Electrical measurements

Critical to all measurements

Worry about:

- Disturbing the system you study
- Adding extra electrical signals
- Eliminating/reducing noise from measurements

Measurements

Believe nothing until you understand the measurement technique.

All instruments have their own impedances and their own limits.

Main questions about instrument:

1- Does it perturb the circuit (change the current paths noticeably)?

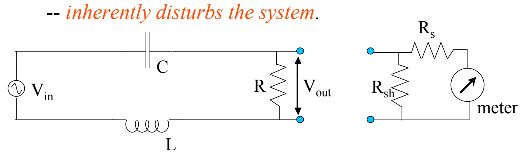
2- How fast does it respond (what's the bandwidth)?

3- How accurate is it (and how do you know)?

"Voltmeter" and oscilloscope

Measurement: take energy out of system to change readings of meter

-- *inherently disturbs the system*.

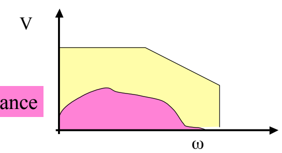


* Are R_{sh} and R_s much larger than circuit impedances? If not then currents are perturbed.

* Can the meter respond faster than the circuit voltages changes? If not it is not much use.

"Bandwidth" (and Fourier space)

Meter performance should exceed the Circuit performance



"Gain-Bandwidth product" not the criterion, since both V range and ω range must be adequate.

Read the specs and the instructions for instruments.

Voltmeter or oscilloscope

Large to extremely high Z_{in} ("$I_{in} = 0$")

Never *assume* that it's "not loading" the circuit

Analog (d'Arsenval meter): uses current through inductor to move needle. Slow (1Hz) and inaccurate (10-50%)

Digital meter: numerical "readout" of voltage drop across big resistor. MUCH more precise (1/1000 – 1/10^7) and accurate (*if calibrated*) but very slow (0.1Hz). Usually very high input impedance.

Oscilloscope: Draws a V(t) graph on screen. Faster (> 10 GHz) and reasonably accurate (2-5%). Digital scope is a little slower (1GHz) but much more precise (1/256 up to 1/65536). Either high input imperdance or matched to 50Ω for high frequencies.

Sensor jargon

A **sensor / transducer** is a device that converts energy from/to some other form (e.g. heat, pressure, etc), into/from electrical signals

Sensitivity: minimum input that makes a detectable output change

Dynamic Range: ratio of maximum and minimum values of input

Precision: degree of reproducibility of the measurements

Accuracy: degree to which you can calibrate the output

Resolution: smallest detectable change in input (sensitivity + noise)

Offset: sensor output that exists when it should be zero

Linearity (calibration) error: difference between the output and the ideal theoretical curve

Hysteresis: difference for increasing and decreasing values of input

Response time: time required for the output to settle to a final value

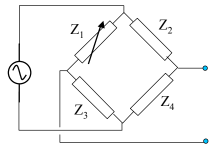
Sensor error: uhm, duh…..

Bridge to measure small deviations

Output from bridge is zero if

$$\frac{Z_1}{Z_3} = \frac{Z_2}{Z_4}$$

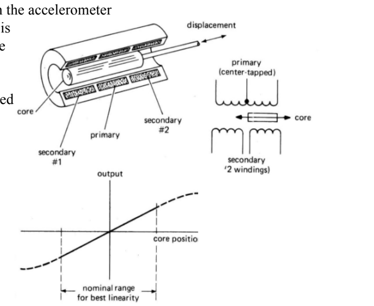
so turn up the gain and look for small deviations from zero caused by small changes in one of the impedances.



Can use AC drive and "lock-in" detection to see one part in ten million change.

Design your sensor to incorporate the bridge

Arrange circuits to balance out spurious noise and to measure only changes of interest. For example, in the accelerometer the equilibrium position is set be zero by placing the weight in symmetric position between coil windings. Circuit designed to have zero output at equilibrium.



What could go wrong?

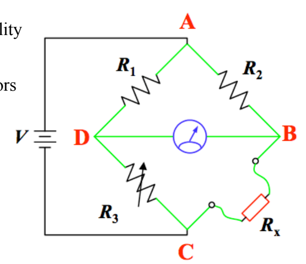
Detector sensitivity and stability

Stability of "standard" resistors

Self-heating in any resistors

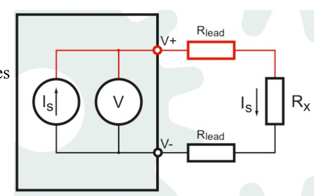
Thermal EMF or other contact potential

Contact resistance to R_x



Two-probe measurement

Current flow through the wires leads to voltage drop and extra resistance measured by the meter.



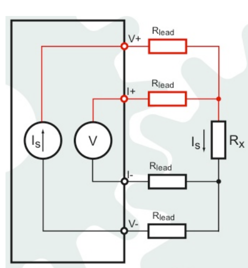
$R_{measured} = R_x + R_{lead1} + R_{lead2}$

Quick and cheap so OK if R_{lead} is small enough

Four-probe measurements

No current flows through wires to voltmeter so R_{lead} is eliminated from the measurement.

More expensive but much more reliable.



What is noise?

Even in a perfect circuit, the ambient signals (radio, power lines, flourescent lamps, … will be picked up and convolved with the instruments signals.

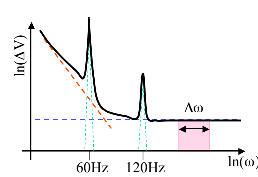
On top of pick-up, there is always noise caused by the components of the instruments.

Component noise has three sources:

(1) Johnson (thermal) noise = random excited motion of charges $(\Delta V)^2 = 4k_BTR\,(\Delta\omega)$

(2) Shot (popcorn) noise = extra bursts of electron population $(\Delta I)^2 = 2qI_{DC}\,(\Delta\omega)$

(3) Flicker (1/f) noise = random changes of resistivity of materials $(\Delta V)^2/(\Delta\omega) \propto 1/\omega$



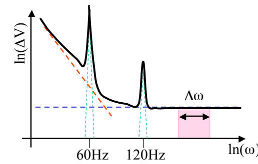
Noise in different components is **uncorrelated** so noise signals add up: $(\Delta V_{total})^2 = (\Delta V_1)^2 + (\Delta V_2)^2 + (\Delta V_3)^2 + \ldots$

Measure of useful signal to noise signal:

$$SNR = 10\log_{10}\left(\frac{V_s^2}{V_n^2}\right)$$

(could use simpler forms like V_s/V_n, in friendly conversation)

How to avoid noise



Since $(\Delta V)^2 \propto (\Delta\omega)$, just limit the bandwidth of the input.

Connect wires and shield them to prevent pick-up.

Connect "grounds" wisely to avoid forming big "ground loops" that pickup power line noise or act as antennae.

Use averaging or phase-sensitive (lock-in) detection to increase signal to noise ratio.

Use low noise components.

Be aware of noise "sweet spots" in components and optimize circuit functions.

Usually the more components you add, the worse it gets…

Noise in Components

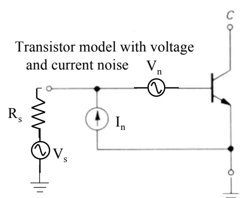
Every component (*especially active ones*) adds noise.

Each will add both current noise and voltage noise.

Design circuits to be operated where the net output noise is minimum.

Remember: at the input gets amplified.

Transistor model with voltage and current noise

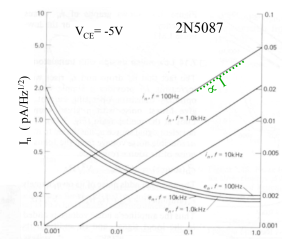


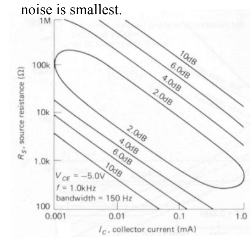
Noise sweet spots

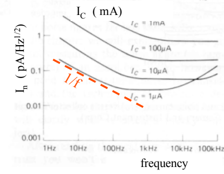
Total noise in any component is sum of $V_{total}^2 = V_n^2 + (I_nR_s)^2$

All noise terms depend on device current and on frequency.

Pick operating point where added noise is smallest.







What about real life?

Each component has own noise contribution:

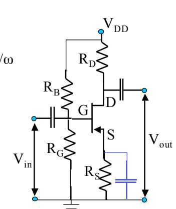
$V_R = V_S + \Delta V_n = IR + 4k_BTR(\Delta\omega) + AR(\Delta\omega)/\omega$
$V_C = I/j\omega C + \Delta V_n = I/j\omega C + \Delta V_{1/f}$
$V_{DD} = V_{ideal} + \Delta V_n$

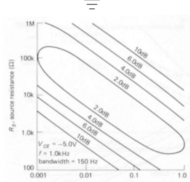
Values in red depend on manufacturing details. (But most numbers are really small.)

Make V_{ideal} for resistors and capacitors by increasing current through components.

Have to add them up and adjust component values, biases, etc to make best solution

BEST is choose components carefully and remember: *input noise is amplified,*





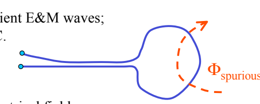
Low noise circuit wiring

After careful choice of circuit components and operating points, connect them together and to the sensor and the transducer wisely.

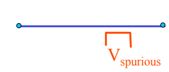
Main point is to avoid spurious coupling of signals from outside the circuit: to avoid interference.

Two main modes of coupling:

Inductive (antenna) sensing of ambient E&M waves; Worse for AC than for DC.



Capacitive sensing of proximate electrical fields. Can be worse problem for DC than for AC.



Wise wiring

To avoid inductive coupling:

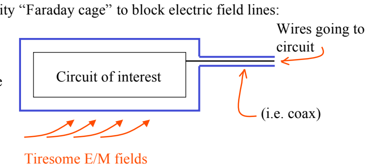
twist wires together to make antenna cancel itself out.

or use high permeability shielding to block flux lines.

To avoid electrostatic coupling:

use high permittivity “Faraday cage” to block electric field lines:

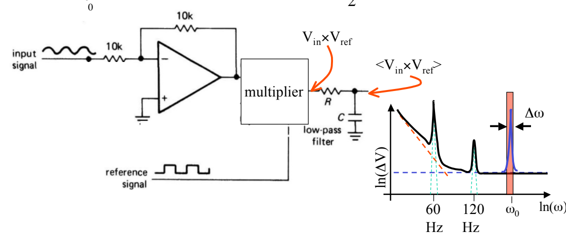
General **shielding** idea is same for both inductive and capacitive problems



Lock-in, phase-sensitive detector

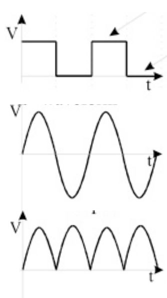
AC signal driven through an unknown impedance can be detected with precision by multiplying it by the driving signal and average the product. Average automatically **removes any signal not in phase with drive**. Removes noise except in narrow range $\Delta\omega$ near ω_0.

$$\langle V_1 \times V_2 \rangle = \int_0^T dt A_1 \sin(\omega_1 t + \theta_1) \times A_0 \sin(\omega_0 t + \theta_0) = \frac{1}{2} A_0 A_1 \delta(\omega_1 - \omega_0) \cos(\theta_1 - \theta_0)$$

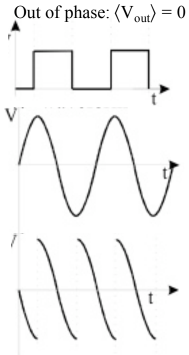


Phase sensitive detection

In phase: $\langle V_{out} \rangle = V_{rms}$



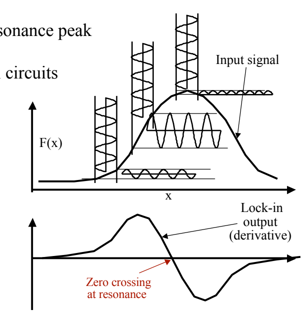
Out of phase: $\langle V_{out} \rangle = 0$



Spectroscopy (old school method)

Creates *derivative* of resonance peak

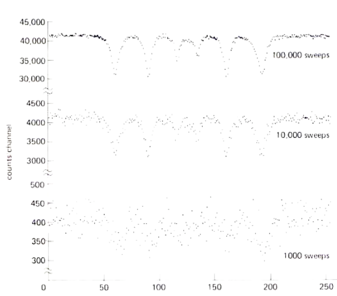
Handy for servo-control circuits



Average to improve signal to noise

If possible to repeat from some reference point, then average many measurements.

$V_s/V_n = N^{1/2}$, so improvement is steady (but slow).

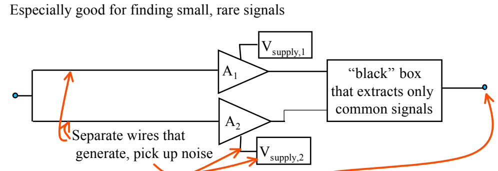


Cross-correlation

Measure the same thing twice and keep only the signals that appear in both.

Great for removing random (uncorrelated noise), but useless for systematic (interference) problems.

Especially good for finding small, rare signals



$$V_{output}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T dt V_1(t) V_2(t-\tau)$$