acquisition units connected
- Following around 400 markers placed over the specimen
- 60Hz sampling frequency
- Cameras at a distance of 6-8 meters from the structure
- Frame dimensions about 1.8 m x 2.0 m

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SERIES-POLYMAST Experiment

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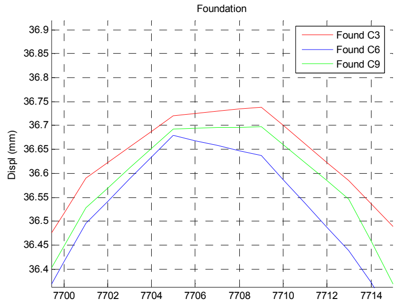
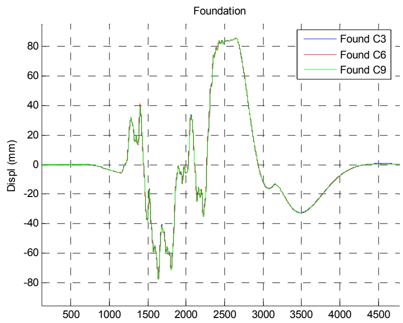


Detail of the displacement measured by three different acquisition units.
Notice the perfect phase of the signals.

Same plot in a wider range. The precision obtained (compared with traditional measurement devices) is near to 0.05 mm, corresponding to a 1/10 – 1/20 sub-pixel in the frame



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Out-of-plane error

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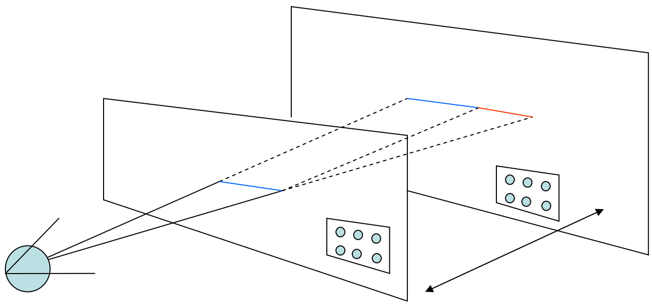
Movements of the measurement plane, like for example movements of the specimen towards the camera resulted in errors and distortions



The idea is to apply a simplified calibration pattern to the target plane and perform an on-line recalibration of the system during the tests

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Out-of-plane error

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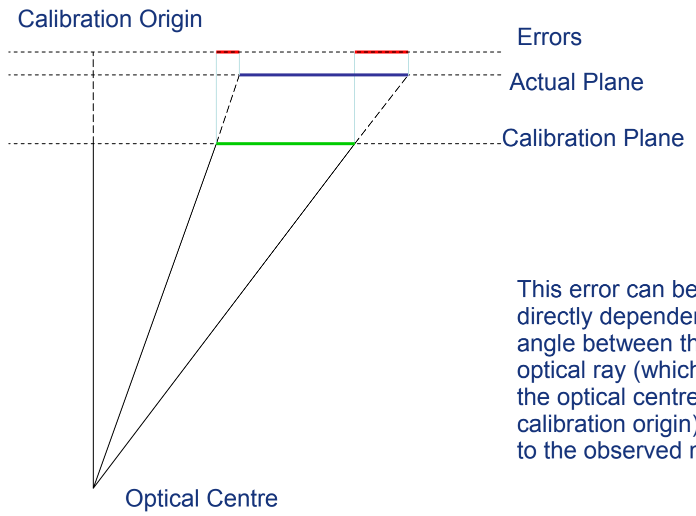

This error can be estimated directly dependent on the angle between the central optical ray (which connects the optical centre and the calibration origin) and the ray to the observed marker.

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Out-of-plane error estimation

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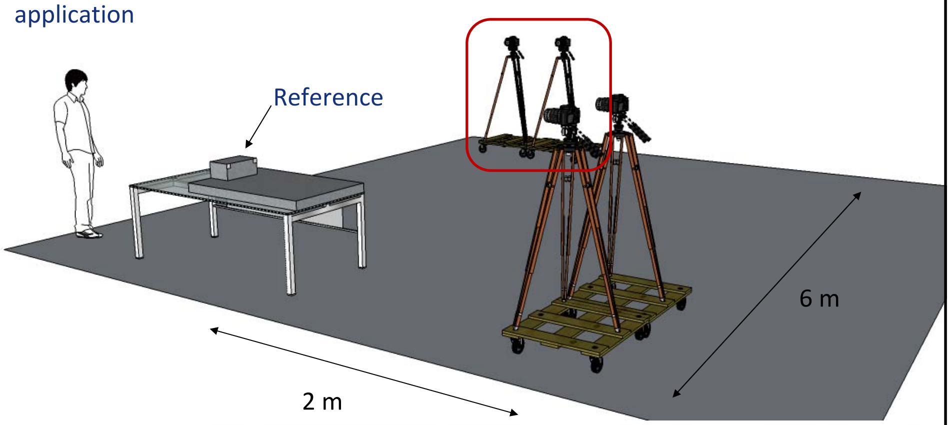
Two cameras at a distance between 6 and 8 meters from the calibration plane will measure the reference object displacements.
This reference is then moved towards the cameras (and in general as orthogonally as possible to the calibration plane) and these movements are recorded by the application



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Out-of-plane error estimation

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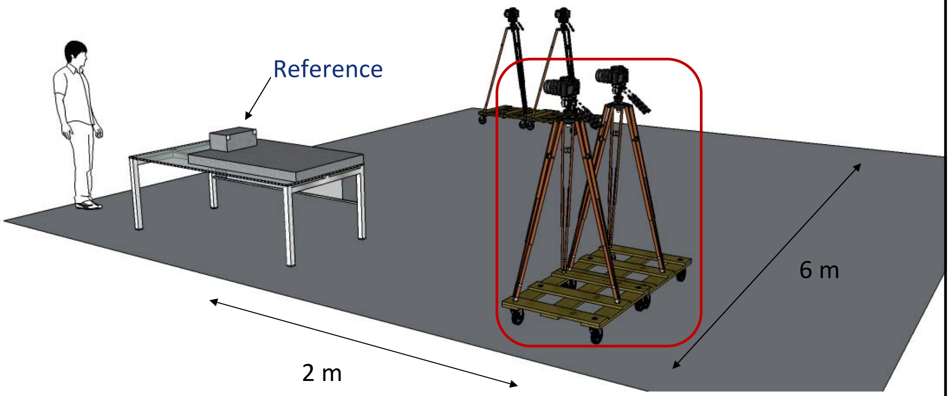
Two other cameras are placed and calibrated in order to follow the out of plane movements above described (they need to be accurate as possible, therefore they will be 2-3 meters away)



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Out-of-plane error estimation

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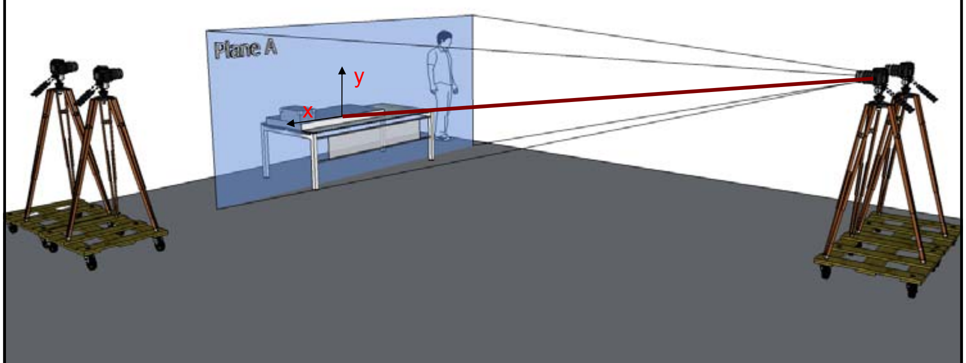
The two front cameras are calibrated on plane A

The reference is displaced along the x axis in order to cause a measurement error by effect of the out of plane offset



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Out-of-plane error estimation

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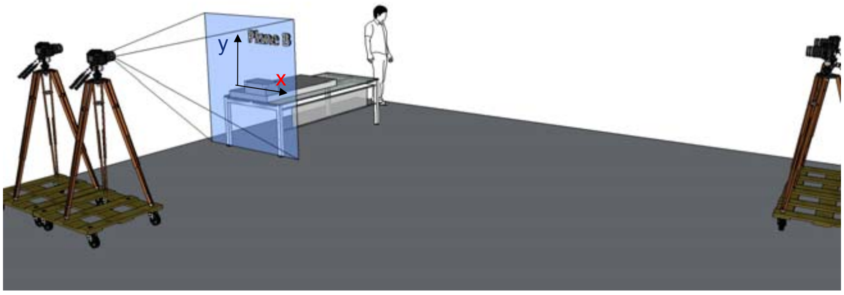
The second couple of cameras is calibrated on a plane which is orthogonal to the previous one (plane B).
They will therefore be extremely precise in the measurements of the out of plane movement
By combining the results on the two planes, the error made by the two frontal cameras will be estimated.



Out-of-plane error reduction

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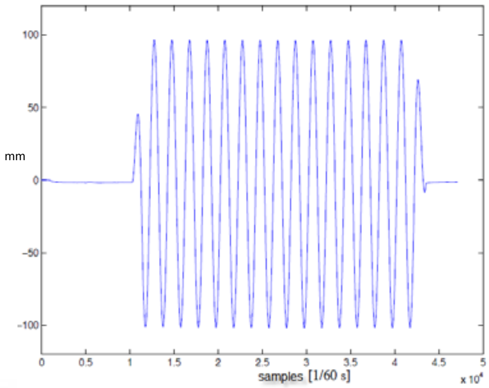
A simple error reduction can be performed by using the desired evolution of a target and comparing it to the actual displacement measured by the system. This can be the recording of a slow rigid movement of the test specimen or coming from an alternative acquisition device.

Slow building movement:

- 200 mm (±100mm)
- Sinusoidal 0.03Hz
- Sampled at 60Hz



Out-of-plane error reduction

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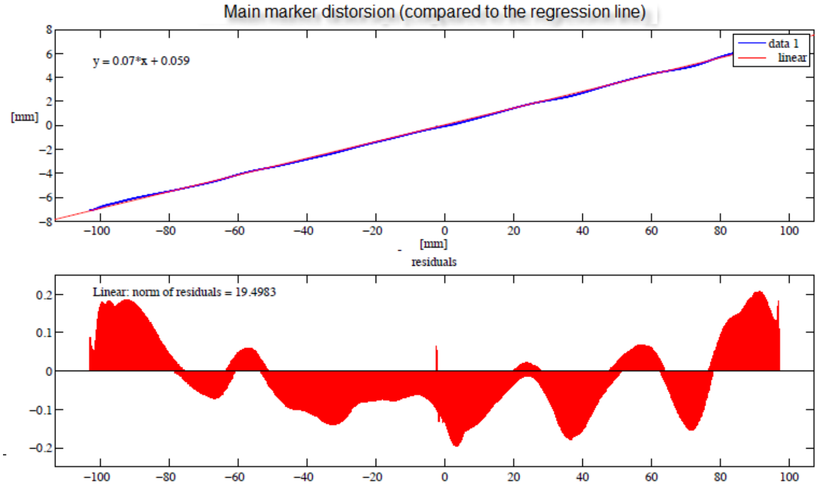
A central marker is used as the reference for the slow movement



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Out-of-plane error reduction

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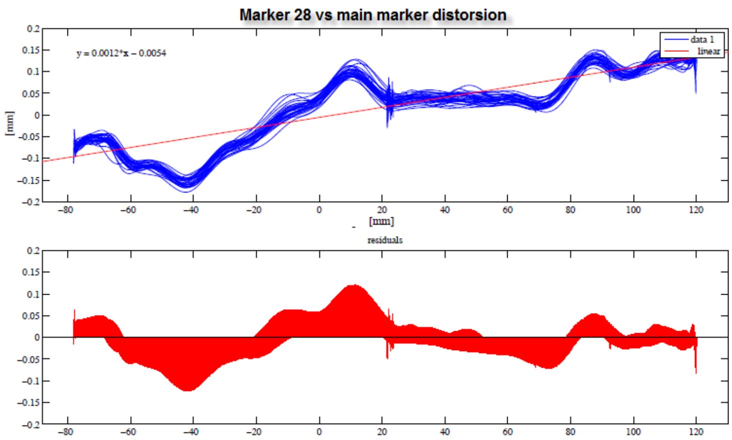
The algorithm considers and reduces the distance between the desired movement (main marker) and the measured evolution of any other marker.



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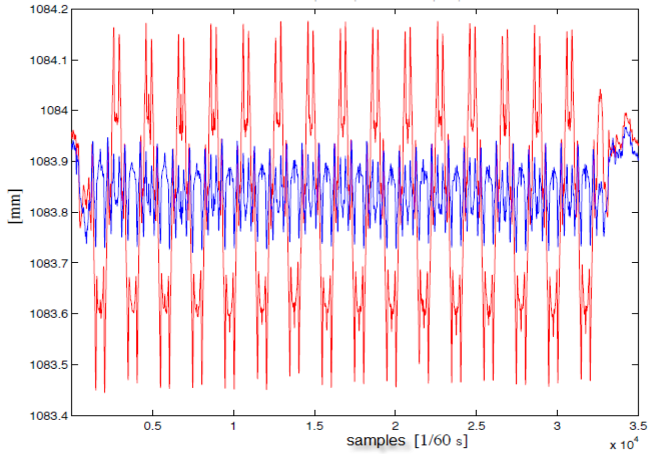
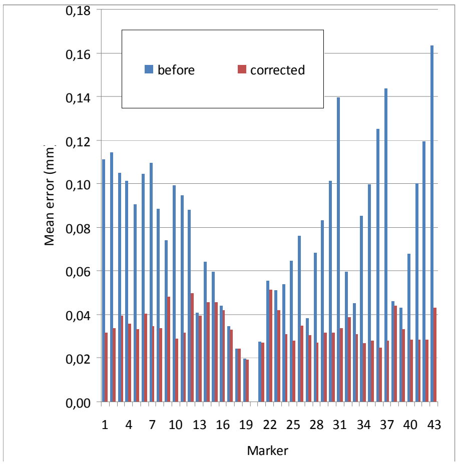
Out-of-plane error reduction

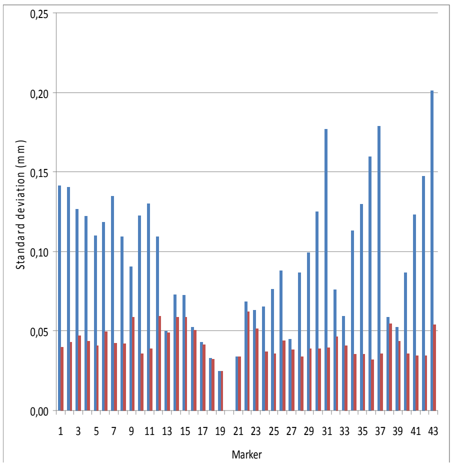
Plot of the evolution of the distance between a generic marker and the main marker. This distance should be as constant as possible in a slow rigid movement. The red line is the measured distance, the blue one is its corrected version.



Out-of-plane error reduction (statistics)

Means and standard deviations of any marker compared to the main one (which histogram value is null by definition)





EU-Vision

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The current implementation of the proposed machine vision system has shown a valuable precision when applied to planar measurements.
The strong hypothesis of having each marker lying in the same plane used for the calibration for the entire acquisition, on the other side, is almost never valid for real applications.
Different off-line algorithms have been developed in order to overcome to the resulting measurement errors and currently a precise estimation of the effect of this issue is undergoing.

At the same time human and software resources have been allocated in light of a future stereoscopic vision mechanism to be combined to the actual architecture.

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Example of application

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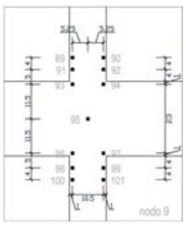
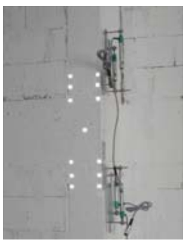
- 8 acquisition units connected
- Following around 250 markers placed over the specimen
- 120Hz sampling frequency
- Cameras at a distance of 6 meters from the structure
- Frames wide around 1.80 x 1 meters





Example scheme and placing of the markers

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Data Acquisition

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National Instruments PXI

National Instruments
Analog-Digital Converter

National Instruments
SCXI Multi-Plexer Chassis

National Instruments
Signal Conditioner Boards

Connection Panels

Instruments


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Data Acquisition

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System Performance

Acquisition speed up to 300 Ksample per second:
(the maximum sampling rate depends on the number of connected instrument)

Sample type: 18 bit

Resolution 2x10^{-17} V

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Architecture of an acquisition system

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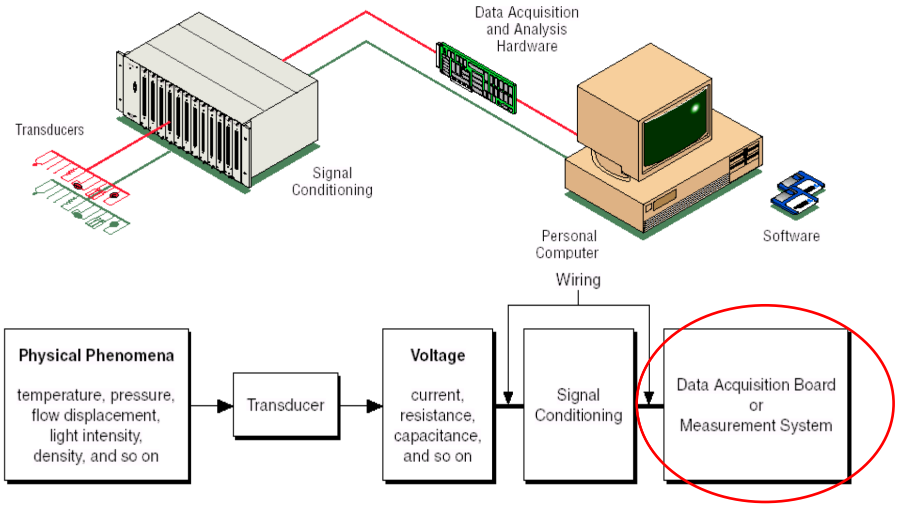

Basics of Analog to Digital Conversion (A/D)

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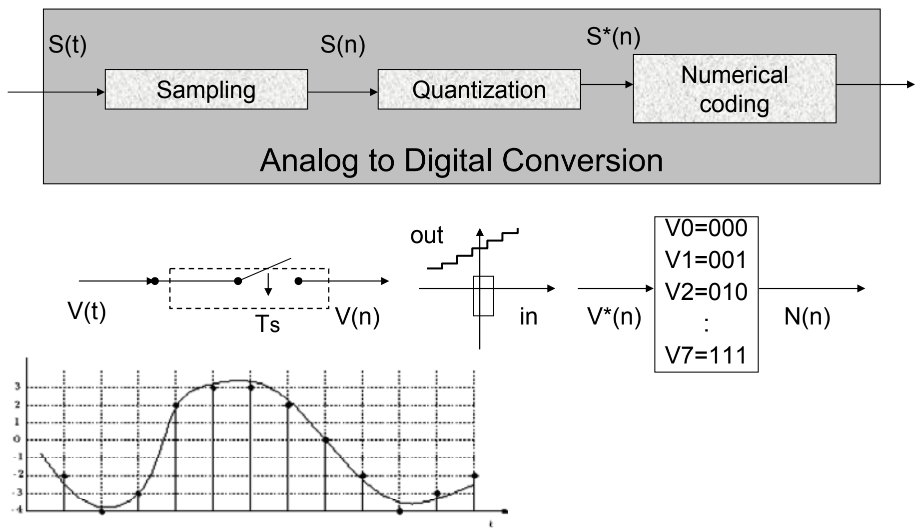

Sampling: the delta distribution (pulse)

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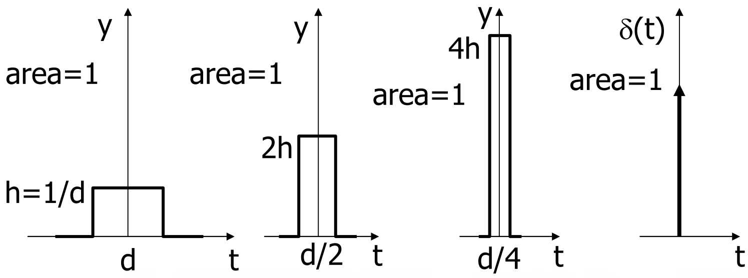
In the field of signal analysis some distributions are fundamental to describe some theoretical aspects.

The pulse or Dirac distribution, $\delta(t)$, can be viewed as the limit of a series of rectangular functions having increasing height and decreasing base in order to maintain a unitary area.



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Sampling an analog signal

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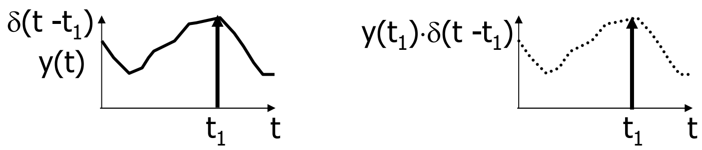
The operation of taking a sample of a continuous function $y(t)$ at a time t_1 is mathematically described as the product of $y(t)$ with the pulse function $\delta(t\text{-}t_1)$.



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Sampling at a constant rate

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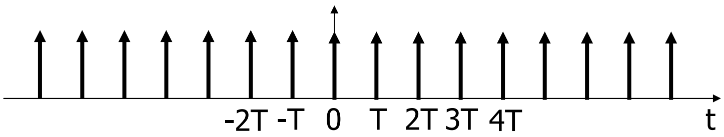
Let us consider a sequence of infinite pulses spaced by a fixed time interval



This distribution can be expressed by the following summation

$$\sum_{i=-\infty}^{\infty} \delta(t - iT)$$

This distribution can be obtained as the limit of a periodic function f, with period T, containing all the harmonics of period T/k for k integer number --> ∞

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Sampling in the time domain

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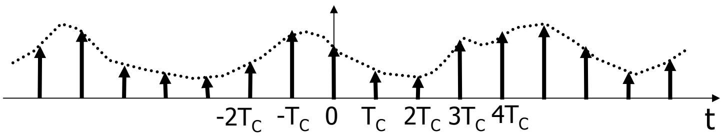
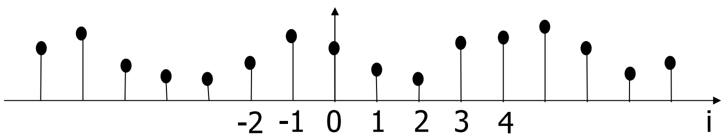
The sampled signal, taken at the constant rate TS, in the continuous time, is described by the product of y(t) and the sequence of delta distributions

$$y(t) \cdot \sum_{i=-\infty}^{\infty} \delta(t - iT_S) = \sum_{i=-\infty}^{\infty} y(iT_S) \cdot \delta(t - iT_S)$$



In the discrete time, it is described by a sequence of numbers yi = $y(iT_S)$



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Sampling in the time domain

The basic question:

" Is the sampled signal equivalent to the analog signal ?"

It is possible to determine if some information is lost during the sampling process and, once the original signal y(t) has been sampled and transformed into a sequence y(n), is it possible to completely recover the original analog signal ?

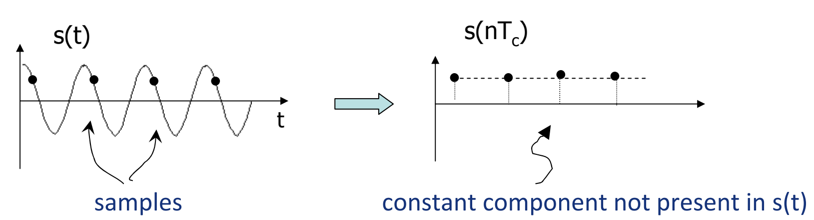
To solve these problems we need to study the sampling process in the frequency domain through the Fourier transform.

The correct sampling rate for a signal can be chosen by making reference to the Nyquist or Shannon theorem.

The sampling theorem (Nyquist or Shannon)

When digitizing an analog signal s(t) having a spectrum s(f) of limited bandwidth B (s(f)=0 for f>B), s(t) must be sampled, without loss of information, at a sampling frequency that is at least twice the signal highest frequency component B (SF $\geq$ 2B).

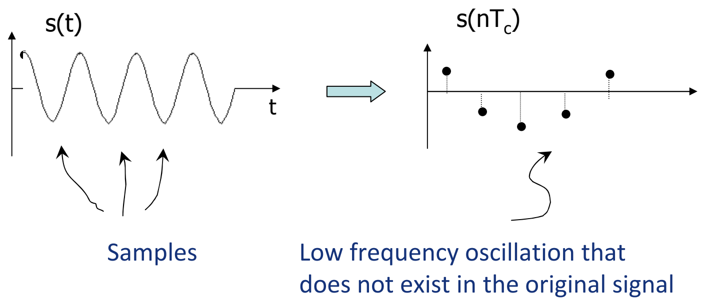
s(t)= sin(2πft), SF=f (Ts=1/f)



Sampling

Examples of errors introduced by a SF too low

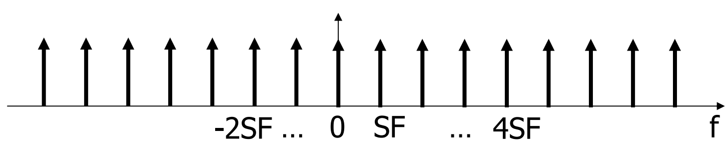
B) $s(t) = \sin(2\pi ft)$, $f < SF < 2f$ $(1/f > T_s > 1/2f)$



Sampling in the frequency domain

We start from the properties of the **Fourier transform** in the continuous time. The **product** in the time domain is equivalent to a **convolution** in the frequency domain.

The sequence of pulses (Delta sequence) is a periodic signal of fundamental period Ts, containing all the harmonics with equal amplitude: then its Fourier transform is still a sequence of pulses equally spaced in the frequency domain of an amount $SF = 1/T_S$



Sampling in the frequency domain

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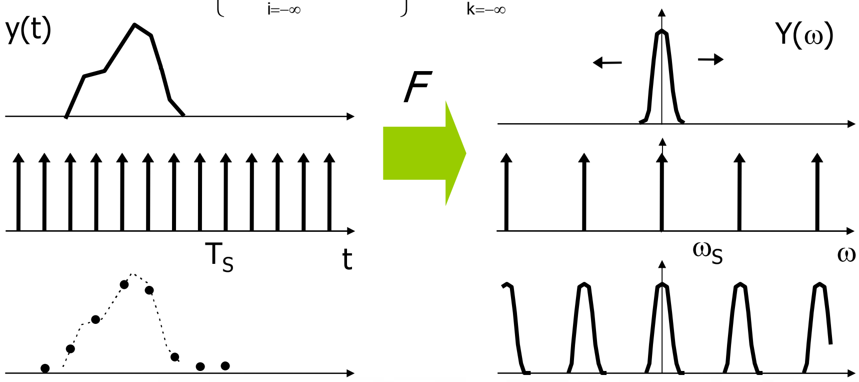
The result of sampling a waveform y(t) at a frequency SF is to replicate the FT of y =Y(ω) around the multiple of $\omega_S = 2\pi SF$

$$\Im\left\{ y(t)\sum_{i=-\infty}^{\infty}\delta(t - iT_S) \right\} = k\cdot\sum_{k=-\infty}^{\infty} Y(\omega - k\omega_S)$$



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Sampling in the frequency domain

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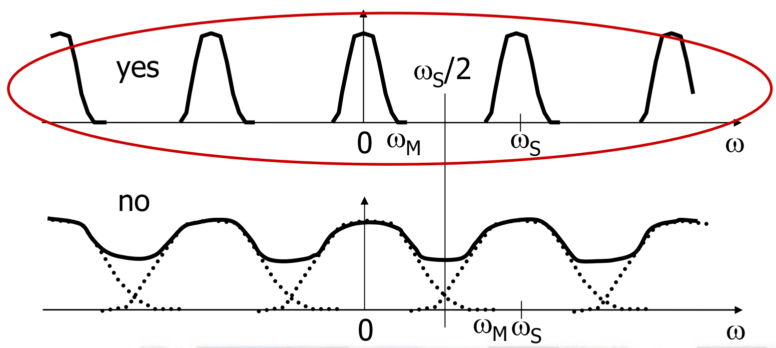
Thus, if the sampling frequency is chosen higher than 2 times the maximum frequency contained in signal, the spectra do not overlap when the sampling process replicate the original spectrum each ω_s. Otherwise we can observe the foldover of the spectra (aliasing).



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Frequency analysis of a sampled signal

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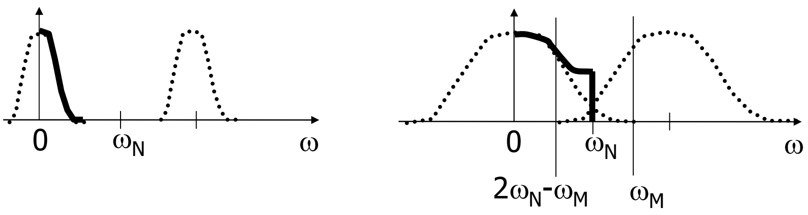
Once fixed the *sampling frequency SF*, the maximum frequency that can be represented is half of the sampling frequency, $f_N = SF/2 = \omega_S/4\pi$ and it is called **Nyquist frequency.**



For this reason, in the right example, the frequencies from ω_N to ω_M are not correctly represented.

Frequency foldover - aliasing

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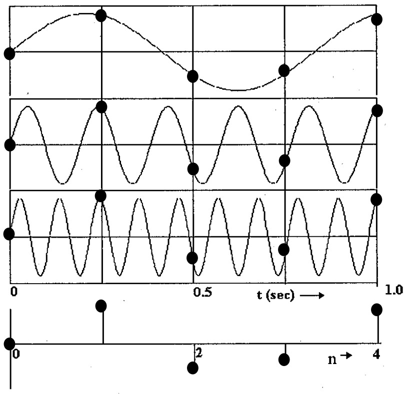
Example: let us consider 3 sinusoids at 1.2, 5.2 e 9.2 Hz all sampled at 4 Hz: they give exactly the same discrete signal that corresponds to the 1.2 Hz sinusoid.

Why?



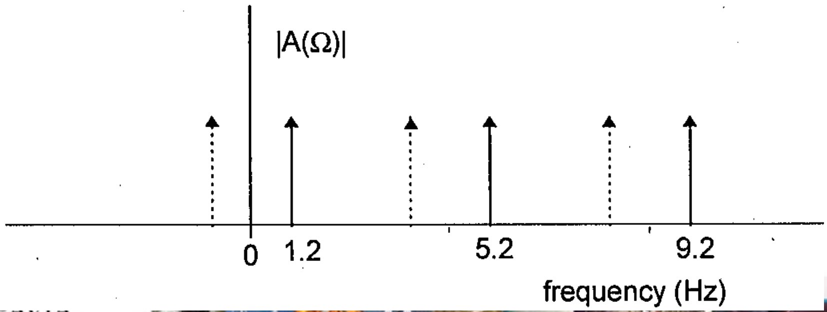
Aliasing: effect of spectra replication

As a matter of fact, the Fourier transform of the sinusoid at 1.2 Hz shows two pulses at +1.2 and at -1.2Hz, which are replicated symmetrically around 4 Hz due to the sampling process: they give pulses at 4k-1.2 e 4k+1.2 Hz for k=1, 2, ..N

5.2 Hz = 4+1.2 Hz --> 4(k-1)-1.2 and 4(k+1)+1.2 Hz

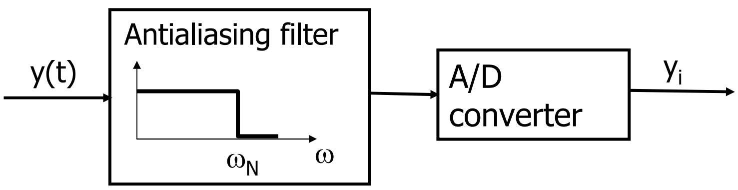
9.2 Hz = 2x4+1.2 Hz --> 4(k-2)-1.2 e 4(k+2)+1.2 Hz

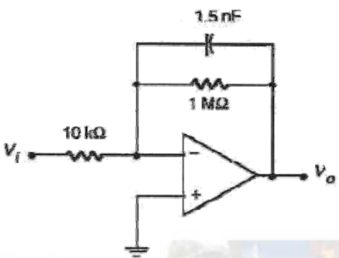
We thus find the same pulses in the frequency domain.



Anti-aliasing filtering

Once a SF has been chosen, we need to eliminate all frequency components higher than SF/2 before sampling the signal y(t) in order to avoid the aliasing phenomenon.





Simple first order antialiasing low pass active filter

Note: the low pass antialiasing filter is the only analog filter that cannot be substituted by a digital filter.

Choice of the sampling frequency

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1) Sampling theorem (SF>2fmax)

2) Time accuracy (if we want to measure events in time with an accuracy of t1, SF>1/t1)

3) Processing algorithms (e.g. Numerical Differentiation – one of the most used algorithms for computing the derivative of a signal is the “two points central difference”, where the output is calculated as

$$y(k) = \frac{x(k+1) - x(k-1)}{2T_s}$$

This algorithm behaves like a derivative up to a frequency F=0.224 SF, then it behaves like a low pass filter.)

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Quantization

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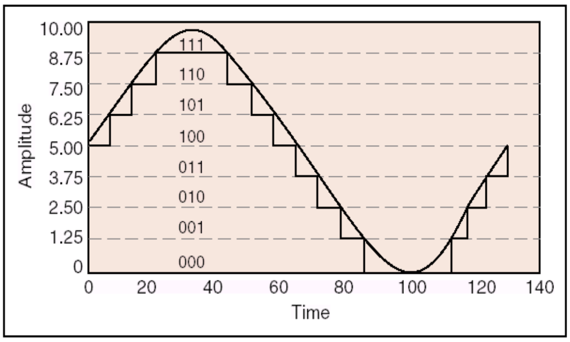
Quantization corresponds to the discretization in amplitude.

The number of levels that the ADC uses to represent the analog signal is the resolution. The amplitude of a single level is called quantization level. The higher the resolution (the smaller the quantization level), the larger the number of divisions the range is broken into, and therefore, the smaller the detectable voltage change. The figure shows a sine wave and its corresponding digital image as obtained by an ideal 3-bit ADC.



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The quantization error

The quantization due to the A/D conversion introduces an approximation error, that can be viewed as an additive noise (n_Q)to the signal (y)

$$y\hat{}=y+n_Q$$

The stochastic characteristics of the noise process can be easily determined:

1) the probability distribution is uniform from -Q/2 and Q/2 (the error can happen with equal probability in the quantization interval Q)

2) thus mean and variance are: $m_Q=0$; $\sigma_Q^2=Q^2/12$

3) it is a white noise

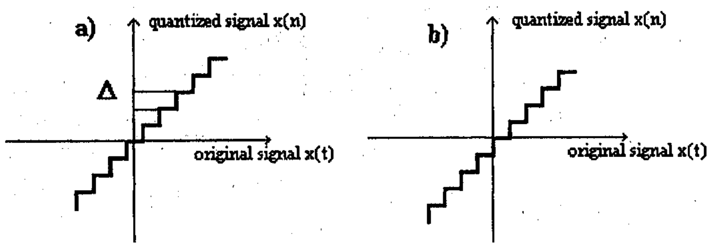
4) the noise is independent from the signal (it is not correlated)

5) the variance of the signal is increased by the quantization noise

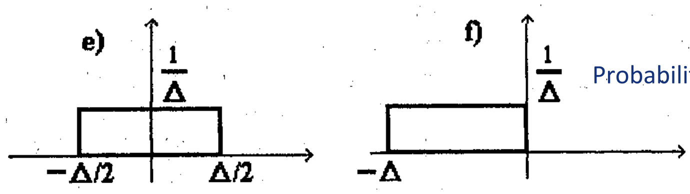
$$\sigma_{y\hat{}}^2 = \sigma_y^2 + Q^2/12$$

125

Quantization noise



Rounding Truncation



Probability density

$m_Q=0$, $\sigma_Q^2=Q^2/12$ $m_Q=-Q/2$

126

Quantization noise

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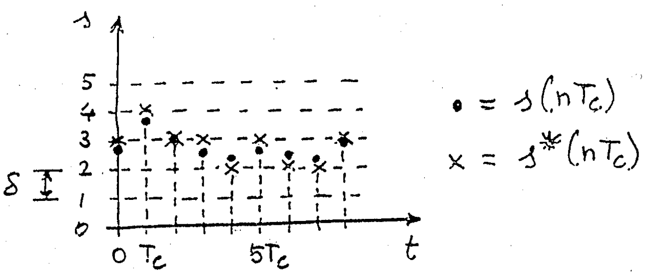

The quantization level determines the accuracy of the A/D conversion.

The quantization level depends on the number of bits used by the A/D converter.

Example:

- 8 bit correspond to 2^8=256 different values.
- Accuracy is 1/256≅0.4% of the whole analog range (usually from –5V to +5V or from –10V to +10V).

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Quantization and numerical coding

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Range – Range refers to the minimum and maximum voltage levels that the ADC can quantize. Recent acquisition devices offer selectable ranges so that the device is configurable to handle a variety of voltage levels. With this flexibility, you can match the signal range to that of the ADC to take advantage of the available measurement resolution.

Code Width – The range, resolution, and gain available on an acquisition device determine the smallest detectable change in voltage. This change in voltage represents 1 least significant bit (LSB) of the digital value and is often called the code width. The ideal code width is found by dividing the voltage range by the gain times two raised to the order of bits in the resolution. For example, a 16-bit acquisition device, has a selectable range of 0 to 10 or -10 to 10 V and selectable gain of 1, 2, 5, 10, 20, 50, or 100. With a voltage range of -10 to 10 V, and a gain of 20, the ideal code width is defined by the following equation:

$$\frac{10+10}{20\times 2^{16}} = 7,63\mu V$$

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Quantization and numerical coding

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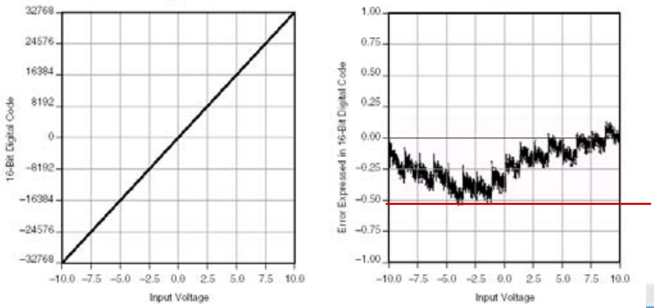
Relative Accuracy – Relative accuracy is a measure in least significant bits of the worst-case deviation from the ideal acquisition device transfer function, a straight line. Relative accuracy is determined by connecting a voltage at negative full scale, digitizing the voltage, increasing the voltage, and repeating the steps until the input range of the device has been covered. When the digitized points are plotted, the result will be an apparent straight line (left diagram). However, you can subtract actual straight-line values from the digitized values and plot these resulting points, as shown in the right diagram. The maximum deviation from zero is the relative accuracy of the device.



Continuous Waveform Acquisition

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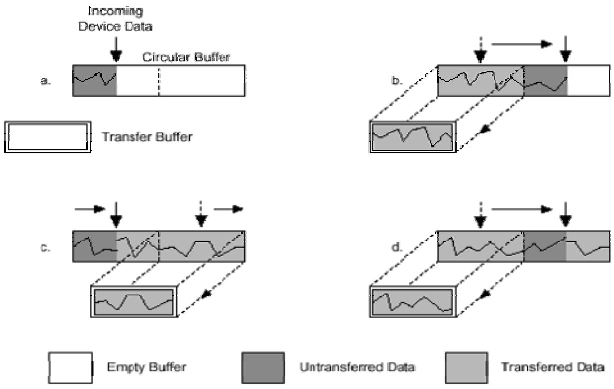
Data acquisition applications that do not have a predetermined number of samples, or that run for such lengths of time that a single buffer of data is too large to practically fit into memory may need to make use of continuous acquisition.

In a continuous acquisition, data is placed into a circular buffer by the hardware. Simultaneously, the software removes previously acquired data from the buffer, process and stores data on a permanent memory (disk). Typical processing operations include mathematical operations, screen display, and file I/O.

As long as the software removes data from the buffer at least as fast as the hardware provides it, the circular buffer never fills, and the operation may continue endlessly.

Double-Buffered Input Operations

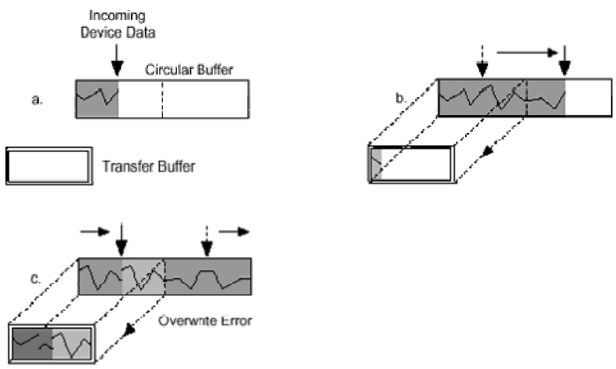
The data buffer for double-buffered input operations is configured as a circular buffer. In addition, the software logically divides the buffer into two equal halves. The coordination scheme is simple - the software copies data from the circular buffer in sequential halves to a transfer buffer created by the user.



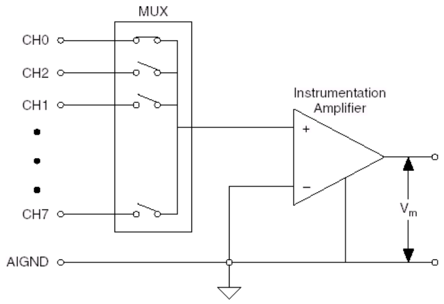
Problems with continuous acquisition

A problem occurs when an input device overwrites data before it has been transferred to the transfer buffer. The situation is presented in Figure

Another problem with continuous waveform acquisition is that the software fails to remove the data as fast as the hardware provides it. When this happens, an overrun condition occurs. This is due to the software loop that is retrieving the data. If it becomes impossible to speed the code any further, the data acquisition will need to be slowed.



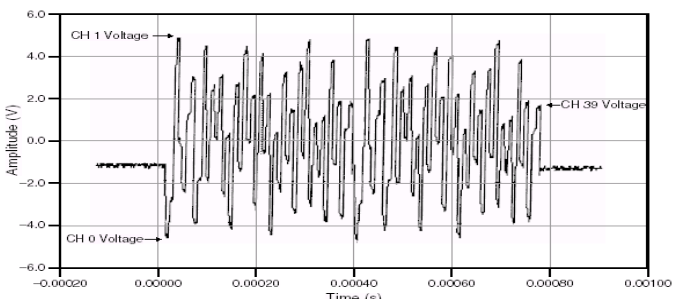
Multiplexing



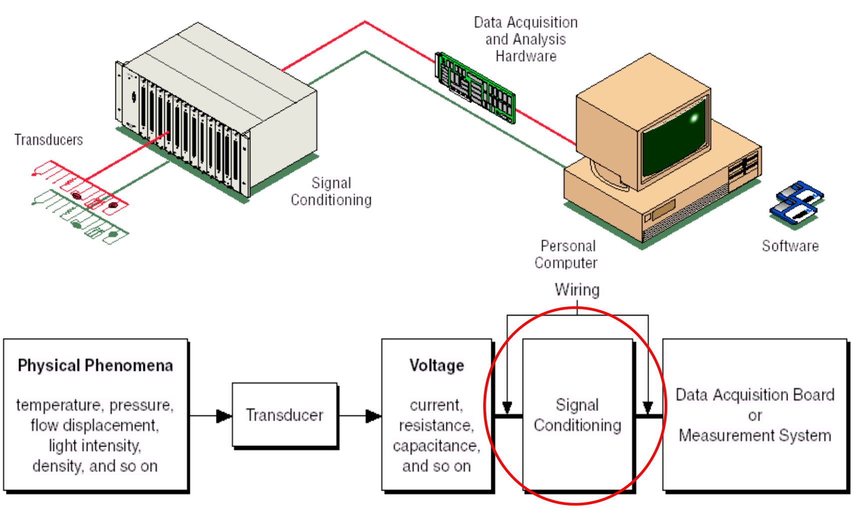
A common technique for measuring several signals with a single ADC is multiplexing. Signal conditioning hardware for analog signals often provides multiplexing for use with slowly changing signals.

The ADC samples one channel, switches to the next channel, samples it, switches to the next channel, and so on. Because the same ADC samples many channels instead of one, the effective sampling rate of each individual channel is inversely proportional to the number of channels sampled. For example, a converter sampling at 1 MS/s on 10 channels will effectively sample each individual channel at 100 KS/s

Problems of multiplexing



1. Samples coming from different channels are never simultaneous
2. Even if singular signals present slow variations in time, the multiplexed signal may appear to be a high frequency oscillating signal (see Figure where a 40 channel multiplexed acquisition signal is represented)
3. The programmable amplifier before ADC must have a very fast response (settling time)



Analog inputs

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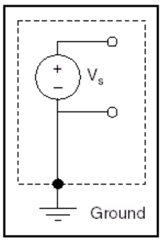
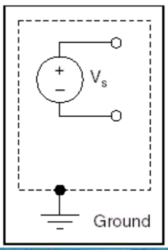
Number of Channels – The number of analog channel inputs is specified for both single-ended and differential inputs for devices with both input types.

Single-ended inputs are all referenced to a common ground reference. These inputs are typically used when the input signals are high level (greater than 1 V), the leads from the signal source to the analog input hardware are short (less than 5 m), and all input signals share a common ground reference.

If the signals do not meet these criteria, you should use differential inputs. With differential inputs, each input has its own ground reference; noise errors are reduced because the common-mode noise picked up by the leads is canceled out.



Single ended
(Potentiometer)



Floating source
(termocouple)

Signal conditioning

We often describe the effect of the signal conditioning by the term transfer function. By this term we mean the effect of the signal transformation on the input signal. Thus, a simple voltage amplifier has a transfer function of some constant that, when multiplied by the input voltage, gives the output voltage.

It is possible to categorize signal conditioning into several general types:

- Signal level changes
- Linearization
- Conversions
- Filters and Impedance matching
- Loading

Level change

The simplest method of signal conditioning is to change the level of a signal. The most common example is the necessity to either amplify or attenuate a voltage level.

Generally, monitoring applications result in slowly varying signals where DC or low-frequency response amplifiers can be employed. An important factor in the selection of an amplifier is the input impedance that the amplifier offers to the sensor (or any other element that serves as an input).

In process control, the signals are always representative of a process variable, and any loading effects obscure the correspondence between the measured signal and the variable value.

In some cases, such as accelerometers and optical detectors, the frequency response of the amplifier is very important.

Conversions

Often, signal conditioning is used to convert one type of electrical variation into another. In these cases, it is necessary to provide a circuit to convert this change either to a voltage or to a current signal. This is generally accomplished by bridges when the fractional resistance change is small and/or by amplifiers whose gain varies with resistance.

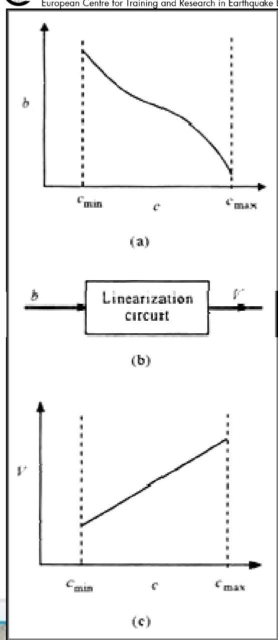
Signal Transmission

An important type of conversion is associated with the need of transmitting signals as 4-20 mA current levels in wire. This gives rise to the need for converting resistance and voltage levels to an appropriate current level at the transmitting end and for converting the current back to voltage at the receiving end. Of course, current transmission is used because such a signal is independent of load variations other than accidental shunt conditions that may draw off some current. Thus, voltage-to-current and current-to-voltage converters are often required.

Linearization

Often, the dependence that exists between input and output of a sensor is **nonlinear**. Even those devices that are approximately linear may present problems when precise measurements of the variable are required. Historically, specialized analog circuits were devised to linearize signals.
The modern approach to this problem is to provide the nonlinear signal as input to a computer and **perform the linearization using software**.

Virtually any nonlinearity can be handled in this manner and, with the speed of modern computers, in nearly real time.



Filters and Impedance matching

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Often, spurious signals of considerable strength are present in the testing environment, such as the 50 or 60-Hz line frequency signals.

Motor start transients also may cause pulses and other unwanted signals in the process-control loop. In many cases, it is necessary to use high-pass, low-pass, or notch filters to eliminate unwanted signals from the loop. Such filtering can be accomplished by passive filters using only resistors, capacitors, and inductors; or active filters, using operational amplifiers and feedback.

Impedance matching is an important element of signal conditioning when transducer internal impedance or line impedance can cause errors in measurement of a dynamic variable. Both active and passive networks are employed to provide such matching.

Loading

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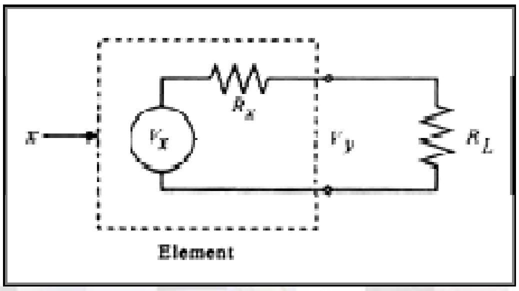
One of the most important concerns in analog signal conditioning is the loading of one circuit by another.
Suppose the open circuit output of some element is a voltage, say Vx, when the element input is some variable of value x. Loading occurs when we do connect something, a load, across the output, and the output voltage of the element drops to some value, $V_y < V_x$.

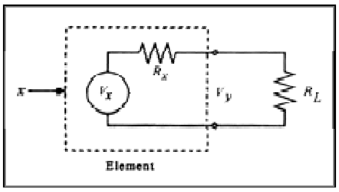
Quantitatively, we can evaluate loading as follows. Thevenin's theorem tells us that the output terminals of any element can be defined as a voltage source in series with an output impedance.



Loading

The element is modeled as a voltage V_X and a resistance R_X. Now suppose a load, R_L, is connected across the output of the element as shown in the figure. R_L could be the input resistance of an amplifier, for example. A current will flow and voltage will be dropped across R_X. It is easy to calculate that the loaded output voltage will thus be given by

$$V_y = V_x\left(1 - \frac{R_x}{R_L + R_x}\right)$$

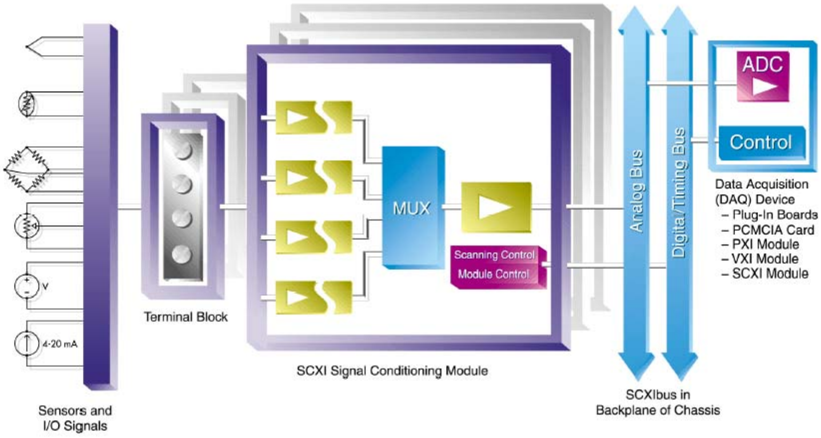


This equation shows how the effects of loading can be reduced. Clearly, the objective will be to make R_L much larger than R_X, that is, $R_L >> R_X$.

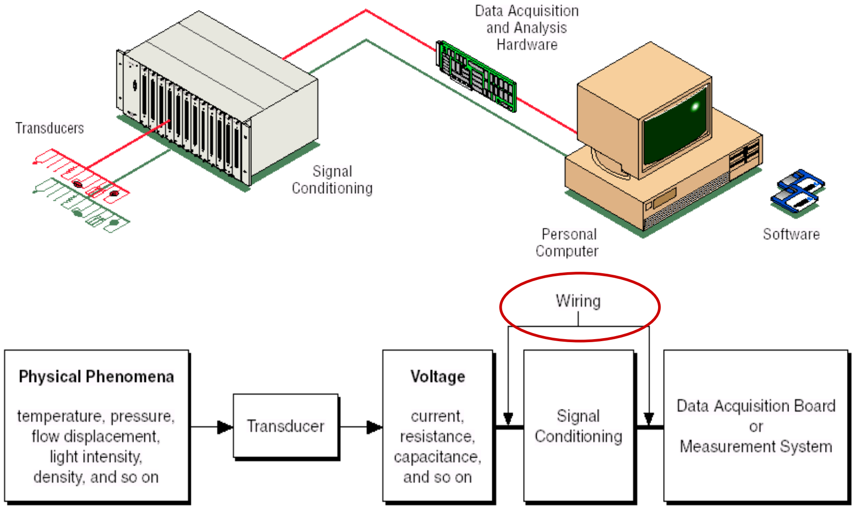
The ratio (Vx-Vy)/Vx is called the loading error (or interconnection error).

Note: The input impedance of a good amplifier is of the order of tenths of MOhms and the output impedance of a transducer may vary from 100 ohms to tenths of kOhms.

Scheme of a commercially available system



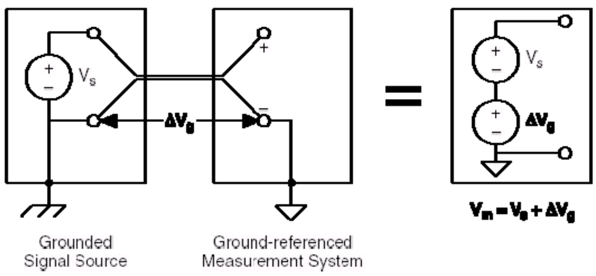
Reducing Noise in Data Acquisition Systems



Grounding problems

Current flow through one or more unintended paths, known as ground loops, creates measurement errors. Each ground has a unique voltage potential, which may differ from other grounds in a data acquisition system. Under general operating conditions, these potential differences, or common-mode voltages, range from millivolts to tens of volts.

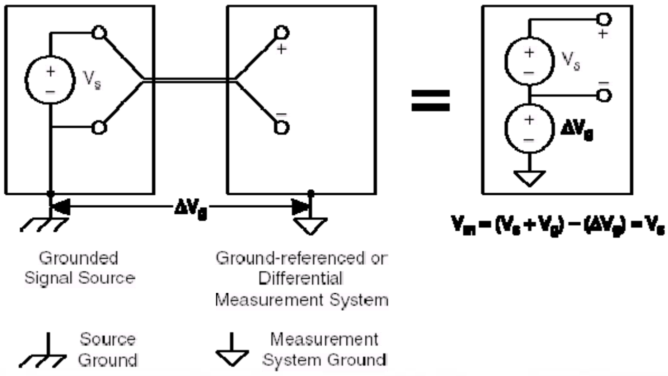
One way to minimize the large differences in ground potential is to use the same grounded AC outlet to power the computer, data acquisition system, and system under test.



Grounding problems

However, even when all the data acquisition equipment operates from the same AC outlet, ground loops still occur.

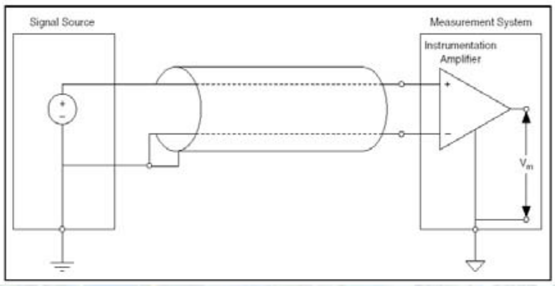
In situations where a common-mode voltage exceeds 10-15 volts, users should consider employing isolated signal conditioning equipment. Generally, data acquisition systems that are isolated or that are floating electrically prevent ground loops.



Input Leads

When installing shielded leads, the shielding should never be grounded at both ends. Any potential difference - causing current flow through the shield (with the capacitive proximity of the shield to the centre conductor) - can result in a noisier connection. Grounding the leads at both ends also simultaneously couples other noise into the signal leads, which negates the advantage of using shielded leads.

Input leads made of twisted pairs often prevent noise as effectively as shielding. Twisted pairs are made by twisting two loose wires into a single spiral pair. The tighter the spiral, the more effective the twisted pair. Twisted pairs also improve most measurements taken in reverse proportion to the signal levels.



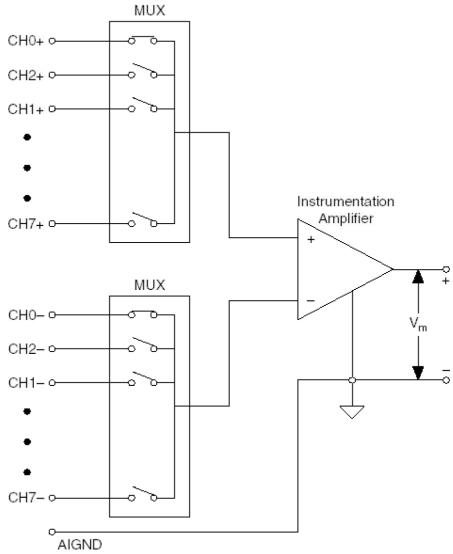
Differential Measurements

In most cases, users can increase data accuracy by making differential voltage measurements (see Figure).

This is accomplished by attaching the channel input leads directly to the voltage point and the most appropriate reference point.

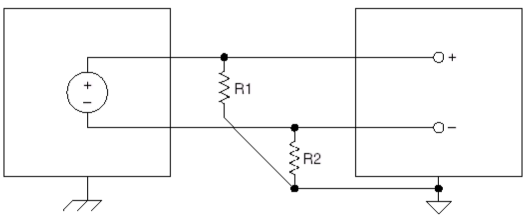
Differential connections work well because the noise on the high analog input lead closely approximates the noise on the low analog input lead. This noise voltage can be considerably higher than the signal that the user is attempting to measure.

$V_m = V^+ - V^-$



Differential Measurements

One of the most common mistakes made when setting up a differential measurement is failing to establish a biasing path between their differential inputs. All differential measurement applications require a biasing path. Although specific applications may already have an established biasing path, others must have one established or the data will be invalid. Users can easily establish a biasing path by connecting a resistor (10 K Ohms to 1 M Ohms) from the low input line to the analog common line. In an application with multiple measurement points referenced to the same analog common line, users need only one connection to the data acquisition system's analog common line.



Wiring configurations

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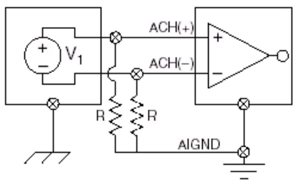
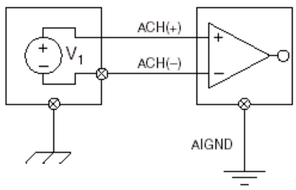
Input Configuration	Signal Source Type	
	Floating Signal Source (Not Connected to Building Ground)	**Grounded Signal Source**
	Examples • Thermocouples • Signal Conditioning with Isolated Outputs • Battery Devices	Examples • Plug-in Instruments with Nonisolated Inputs
Differential (DIFF)	 Two resistors (10 kΩ<R<100 kΩ) provide return paths to ground for bias currents	

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Wiring configurations

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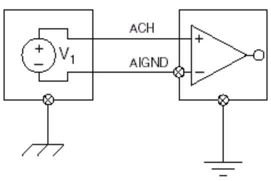
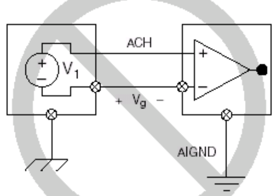
	Floating Signal Source (Not Connected to Building Ground)	**Grounded Signal Source**
	Examples • Thermocouples • Signal Conditioning with Isolated Outputs • Battery Devices	Examples • Plug-in Instruments with Nonisolated Inputs
Single-Ended – Ground Referenced (GRSE)		NOT RECOMMENDED  Ground-loop losses, V_g, are added to measured signal.

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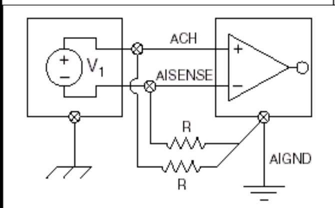
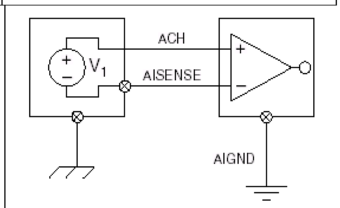
Wiring configurations

Input Configuration	Signal Source Type	
	Floating Signal Source (Not Connected to Building Ground)	**Grounded Signal Source**
	Examples • Thermocouples • Signal Conditioning with Isolated Outputs • Battery Devices	Examples • Plug-in Instruments with Nonisolated Inputs
Single-Ended – Nonreferenced (NRSE)		

Averaging

Many users may not consider averaging their data for fear of losing valuable information on signal variations. However, when the signal can be considered as steady, averaging provides more accurate data by reducing noise via the square root of a number of averaged data samples.

Data collected for dynamic signals should not be averaged because it tends to become distorted.

Before a user decides to average the data for their steady signal measurements, they should consider several important factors. Averaging generally eliminates only random noise; it cannot eliminate many types of system noise (e.g. noise that occurs with the same delay after a triggering event).

Averaging is useful only to the extent that the noise component of a signal averages to zero. Noise in measurements decreases only as the square root of the number of measurements. Therefore, in certain applications, reducing the RMS noise to a single count by averaging would require far too many samples.

Analog and Digital Filtering

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Some 50 (60), 100 (120), and 150 (180)-Hz residual noise emitted from AC equipment is virtually impossible to eliminate only by an accurate wiring connections.

Depending on the frequency of the signal being measured, users can employ either low, or high-pass, or notch filtering. Multiple filters provide greater attenuation. Sometimes a simple filtering approach at the signal source helps. For example, a small capacitor (range 0.001 μF to 0.1 μF) across a signal source removes much of the high-frequency noise. This technique works well with strain gage outputs and other low-level, low-frequency sensors.

However, the best method to eliminate noise within the signal frequency range is through digital filters. They have numerous advantages with respect to analog filters:

1. they can be very sharp in eliminating undesired frequencies (notch).
2. they can be designed with zero phase shift (differently from analog filters that always present phase lead or lag).
3. most of them can operate in real-time acquisition

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