Advanced Measurement Systems & Sensors (0640732)

Lecture (6)

Interface Electronic Circuits

Part: 2

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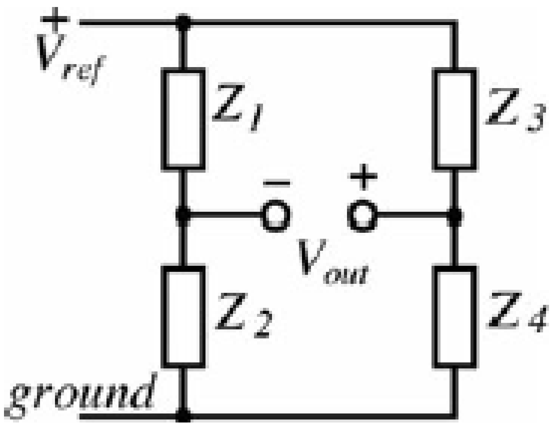
Bridge Circuits:

The Wheatstone bridge circuits are popular and very effective implementations of the ratiometric technique on a sensor level.

Impedances Z may be either active or reactive, that is they may be either simple resistances, like in the piezoresistive gauges, or capacitors, or inductors, or combinations of the above.

For a pure resistor, the impedance is R, for an ideal capacitor, the magnitude of its impedance is equal to 1/(2pfC) and for an inductor, it is 2pfL, where f is the frequency of the current passing through the element. The bridge output voltage is represented by:

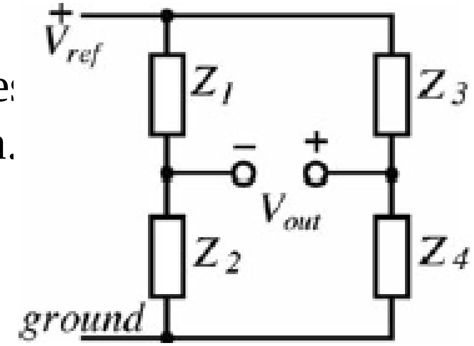
$$V_{out} = \left(\frac{Z_1}{Z_1 + Z_2} - \frac{Z_3}{Z_3 + Z_4}\right) V_{ref}.$$



The bridge is considered to be in a balanced state when the following condition is met:

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

- Under the balanced condition, the output voltage is zero.
- When at least one impedance in the bridge changes, the bridge becomes imbalanced and the output voltage goes either in a +ve or -ve direction.
- To determine the bridge sensitivity with respect to each impedance;



$$V_{out} = \left(\frac{Z_1}{Z_1 + Z_2} - \frac{Z_3}{Z_3 + Z_4}\right) V_{ref}$$

$$\frac{\partial V_{out}}{\partial Z_1} = \frac{Z_2}{(Z_1 + Z_2)^2} V_{ref} \qquad \frac{\partial V_{out}}{\partial Z_2} = -\frac{Z_1}{(Z_1 + Z_2)^2} V_{ref} \qquad \frac{\partial V_{out}}{\partial Z_3} = -\frac{Z_4}{(Z_3 + Z_4)^2} V_{ref} \qquad \frac{\partial V_{out}}{\partial Z_4} = \frac{Z_3}{(Z_3 + Z_4)^2} V_{ref}$$

By summing these equations, we obtain the bridge sensitivity:

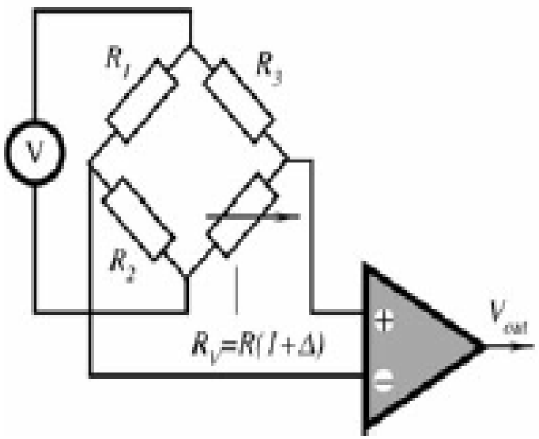
$$\frac{\delta V_{out}}{V_{ref}} = \frac{Z_2 \delta Z_1 - Z_1 \delta Z_2}{(Z_1 + Z_2)^2} - \frac{Z_4 \delta Z_3 - Z_3 \delta Z_4}{(Z_3 + Z_4)^2}$$

- Only the adjacent pairs of the impedances {i.e., (Z1 & Z2), (Z3 & Z4)} have to be identical in order to achieve the ratiometric compensation (such as the temperature stability, drift, etc.).
- It should be noted that impedances in the balanced bridge do not have to be equal, as long as a balance of the ratio is satisfied. In many practical circuits, only one impedance is used as a sensor, thus for Z1 as a sensor, the bridge sensitivity becomes;

$$\frac{\delta V_{out}}{V_{ref}} = \frac{\delta Z_1}{4 Z_1}$$

Disbalanced Bridge: (Wheatstone bridge circuit)

(Deflection Method of Measurement)



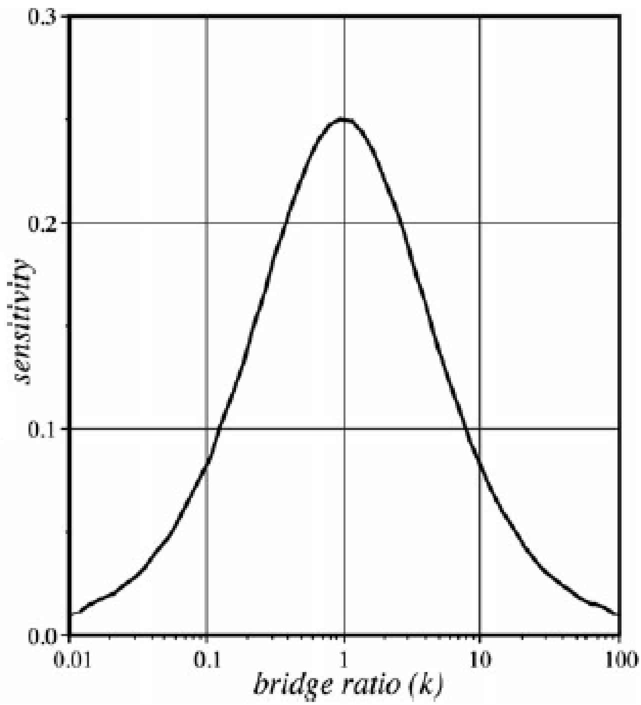
- It is based on a detecting the voltage across the bridge diagonal. The bridge output voltage is a nonlinear function of a disbalance (Δ), where the sensor's resistance $R_v = R(1+ \Delta)$.
- For a small change ($\Delta < 0.05$), the bridge output may be considered quasi-linear.
- The bridge maximum sensitivity (α) is obtained when $R_1= R_2$ and $R_3 = R$.
- When $R_1 >> R_2$ or $R_2 >> R_1$, the bridge output voltage is decreased.
- The bridge sensitivity may be expressed as:

$$\alpha = \frac{V}{R}\frac{k}{(k+1)^2}$$

where; $k = R_1/R_2$

- If the bridge is fed by a current source (i), rather by a voltage source, its output voltage for small Δ and a single variable component is represented by;

$$V_{out} = i\frac{k\Delta}{2(k+1)}$$



Bridge Amplifiers:

The bridge amplifiers for resistive sensors are probably the most frequently used sensor interface circuits.

They may be of various configurations, depending on the required bridge grounding and availability of either grounded or floating reference voltages.

1. Active bridge; where a variable resistor (the sensor) is floating, i.e., isolated from ground, and is connected into a feedback of the OpAmp.

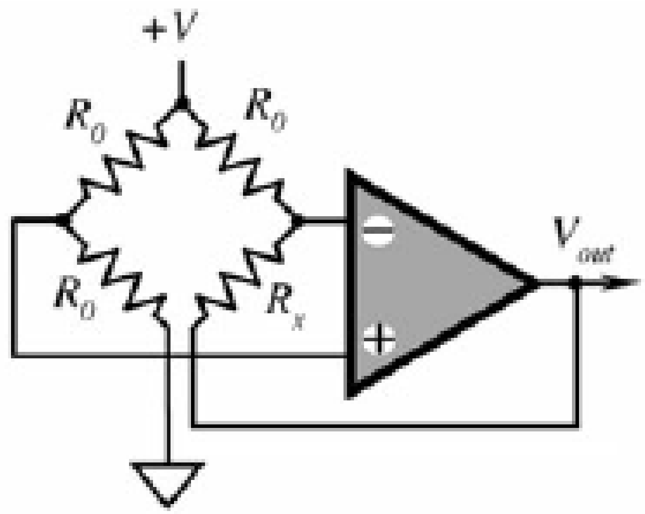
If a resistive sensor's transfer function can be modeled by a first order function:

$$R_x \approx R_o(1+\alpha)$$

where α is the input stimulus,

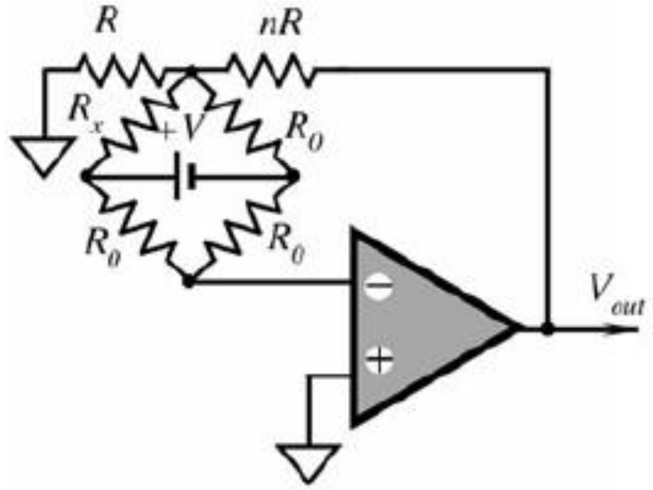
A transfer function of this circuit is;

$$V_{out} = \frac{V}{2} - \frac{1}{2}\alpha V$$



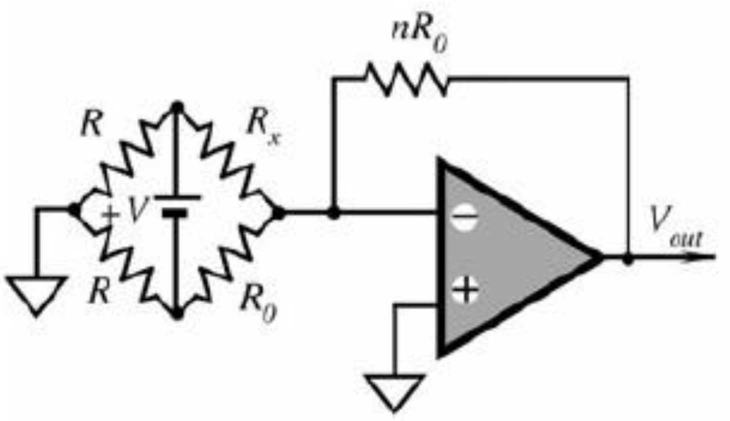
Bridge Amplifiers:

2. A circuit with a floating bridge and floating reference voltage source (V), may provide gain which is determined by a feedback resistor whose value is nR_o:



$$V_{out} = \frac{V}{2} + (1+n)\alpha\frac{V}{4}\frac{1}{1+\frac{\alpha}{2}} \approx \frac{V}{2}\left(1 + \frac{(1+n)\alpha}{2}\right)$$

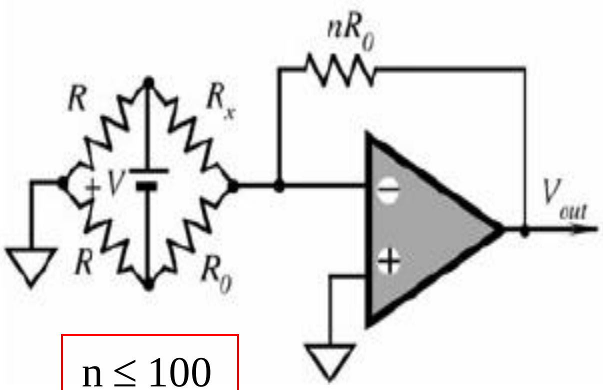
3. A bridge with the asymmetrical resistors (R_6=R_o): It requires a floating reference voltage source V:



$$V_{\text{out}} = \frac{V}{2} + n\alpha\frac{V}{4}\frac{1}{1+\frac{\alpha}{2}} \approx \frac{V}{2}\left(1 + \frac{n\alpha}{2}\right)$$

Bridge Amplifiers:

4. When a resistive sensor is grounded and a gain from the interface circuit is desirable. Its transfer function is;



$$V_{out} = \frac{V}{2} - \frac{n}{2}\frac{V}{1+\frac{1}{2n}}\frac{\alpha}{1+\alpha} \approx 0.5V\left(1 - \frac{n}{1+\frac{1}{2n}}\alpha\right)$$

$n \leq 100$

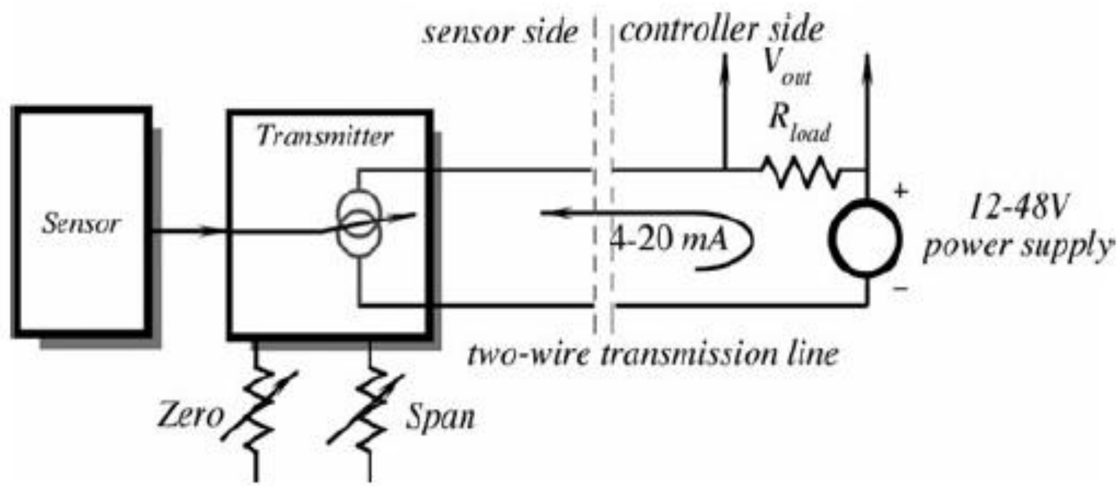
A potentiometer may be required to adjust the bridge component tolerances or offset the bridge balance by some fixed bias. When the bridge is perfectly balanced, its output voltage (V_{out}) is equal to a half of the bridge excitation voltage (V).

Data Transmission:

Signal from a sensor may be transmitted to a receiving end of the system either in a digital format or analog. Transmission in a digital format has several advantages. The sensor's output signal is transmitted to the receiving site in an analog form. Depending on connection, the transmission methods can be divided into a 2, 4, and 6-wire methods.

1. Two-wire Transmission:

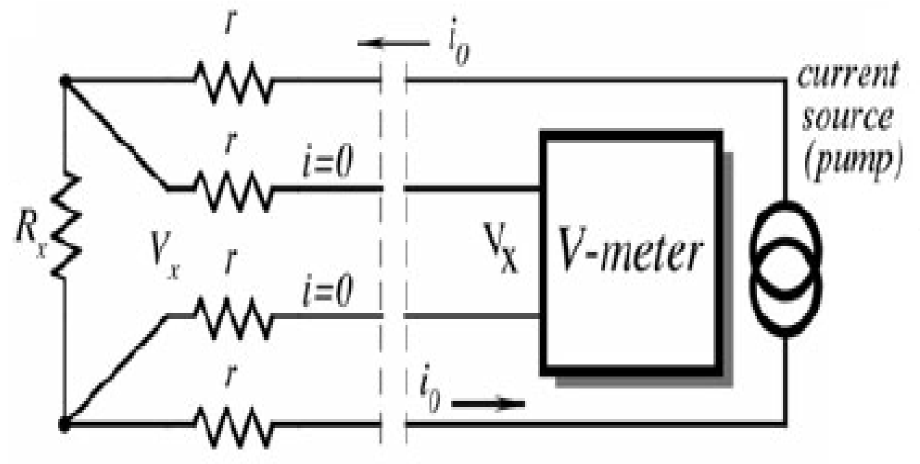
- Two-wire analog transmitters are used to couple sensors to other devices.
- Two wires can be used to transmit either voltage or current (industry standard). The current varies in the range (4 to 20) mA, which represents the entire span of the measured variable.



- An advantage of the two wire method is that the transmitting current is independent of the connecting wires resistance (as long as they do not change) and thus of the transmission line length (within the limits).

Four-wire transmission:

- When a sensor has a relatively low resistance (order of 100 Ω), such as RTDs or piezoresistors, the connecting wire resistances pose a serious problem since they alter the excitation voltage across the sensor. This problem can be solved by using 4-wire method.
- A sensor is connected to the interface circuit through four wires. Two wires are connected to a current source and two others to a voltmeter or amplifier.



- A voltage drop across the resistor (Rx) is;

$$V_x = R_x i_o$$

which is independent of any resistances (r) of the connecting wires.

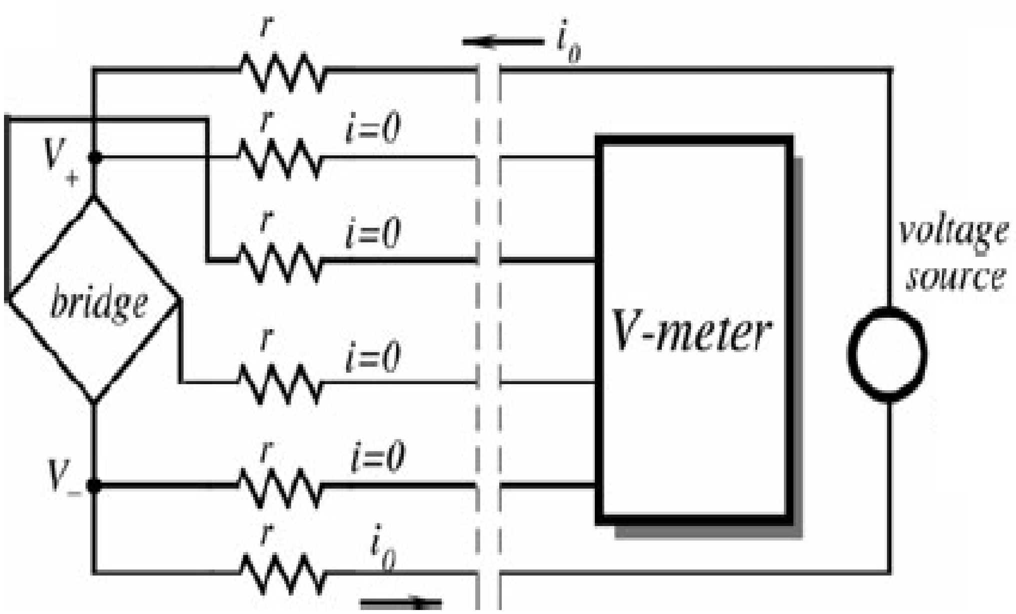
- The 4-wire method is a very powerful means of measuring resistances of remote detectors and is used in industry and science.

3. Six-Wire Sensing:

When a Wheatstone bridge circuit is remotely located, voltage across the bridge plays an important role in the bridge temperature stability.

Long transmitting wires may introduce unacceptably high resistance in series with the bridge excitation voltage, which interferes with the temperature compensation. This problem may be solved by providing two additional wires to feed the bridge with voltage and to dedicate two wires to measuring the voltage across the bridge.

Note: The actual excitation voltage across the bridge and the bridge differential output voltage are measured by a high-input impedance voltmeter with negligibly small input currents. Thus, the accurate bridge voltages are available at the data processing site without being affected by long transmission lines.



Noise in Sensors and Circuits:

There are two basic classifications of noise;

1. Inherent noise; which is noise arising within the circuit, and
2. Interference (transmitted) noise; which is noise picked up from outside the circuit.

1. Inherent Noise:

- A signal, which is amplified and converted from a sensor into a digital form, should be regarded not just by its magnitude and spectral characteristics, but also in terms of a digital resolution.
- Noise can be produced by the monolithic amplifiers and other components, which are required for the feedback, biasing, bandwidth limiting, etc.
- The noise signals (voltage and current) result from physical mechanisms within the resistors and semiconductors that are used to fabricate the circuits.
- There are several sources of noise whose combined effect is represented by the noise voltage and current generators.
- One cause for noise is a discrete nature of electric current because current flow is made up of moving charges, and each charge carrier transports a definite value of charge

- In a resistor, these thermal motions cause Johnson noise to result. The mean-square value of noise voltage (which is representative of noise power) can be calculated from;

$$\bar{e}_n^2 = 4kTR\Delta f \; [\mathrm{V^2/Hz}]$$

where; k = 1.38*10^{-23} J/K (Boltzmann constant), T is temperature in K, R is the resistance in Ω, and Δf is the bandwidth over which the measurement is made.

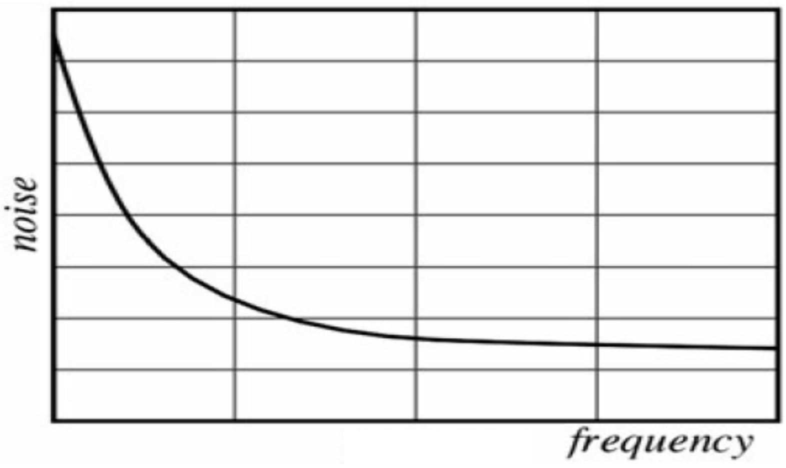
- Even a simple resistor is a source of noise, a small resistors generate extremely small noise.
- Noise voltage is proportional to square root of the bandwidth. It implies that if we reduce the bandwidth 100 times, noise voltage will be reduced by a factor of 10.
- Another type of noise results because of dc current flow in semiconductors. It is
- called **shot noise**, which is also white noise. Its value becomes higher with the increase in the bias current. This is the reason why in FET and CMOS semiconductors the current noise is quite small. A convenient equation for shot noise is;

$$i_{\mathrm{sn}} = 5.7 \times 10^{-4}\sqrt{I\Delta f}$$

where I is a semiconductor junction current in pA and Δf is a bandwidth of interest in Hz.

Pink noise:

- An additional ac noise mechanism exists at low frequencies.
- Both the noise voltage and noise current sources have a spectral density roughly proportional to 1/f, which is called the pink noise, because of the higher noise contents at lower frequencies.



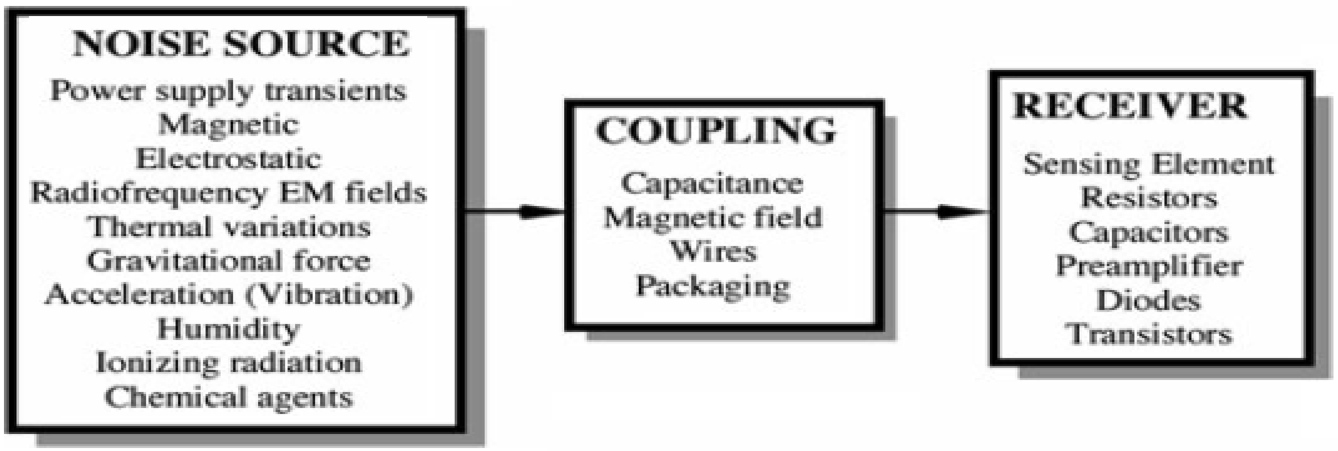
- This 1/f noise occurs in all conductive materials, therefore it is also associated with resistors.
- At extremely low frequencies it is impossible to separate the 1/f noise from dc drift effects. The 1/f noise is sometimes called a flicker noise.
- A combined noise from all voltage and current sources is given by sum of squares of individual noise voltages:

$$e_E = \sqrt{e_{n1}^2 + e_{n2}^2 + \cdots + (R_1 i_{n1})^2 + (R_1 i_{n2})^2 + \cdots}$$

$$E_{rms} = \sqrt{\frac{1}{T}\int_0^T e^2 dt}$$

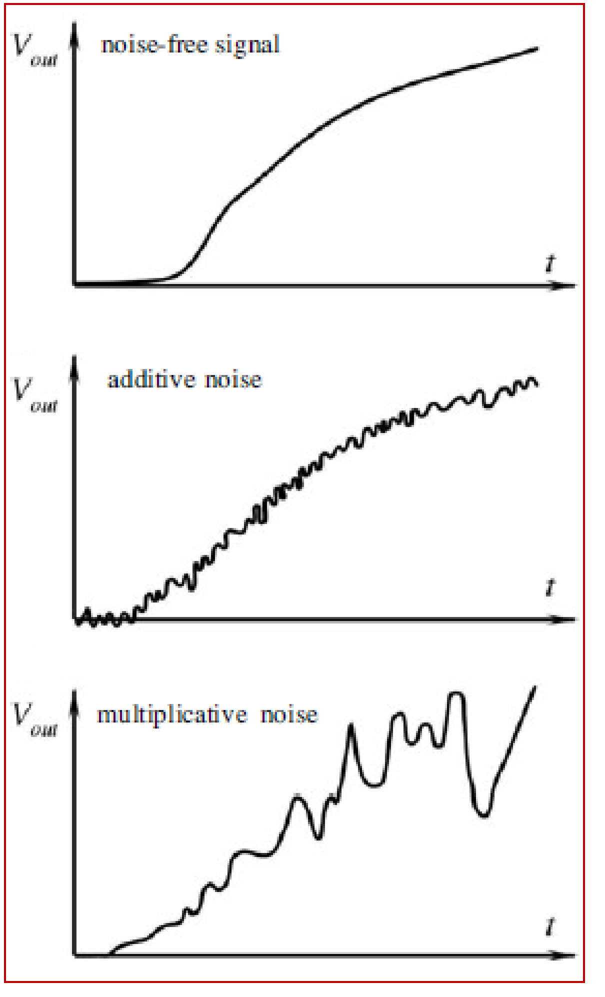
where T is time of observation, e is noise voltage and t is time.

2. Interference (Transmitted) noise:



- Noise comes from a source which often cannot be identified. Examples of the sources are: voltage surges in power lines, lightnings, sun activity, change in ambient temperature, etc.
- These interferences propagate toward the sensor and the interface circuit, and to present a problem eventually must appear at the output.
- They somehow must affect the sensing element inside the sensor, its output terminals or the electronic components in the circuit. Both the sensor and circuit act as receivers of the interferences.

- There can be several classifications of transmitted noise, depending on how it affects the output signal, how it enters the sensor or circuit, etc.
- With respect to its relation to the output signals, noise can be either additive or multiplicative.



Additive noise (e_n) is added to the useful signal (V_s) and mixed with it as a fully independent voltage (or current);

$$V_{out} = V_s + e_n$$

Note: the noise magnitude does not change when the actual signal changes. As long as the sensor and interface electronics can be considered linear, the additive noise magnitude is totally independent of the signal magnitude

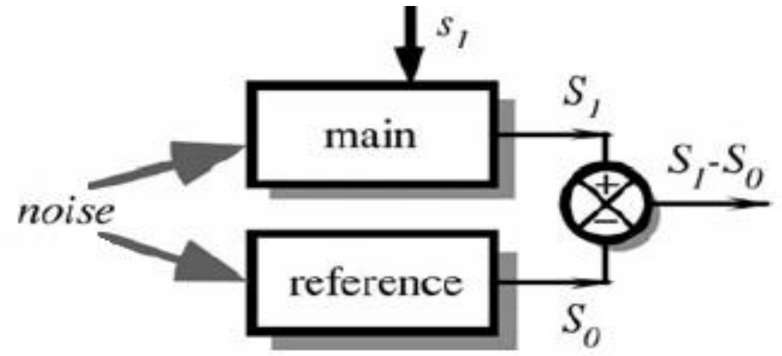
Multiplicative noise affects the sensor's transfer function or the circuit's nonlinear components in such a manner as Vs signal's value becomes altered or modulated by the noise:

$$V_{out} = [1 + N(t)]V_s$$

where $N_{(t)}$ is a function of noise.

Differential Technique Method:

To improve noise stability against transmitted additive noise, sensors are combined in pairs, they are fabricated in a dual form whose output signals are subtracted from one another.



- Since additive noise is specific for the linear or quasilinear sensors and circuits, the reference sensor does not have to be subjected to any particular stimulus.
- Both sensors are subjected to identical transmitted noise (noise generated inside the sensor cannot be cancelled by a differential technique), it is a common-mode noise. This means that noisy effects at both sensors are in-phase and have the same magnitude. If both sensors are identically influenced by common mode spurious stimuli, the subtraction removes the noise component.
- The quality of noise rejection is described by a number which is called the common-mode rejection ratio (CMRR):

$$\mathrm{CMMR} = 0.5\frac{S_1 + S_0}{S_1 - S_0}$$

- The ratio shows how many times stronger the actual stimulus will be represented at the output, with respect to a common mode noise having the same magnitude.

Electric Shielding:

Interferences to electric fields can be significantly reduced by appropriate shielding of the sensor and circuit, especially of high impedance and nonlinear components.

Each shielding problem must be analyzed separately and carefully.

It is very important to identify the noise source and how it is coupled to the circuit.

A shielding serves two purposes;

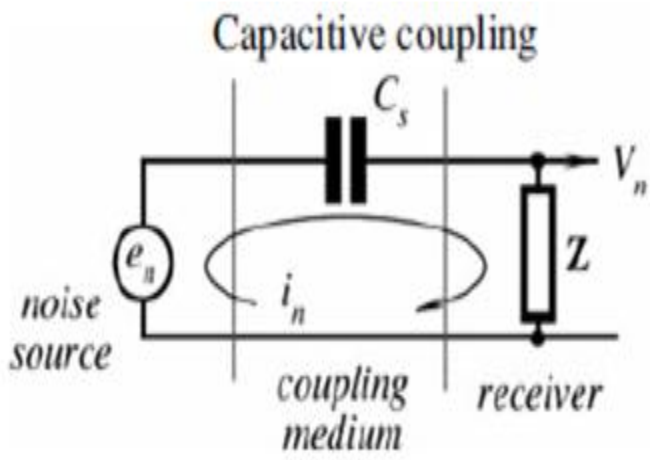
1. It confines noise to a small region, to prevent noise from getting into nearby circuits.
2. If noise is present in the circuit, shields can be placed around critical parts to prevent the noise from getting into sensitive portions of the detectors and circuits. These shields may consist of metal boxes around circuit regions or cables with shields around the center conductors.

A noise current is defined as;

$$i_n = \frac{V_n}{Z + Z_s}$$

and actually produces noise voltage;

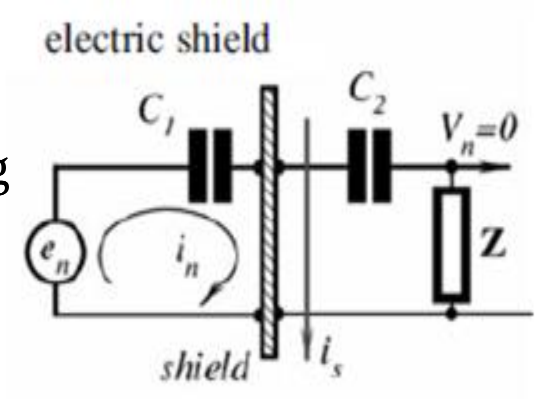
$$V_n = \frac{e_n}{\left(1 + \frac{Z_c}{Z}\right)}$$



For example: if C_s=2.5pf, Z=10 kΩ (resistor) and e_n= 100 mV, at 1.3 MHz. Then, the output noise will be 20 mV.

When a shield is added;

Assume that the shield has zero impedance, the noise current at the left side will be $i_n = e_n/Z_c$.



Noise current will be essentially zero since there is no driving source at the right side of the circuit.

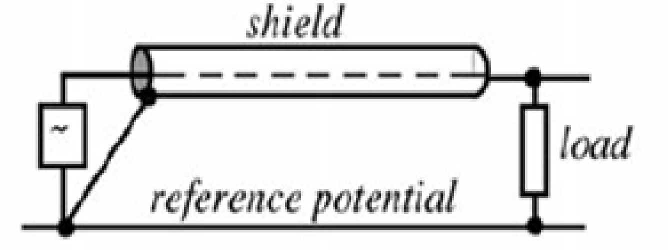
The noise voltage over the receiving impedance will also be zero and the sensitive circuit becomes effectively shielded from the noise source.

One must be careful, there is no significant currents is flow over the shield.

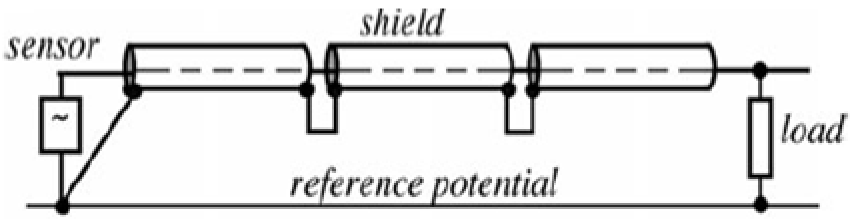
Electrostatic shields:

There are several practical rules when applying electrostatic shields;

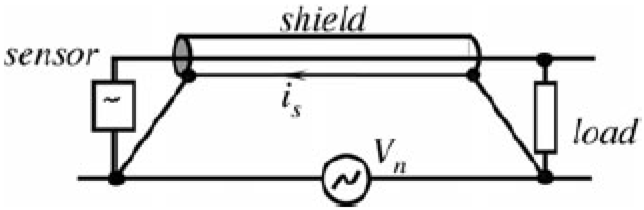
1. It should be connected to the reference potential of any circuitry contained within the shield.
2. If a shielding cable is used, its shield must be connected to the signal referenced node at the signal source side.



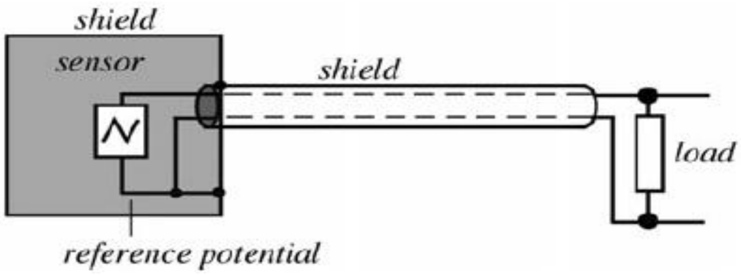
3 If the shield is split into sections, as might occur if connectors are used, the shield for each segment must be tied to those for the adjoining segments, and ultimately connected only to the signal referenced node.



4. The number of separate shields required in a data acquisition system is equal to the number of independent signals that are being measured.



5. If a sensor is enclosed into a shield box and data are transmitted via a shielded cable. The cable shield must be connected to the box.

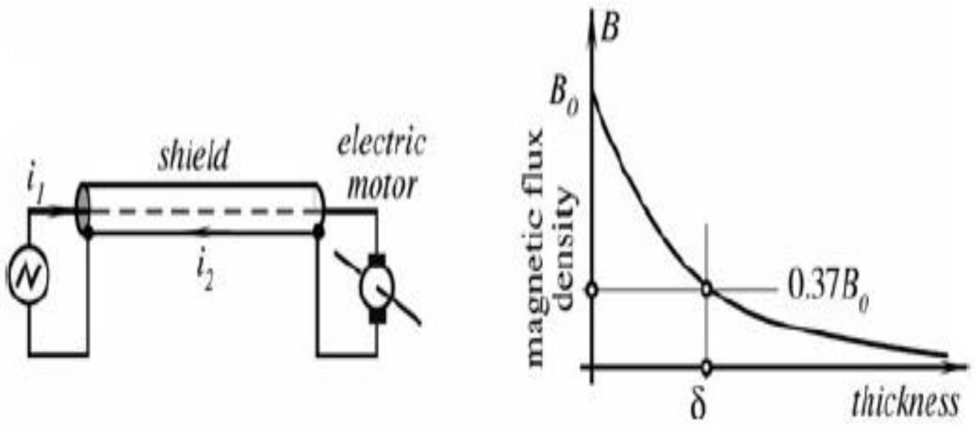


6. Never allow the shield to be at any potential with respect to the reference potential.

7 Connect shields to a ground via short wires to minimize inductance. This is especially important when both analog and digital signals are transmitted.

Magnetic Shielding:

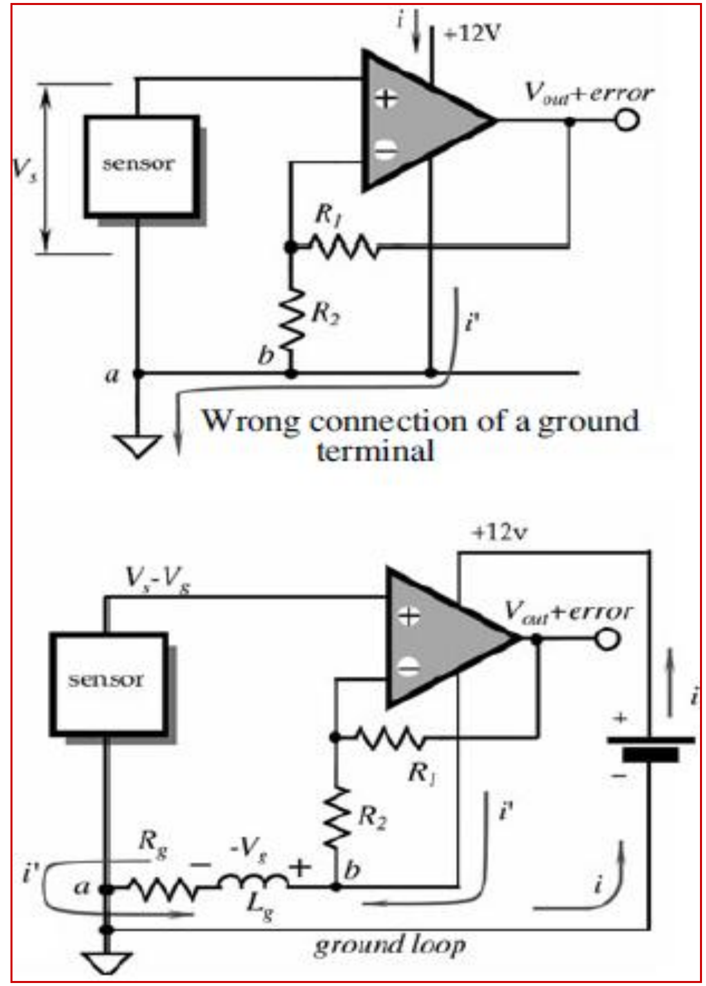
- Proper shielding may reduce noise resulting from electrostatic and electrical fields.
- It is much more difficult to shield against magnetic fields because it penetrates conducting materials.
- A typical shield placed around a conductor and grounded at one end has little if any effect on the magnetically induced voltage in that conductor.
- Reduction of a transmitted magnetic noise by powering a load device through a coaxial cable.

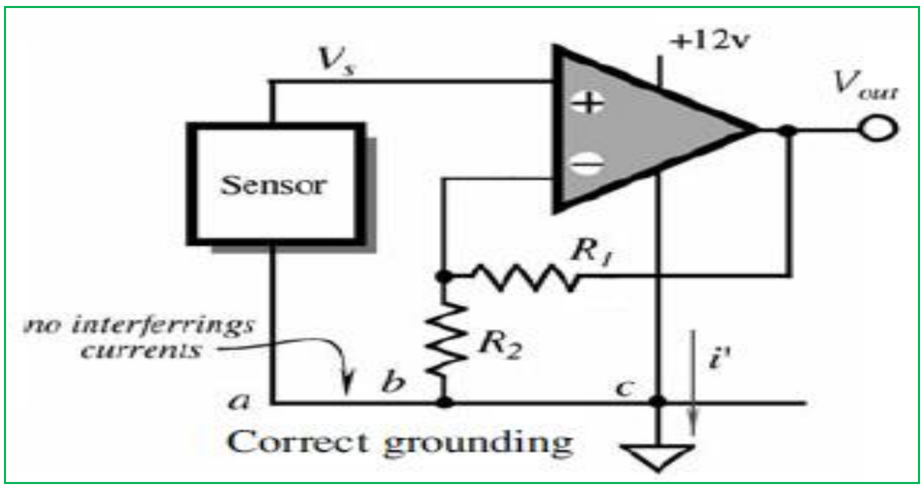


- Since magnetic shielding is very difficult, the most effective approach at low frequencies is to;
  - ✓ minimize the strength of magnetic fields,
  - ✓ Minimize the magnetic loop area at the receiving end, and
  - ✓ selecting the optimal geometry of conductors.

Ground Loops and Ground Isolation:

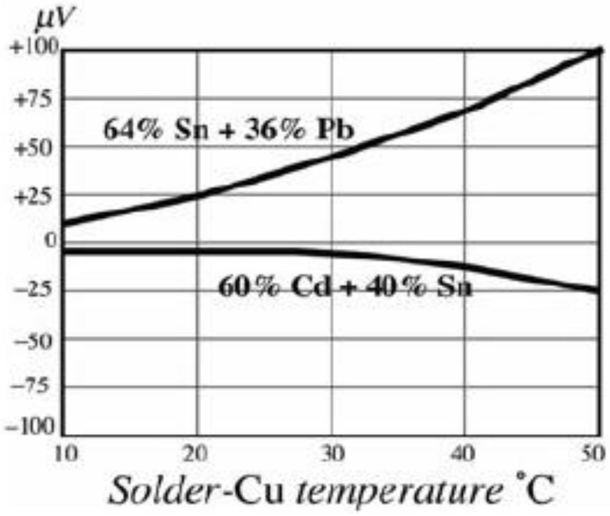
- A power supply bus carries supply currents to all stages.
- A ground bus also carries supply currents, but, in addition, it is often used to establish a reference base for an electrical signal. For any measurement circuit cleanliness of a reference base is essential.
- Interaction of the two functions (power supply and reference) may lead to a problem which is known as ground loop.

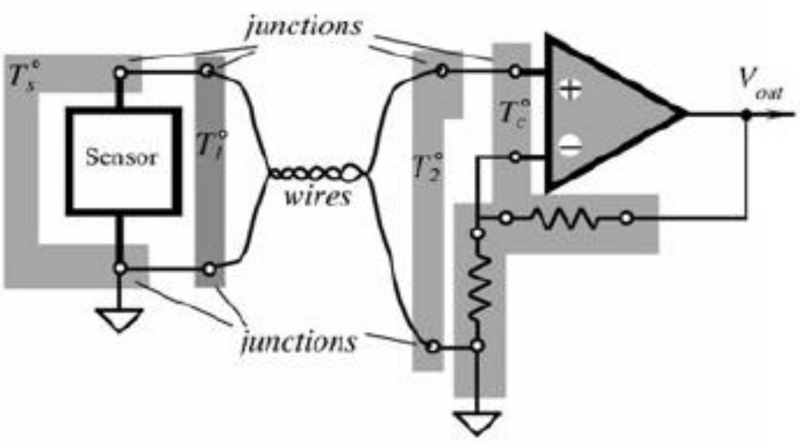




Seebeck Noise:

- This noise is a result of the Seebeck effect, which is manifested as the generation of an electromotive force (e.m.f.) when two dissimilar metals are joined together.
- The Seebeck e.m.f. is small and for many sensors may be simply ignored.
- When absolute accuracy on the order of 10–100 mV is required, that noise must be taken into account.
- Seebeck e.m.f. may be eliminated by a proper circuit layout and thermal balancing.
- It is a good practice to limit the number of junctions between the sensor and the front stage of the interface circuit. Avoid connectors, sockets, switches and other potential sources of e.m.f. to the extent possible.





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