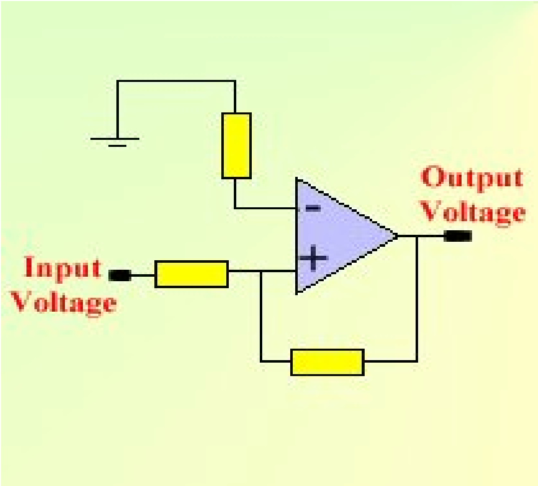
CHAPTER (3)



Instrumentation Amplifier

Objectives:

This chapter will consider the instrumentation amplifier and analog signal conditioning. After you have read this chapter, you should be able to

- Analyze instrumentation amplifier circuits
- Develop Op-Amp signal conditioning circuits
- Develop signal conditioning circuits using Wheatstone bridge
- Define the purpose and techniques of analog signal conditioning

3.1 Instrumentation amplifier (Op Amp)

The term operational amplifier, abbreviated op amp, was coined in the 1940s to refer to a special kind of amplifier that, by proper selection of external components, can be configured to perform a variety of mathematical operations. Early op amps were made from vacuum tubes consuming lots of space and energy. Later op amps were made smaller by implementing them with discrete transistors. Today, op-amps are monolithic integrated circuits IC, highly efficient and cost effective.

Amplifier basics

An amplifier has an input port and an output port. In a linear amplifier, output signal = A multiplied by input signal, where A is the amplification factor or gain. Depending on the nature of input and output signals, we can have four types of amplifier gain:

- Voltage out/Voltage in
- Current out/Current in
- Voltage out/Current in
- Current out/Voltage in

Since most op amps are voltage amplifiers, we will limit our discussion to voltage amplifiers.

Standard Op Amp Model

Figure 3.1 showing the standard op-amp notation. An op amp is a differential to single-ended amplifier. It amplifies the voltage difference, $V_d = V_p - V_n$, on the input port and produces a voltage, VO, on the output port that is referenced to ground.

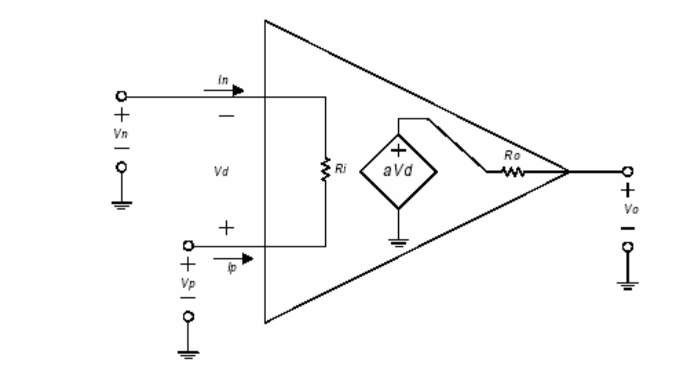


Figure 3.1 Standard Op-Amp notation

Ideal Op Amp Model

The ideal op-amp model was derived to simplify circuit calculations by making three simplifying assumptions:

- Gain is infinite ($A>10^5$)
- Input resistance is infinite.
- Output resistance is zero
- $V_d=V_p - V_n$ is zero, (virtual short between points)

The following figure shows the ideal op-amp in applying the above assumptions.

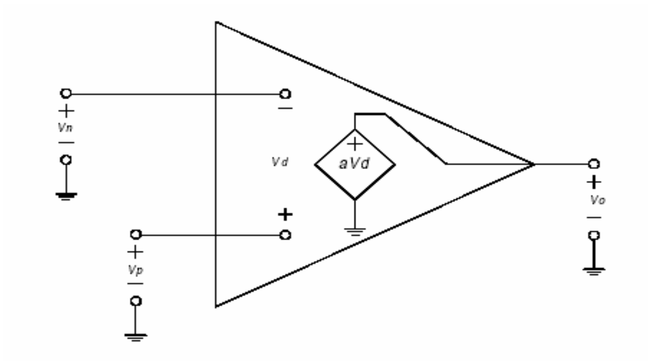


Figure 3.2 Ideal Op-Amp model

Basic equation

$$V_o = A\,(V_p - V_n) \tag{3.1}$$

Practical issues

There are several practical issues associated with op amp applications that appear as extra components in op amp circuits but which do not contribute to the circuit transfer function such as:

- In general, op amps require bipolar power supplies, +Vs and –Vs, of equal magnitude, which are connected to designated pins of the IC. Typically, the value of these supply voltages is in the range of V_{DC} = 9 to 15 volts, although op amps are available with many other supply requirements.

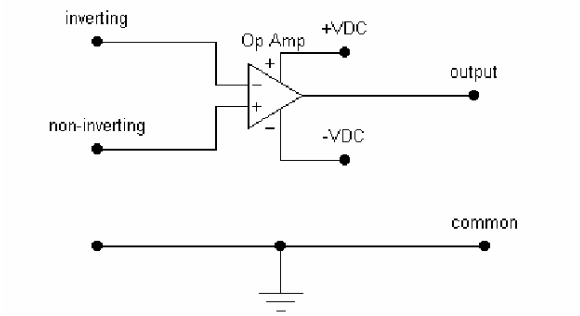


Figure 3.3 Op-Amp with balanced power supply

- Approximate input offset current compensation can be provided by making the resistance feeding both input terminals approximately the same.
- Compensation for input offset voltage can be provided either using pin connections with supply or using external input offset voltage on the input.
- General purpose IC op-amps can source, or sink, no more than about 20 mA, which includes the current in the feedback circuit. Think of use mA and kΩ when designing circuits that use op-amps.

Most of the op-amp circuits shown in this text will not include power supply connections or compensation components. This is done to simplify the circuits so the essential working principles can be understood. You should realize, however, that a practical circuit will usually need theses compensation elements.

Applications of Op-Amp

The op-amp is used in wide applications. We will focus only on the common applications as in the following:

- Voltage follower
- Inverting amplifier
- Non-inverting amplifier
- Nonlinear (algorithmic) amplifier
- Differential amplifier
- Summing amplifier
- Differentiator
- Integrator

3.1.1Voltage follower

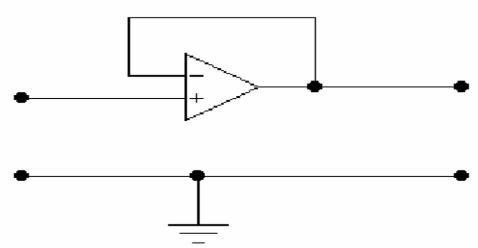


Figure 3.4 Voltage follower

The circuit gain is unity with very high input impedance. Assume that we have a battery with open circuit voltage of the value V_s volts and is connected to drive a load of R_L Ω. If the load is not high and we measure the output voltage from battery when the circuit is closed, we will find a difference between this reading and the open circuit value (with no load). This is due to the consumed current by load (loading effect problem). To avoid this problem, it is ideal to use a load with infinity impedance value. As the voltage follower circuit has infinity input impedance and its input current is approximately zero, it can be inserted between the load and the supply to overcome the loading effect problem.

3.1.2 Inverting amplifier

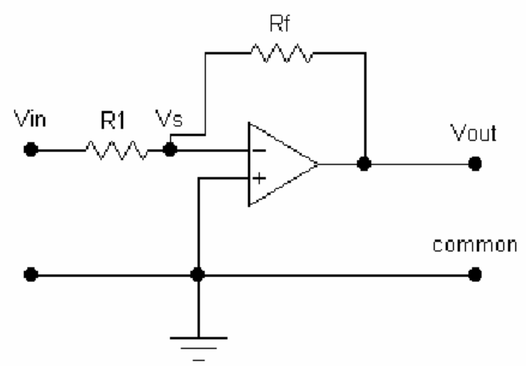


Figure 3.5 Inverting amplifier

The sum of the input current and feed back current is equal to zero. Thus,

$I_{in} + I_f = 0$ there is no net current into the summing junction

$$\frac{V_{in} - V_s}{R_1} + \frac{V_{out} - V_s}{R_f} = 0$$

The gain equation

$$V_{out} = -AV_s \quad \text{therefore } V_s = -\frac{V_{out}}{A} \approx 0$$

the summing junction is a virtual ground

$$\frac{V_{in}}{R_1} + \frac{V_{out}}{R_f} = 0$$

$$\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_1} = G \text{ (the gain of the inverting amplifier)}$$

The input resistance is given by:

$$R_{in} = \frac{V_{in}}{I_{in}} = \frac{V_{in}}{V_{in} - V_s} R_1 \approx R_1$$

The summing junction is a virtual ground.

Example
Develop a high input impedance amplifier with a voltage gain of 10

Solution
We use the inverting circuit in figure 3.5 with resistors selected from $R_f = 10\ R_1$. So we could choose $R_1 = 1\ k\Omega$, which requires $R_f = 10\ k\Omega$. The gain will be equal to -10, so the circuit has to be followed with a similar one that has equal resistors (unity gain). The over all gain is equal to (-10)(-1) = 10, which is required value. Note that, the circuit can be developed by using non-inverting amplifier to use an effective number of components.

3.1.3 Non-inverting amplifier

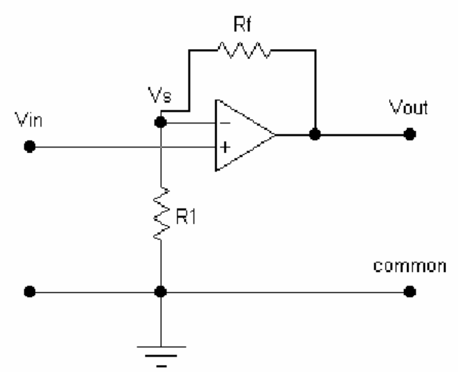


Figure 3.6 Non-inverting amplifier

The gain equation

$$V_{out} = A(V_{in} - V_s)$$

therefore $V_{in} - V_s = \frac{V_{out}}{A} \approx 0$

Consider the currents into the summing junction

$$\frac{V_{out} - V_s}{R_f} - \frac{V_s - 0}{R_1} = 0$$

now

$$\frac{V_{out} - V_{in}}{R_f} = \frac{V_{in}}{R_1}$$

$$G = \frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_1}$$

Input resistance

R_{in} is very large

Example

Develop a high input impedance amplifier with a voltage gain of 10

Solution

We have solved the same example before using inverting amplifier. Now, we can develop the circuit using the non-inverting amplifier. The resistors could be selected from $(1+R_f/R_1) = 10$. So, we could choose R_1 = 1 kΩ, which requires R_f = 9 kΩ. The gain will be equal to 10 without need of the inverter to inverse the gain sign.

3.1.4 Nonlinear (logarithmic) amplifier

The op-amp can also implement a nonlinear relationship, this is achieved by placing a nonlinear element in the feedback of the op-amp. For example, a diode can be used as shown figure.

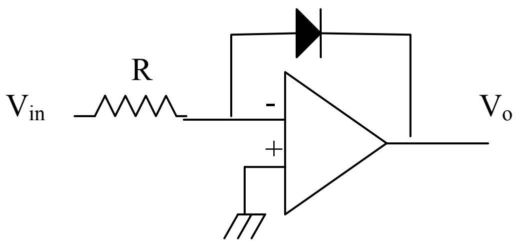


Figure 3.7 Logarithmic amplifier

The summation of currents provides

$$\frac{V_{in}}{R} + I(V_{out}) = 0 \qquad (3.2)$$

Were I is the current passes through R and at the same time in the diode. Note that the current in the diode has a nonlinear relation as function of V_{out}. In the diode we have the relation

$$I(V_{out}) = I_o \exp(\alpha V_{out}) \qquad (3.3)$$

Where I_o= amplitude constant and α=exponential constant. The inverse of this relation is the logarithm, and thus

$$V_{out} = \frac{1}{\alpha} Log_e(V_{in}) - \frac{1}{\alpha} Log_e(I_o R) \tag{3.4}$$

which constitutes a logarithmic amplifier.

3.1.5 Differential amplifier

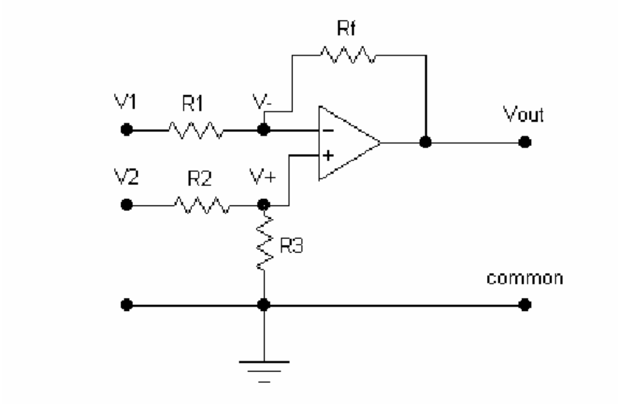


Figure 3.8 Differential amplifier

$$V_+ = \left(\frac{R_3}{R_2 + R_3}\right) V_2$$

The current into the summing junction

$$\frac{V_1 - V_-}{R_1} + \frac{V_{out} - V_-}{R_f} = 0$$

The gain equation

$$V_{out} = A(V_+ - V_-) \text{ then } \frac{V_{out}}{A} = (V_+ - V_-) \approx 0$$

because A >> 1

therefore

$$V_+ = V_-$$

$$\frac{V_1 - \left(\frac{R_3}{R_2 + R_3}\right) V_2}{R_1} + \frac{V_{out} - \left(\frac{R_3}{R_2 + R_3}\right) V_2}{R_f} = 0$$

$$V_{out} = \frac{R_1 + R_f}{R_2 + R_3}\left(\frac{R_3}{R_1}\right) V_2 - \frac{R_f}{R_1} V_1$$

Note that the output voltage as given equation (3.1) does not depend on the values or polarity of either input voltage, but only on their difference. To define the degree to which a differential amplifier approaches the ideal, we use the following definitions. The common mode input voltage is the average of voltage applied to the two terminals.

$$V_{cm} = \frac{V_1 + V_2}{2} \tag{3.5}$$

An ideal differential amplifier will not have any output that depends on the value of the common mode voltage; that is, the circuit gain for common mode voltage, A_{cm} will be zero. The common mode rejection ratio (CMRR) of a differential amplifier is defined as the ratio of the gain to the common mode gain. The common mode rejection (CMR) is the CMRR expressed in dB.

$$CMRR = \frac{A}{A_{cm}} \quad ; \quad CMR = 20\log_{10}(CMRR) \tag{3.6}$$

Clearly, the larger these numbers, the better the differential amplifier. Typical values of CMR range from 80 to 100 dB.

Case where $R_1 = R_2$ and $R_f = R_3$

Then

if $G = \frac{R_f}{R_1}$ is the differential gain and

$V_{out} = G(V_2 - V_1) = GV_{dif}$

Common Mode Signal

$V_{cm} = (V_2 + V_1)/2$

Common Mode Gain

$G_{cm} = V_{out} / V_{cm}$

Common Mode Rejection Ratio

$CMRR = G / G_{cm} = V_{cm} / V_{dif}$

typically $CMRR \approx 10^4$

$CMRR(dB) = 20\log_{10}(CMRR)$

(3.7)

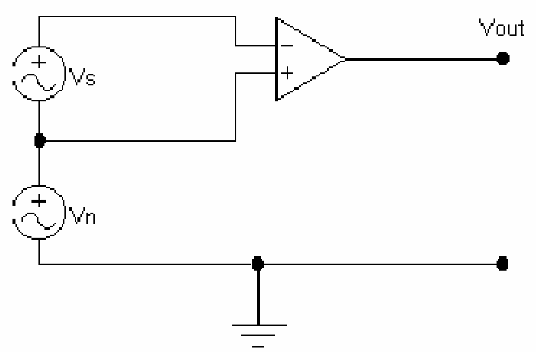


Figure 3.9 Differential amplifier with CMRR

Any signal common to both inputs is effectively canceled and free to put the ground anywhere, the noise is common.

$$V_{out} = G\,V_s + G_{cm}\,V_n$$
$$= G\left[V_s + \frac{V_n}{CMMR}\right]$$

A typical example of an op amp is a 741 integrated circuit IC.

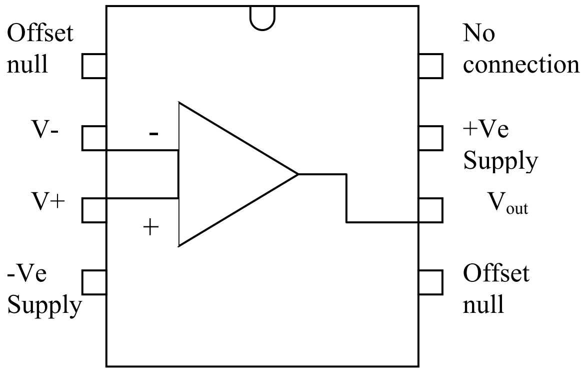


Figure 3.10 Op-Amp 741 pin configuration

Compensation for input offset voltage can be provided as a variable resistor connected to two terminals (offset null).

3.1.6 Summing amplifier

A common modification of the inverting amplifier is an amplifier that sums or adds two or more applied voltages. This circuit is shown in the following figure.

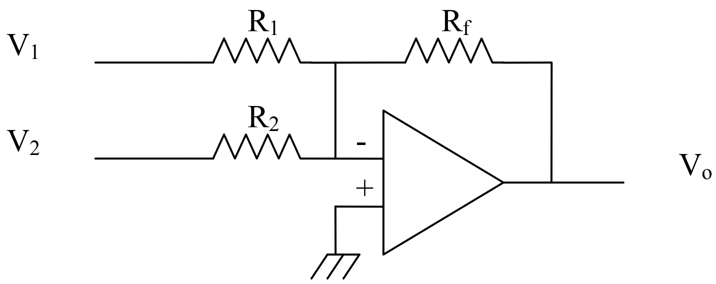


Figure 3.11 Summing amplifier

The output voltage is given by:

$$V_o = -\frac{R_f}{R_1} V_1 - \frac{R_f}{R_2} V_2 \tag{3.8}$$

The sum can be scaled by proper selection of resistors. For example, if we select $R_f = R_1 = R_2$, the output is simply (inverted) sum of the input voltages. The average can be found by making $R_1 = R_2$ and $R_f = R_1/2$.

3.1.7 Differentiator

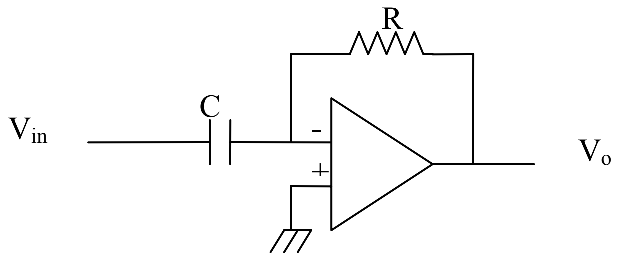


Figure (3.12) Differentiator

The output voltage is given by:

$$V_o(t) = - CR \frac{d\,V_{in}(t)}{dt} \tag{3.9}$$

3.1.8 Integrator

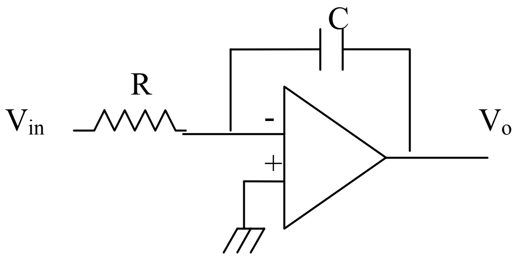


Figure (3.13) Integrator

The sum of the currents at the summing point is

$$\frac{V_{in}}{R} + C\frac{dV_{out}}{dt} = 0 \tag{3.10}$$

Thus, the output voltage is given by:

$$V_o(t) = -\frac{1}{RC}\int V_{in}(t)\,dt \tag{3.11}$$

<u>**Example**</u>
Develop a circuit to realize the following equation

$$V_{out} = 10\,V_{in} + 4\int V_{in}\,dt$$

Solution
See the following figure that illustrates the required circuit.

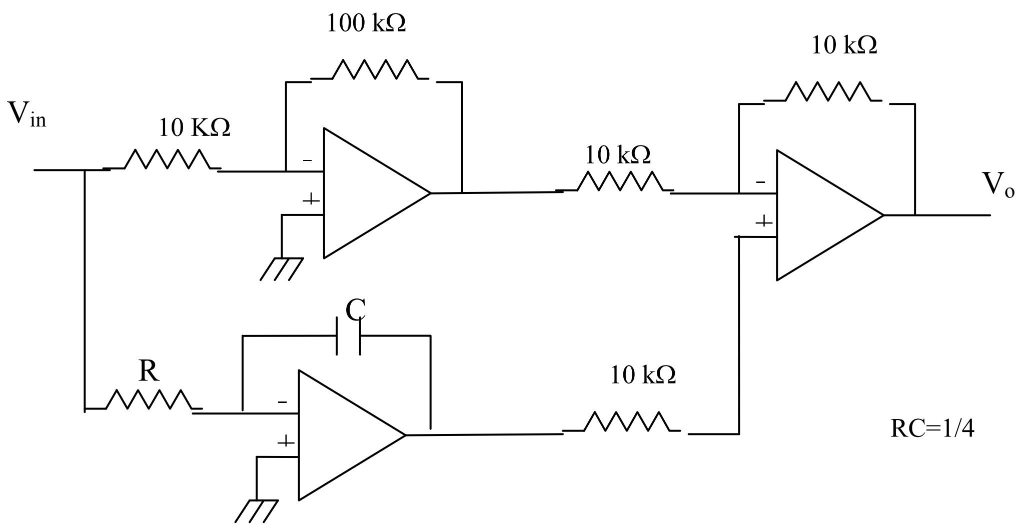


Figure (3.14) Circuit realization

The above circuit consists of three op-amp circuits. The first one at the top to left is used to realize the gain = (-10), while the second one is the integrator with gain =(-4). The last one at the top to right is a summing amplifier with inverse sign to produce the final output.

3.2 Analog signal conditioning

Measurement systems are usually used for:

- Displaying data about some event or variable
- Inspection or testing, i.e to determine whether an item is to specification or not (calibration)
- Providing feedback information in the control loop

The measurement system consists of basic three components:

- Sensor to transform the variations in the physical variable into a measured form (resistance, displacement, current or volt)
- Signal conditioning to change the sensor output signal either in its form or range to met the control loop requirements (signal processing)
- Display element to monitor the variations in the physical variable

Example: temperature measurement

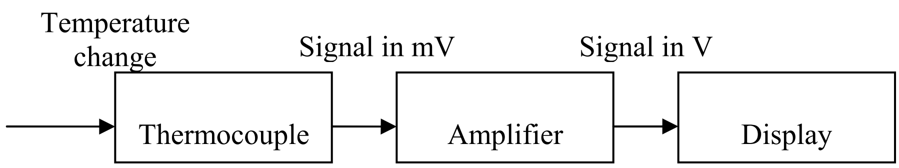


Figure 3.15 Temperature measurement

Analog signal conditioning includes:

- Signal level change
    - Attenuation (gain<1)
    - Amplification (gain>1)
- Linearization, if the transducer gain is nonlinear, anon linear amplifier can be used to compensate this problem. Finally, the over all gain of transducer and amplifier is linear. Note that, linearity is a very important characteristic in control loop that we have to maintain.
- Conversion of the nature of signal as
    - Passive change (resistance, capacitance or inductance) to active change (volt or current)
    - Voltage to current
    - Current to voltage
    - Electric current to pneumatic signal
- Filtering and impedance matching

Signal conditioning circuits could be implemented using:

- Passive circuits
    - Divider circuits
    - Bridges
    - RC filters (*will not be included in the text*)
- Op-amps

3.2.1 Passive circuits

Voltage divider

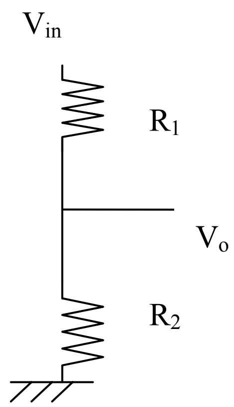


Figure 3.16 Potentiometer (wiper)

The voltage output is given by:

$$V_o = \frac{R_2}{R_2 + R_2} V_{in} \tag{3.12}$$

The above circuit can be used to attenuate the input voltage to the desired value or it can be used to convert the sensor resistance variation into voltage output (i.e. input voltage is constant and sensor may be R_1 or R_2).

Note that:

1- The relation between the output voltage and either R_1 or R_2 is nonlinear (V_{in} is fixed)
2- Output impedance is a parallel combination R1//R2, so it may be not high and consequently loading effect problem can be considered
3- Power dissipated in resistors is considered.

Bridge circuit (Wheatstone bridge)

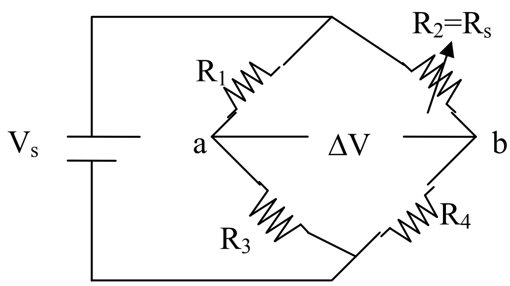


Figure 3.17 Wheatstone bridge

The unbalanced output voltage is given by:

$$\Delta V = V_a - V_b = V_s \frac{R_3R_2 - R_1R_4}{(R_1 + R_3)(R_2 + R_4)} \tag{3.13}$$

If $R_1R_4 = R_2 R_3$, that means null detection and output will be zero. The above circuit is used to convert the variation in sensor resistance into output voltage. Assume that $R_2=R_3=R_4=R_0$ (nominal resistance) and $R_1 = R_s= R_o+\Delta R$. The final relation is given by:

$$\Delta V = \frac{V_s}{4}\frac{\Delta R}{R_o}\left(\frac{1}{1+\frac{\Delta R}{2R_o}}\right) \tag{3.14}$$

Note that: ΔV has a nonlinear relation with respect to ΔR.

Linearization of Wheatstone bridge using feedback

Consider the circuit shown in figure where R_s is the sensor resistance.

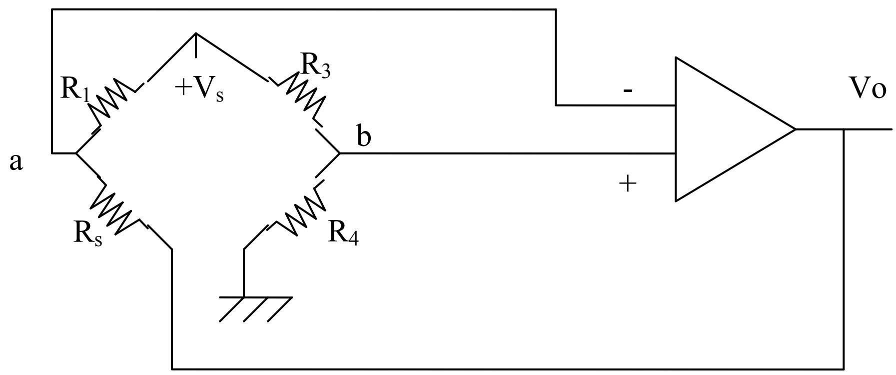


Figure 3.18 Feedback linearization

Assume that $R_1 = R_3 = R_4 = R_0$ and $R_s = R_0 + \Delta R$.

So, $$V_b = \frac{R_4}{R_3+R_4}V_s = \frac{V_s}{2} \tag{3.15}$$

$$V_a = V_s - \left(\frac{V_s - V_o}{R_1+R_s}\right)R_1 = \frac{V_s(R_o+\Delta R)+V_oR_o}{2R_o+\Delta R} \tag{3.16}$$

Knowing that, $V_a= V_b$ as inputs to the op amp, so we can obtain the output as:

$$V_o = -\frac{V_s}{2}\frac{\Delta R}{R_o} \tag{3.17}$$

This relation is linear and more suitable for control applications. The use of op amp with feedback linearization has the advantage that loading effect problem is also avoided.

3.2.2 Active circuits

Current to voltage converter

Consider the following circuit.

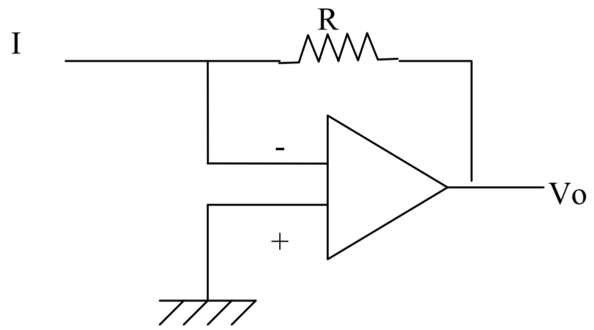


Figure 3.19 Current to voltage converter

The current signal I (mA) is supplied from the transducer and R (KΩ) , so the output voltage is:

$$V_o = - I R \tag{3.18}$$

To avoid the negative sign in the above relation the circuit may be modified as following

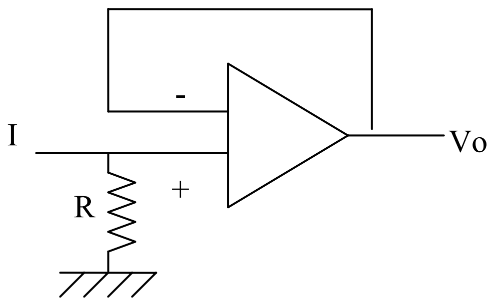


Figure 3.20 Alternative current to voltage circuit

The output voltage is given by:

$$V_o = I R \tag{3.19}$$

Example: Develop a signal conditioning circuit to convert a transducer output (4 → 20 mA) into a voltage range (0 → 10 Volt) and draw the circuit diagram.

Solution:
First step we have to change the current signal into voltage signal. We can use the circuit in figure 3.18 by selecting R = 100 Ω. Therefore the current range will be converted into a voltage range (0.4 → 2 volt). Second step, we will use an amplifier to obtain the required output voltage range in assuming linear relation as:($V_{out} = G V_{in} + H$). Substitute in the above relation by the values (V_{out}= 0 at V_{in}= 0.4 V) and (V_{out} = 10 V at V_{in}= 2 V). We will obtain the equations:

$$10 = G(2) + H$$
$$0 = G(0.4) + H$$

By solving these equations, the parameters of the circuit will be G = 6.25 & H= -2.5 Volt. The complete circuit diagram is given in the following circuit.

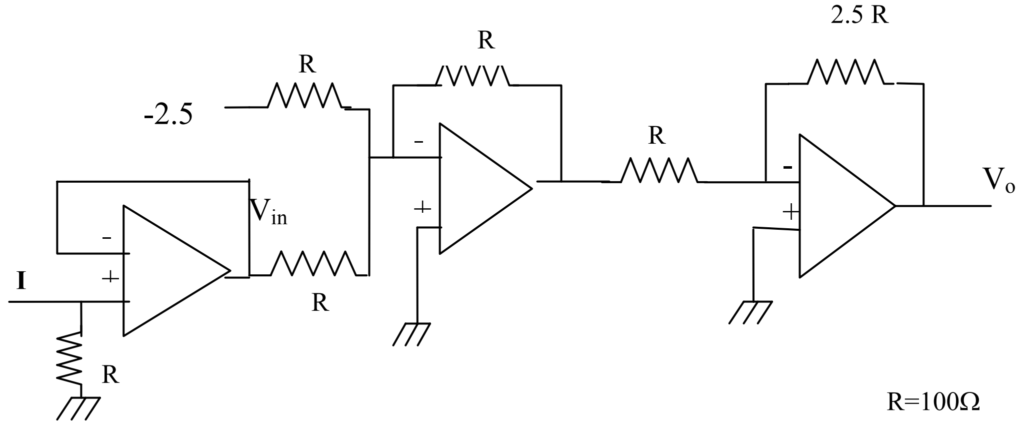


Figure 3.21 Signal conditioning circuit (current to voltage)

Voltage to current converter

Consider the following circuit that converts voltage signal to a current signal.

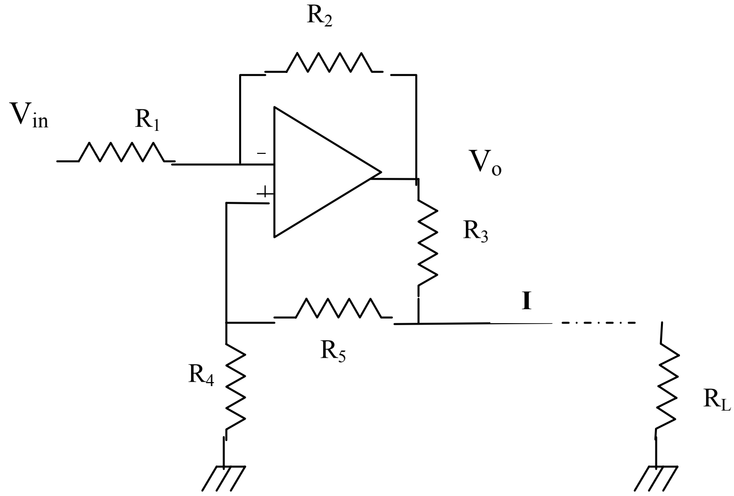


Figure 3.22 Voltage to current converter

The relation is given by the following equation:

$$I = \frac{-R_2}{R_1 R_3} V_{in} \qquad ; \qquad R_1(R_3+R_5) = R_2 R_4 \tag{3.20}$$

Maximum load resistance R_L and maximum current I_m are related to the saturation condition in op am. This condition is given in the following equation:

$$R_L = \frac{(R_4 + R_5)\left(\frac{V_{sat}}{I_m} - R_3\right)}{R_3 + R_4 + R_5} \tag{3.21}$$

3.3 Guidelines for analog signal conditioning

This section discusses typical issues that should be considered in analog signal conditioning development. The main stages are:

1. Define the measurement objective
    a. What is the nature of the measured variable: pressure, temperature,...etc?
    b. What is the range of measurement?
    c. What is the required accuracy 5% of full scale, …etc?
    d. Must the measurement output be linear?
    e. What is the nose level, and define if filtering is required.
2. Define the sensor characteristics
    a. What is the nature of sensor output: resistance variation, voltage, current
    b. What is the transfer function of the sensor (input-output relationship): linear, nonlinear.
    c. What is the range of sensor output for the given measurement range?
    d. What is the power specification of the sensor?
3. Develop the analog signal conditioning
    a. What is the nature of the desired output? The most common is voltage, but current and frequency are sometimes specified.
    b. What is the desired range of the output parameter (e.g., 0-5 volt, 4-20 mA,…etc)
    c. What input impedance should the circuit present to the input signal source?
    d. What output impedance should the circuit offer to the output load circuit?
4. Notes on development
    a. If the input is a resistance change and a bridge or divider must be used, be sure to consider both the effect of input voltage nonlinearity with resistance and the effect of current through the resistive sensor.
    b. For the op-amp portion development, the easiest approach is to develop an equation for output voltage versus input voltage. From this equation, it will be clear that types of circuits that may be used. This equation represents the static transfer function of the signal conditioning.
    c. Always consider any possible loading of voltage sources by the signal conditioning. Such loading is a direct error in the measurement system.

Note that
Measurement systems and signal conditioning have to be analyzed carefully in control applications, taking into account the main properties of:
Resolution: related to smallest change to be measured
Range: the minimum and maximum value to be measured
Accuracy: is the extent to which the reading it gives might be wrong
Linearity: the input-output characteristic is preferred to be linear. If it was nonlinear, a linearization circuit has to be developed
Sensitivity: ratio between change in instrument scale reading and change in the quantity being measured
Dynamic response: fast sensors have a small time constant as shown before. It is preferred to be first order to avoid that the output can oscillate.

3.4 Basic concept (MCQ)

Place the letter of statement that **best** completes the sentence in space provided.

1] The Op-amp has a ___________ output impedance

A) Very high
B) Very small
C) Zero

2] The Op-amp has a ___________ input impedance

A) Very small
B) Zero
C) Very high

3] The loading effect problem can be avoided if the load impedance is _______.

A) Very small
B) Zero
C) Very high

4] Logarithmic amplifier can be used for _________

A) Linearization
B) Amplification
C) Compensation

5] A good differential amplifier has a _________ CMRR

A) Small
B) Large
C) Zero

6] The Op-amp can not be used without feedback to obtain a ___________ gain

A) Stable
B) High
C) Small

7] Voltage follower circuit can be used to ________ the loading effect

A) Treat
B) Connect
C) Disconnect

3.5 Problems

1] A sensor resistance varies from 520 to 2500 Ω. This is used for R_1 in the potential divider circuit, along with R_2 = 500 Ω, and the supply voltage V_{in} is equal to 10 V. Find
(a) divider voltage range in V_o
(b) power dissipation range in the resistor

2] A Wheatstone bridge is null with R_1 = 227 Ω, R_2 = 448 Ω, and R_3= 1414 Ω. Find R_4.

3] Draw a circuit to implement the square function ($V_o = \sqrt{V_{in}}$) using op amp (*hint*: use an analog multiplier in the feedback of op-amp circuit).

4] Draw a circuit to implement the square function ($V_o = Log^{-1}(V_{in})$) using op amp (*hint*: use a nonlinear element as diode with op-amp circuit).

5] Using an integrator with RC = 10 s and any other required amplifiers, develop a voltage ramp generator with 0.5 V/s.

6] A differential amplifier as shown has R_2=R_1=2.7 K Ω, R_3=R_f=470 KΩ. When the amplifier inputs V_1 = V_2 = 2.5 volts, the output is found to be 78 mV. Find CMR and CMRR

7] Use an inverting amplifier, an integrator, and summing amplifier to develop the output voltage given by

$$V_{out}(t) = 5\,V_{in}(t) + 2\int V_{in}(t)\,dt$$

8] A process signal varies from 4 to 20 mA. The set point is 9.5 mA. Use a current to voltage converter and a summing amplifier to get a voltage error signal with a scale factor of 0.5 V/mA.

9] A pressure sensor outputs a voltage varying as 100mV/psi and has a 2.5 KΩ output impedance. Develop a signal conditioning circuit to provide 0 to 2.5 volts as the pressure varies from 50 to 150 psi.

10] A transducer outputs current signal varies from 4 to 20 mA. Develop a signal conditioning circuit to provide -10 to 10 volts as the output range.