Chapter 2: Signal Conditioning and Processing
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1. Introduction
The first component of a measurement system is the sensor that converts the physical variable to be measured into an electrical quantity. However, the signal is usually in a format that cannot be directly used: it requires 'conditioning'.

Hence the second part of any measurement system is the signal conditioning component that converts the electrical signal from an unsuitable format to a suitable format. Signal processing further modifies the signal to prepare it for transmission. More details about signal conditioning and processing can be found in [1] and [2].

2. Operational Amplifiers
An operational amplifier is possibly the most versatile integrated circuit linear building block. It is an amplifier which is designed with a very high gain, and thus can be adapted in circuit to the required gain and bandwidth.

A model of an operational amplifier is shown in Figure 1. The operational amplifier (or *op-amp* as it is known) has two input terminals and one output terminal. The two input terminals are labelled "+" and "-", or non-inverting and inverting inputs respectively.

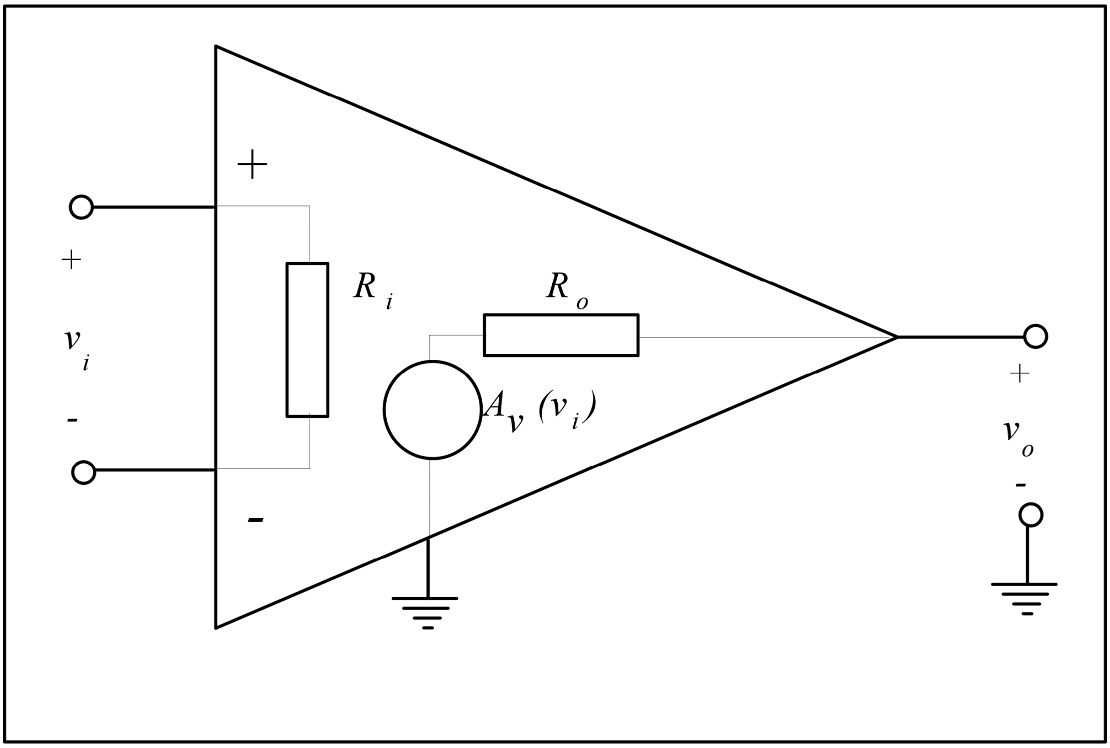


Figure 1: Internal model of an Operational amplifier.

The ideal characteristic of an operational amplifier are:

- Infinite open loop gain, A_v.

- Infinite input resistance, R_i.
- Zero output resistance, R_o.
- Infinite bandwidth.
- The output voltage should be zero when V_1=V_2, independent of the magnitude of V_1.
- Its characteristics should not drift with temperature.

In practice however, the real amplifier does not achieve these ideal values.

- The input resistance is usually in the range of 10^5 to 10^7 Ω.
- The output resistance is in the range of 50Ω to 4kΩ.
- The voltage gain is in the range of 10,000 to 200,000 (open loop gain, i.e., without feedback).

3. Amplifier Configurations

Having introduced the basic concepts related to op-amps, this section discusses the various applications and configurations of op-amps.

3.1 Inverting Amplifier

The most versatile and widely used configuration for op-amps is to use it as an inverting amplifier. In this configuration, the non-inverting terminal is connected to earth; the input voltage is connected via a resistor to the inverting terminal; and the output is connected to the non-inverting input via a feedback resistor.

The configuration is shown in Figure 2.

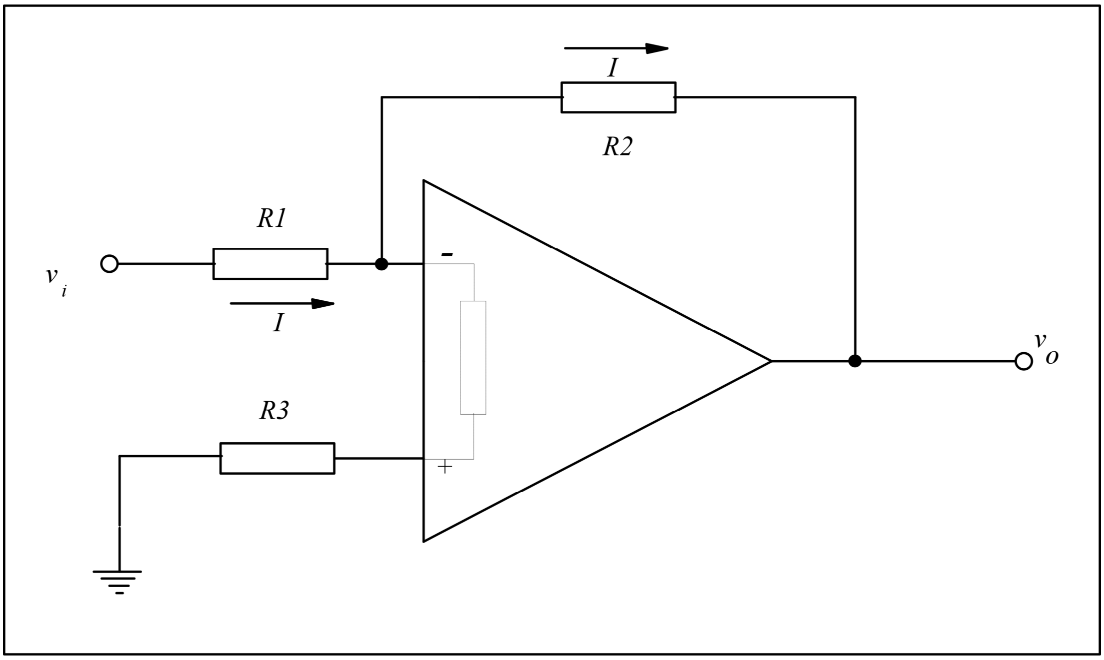


Figure 2: Inverting amplifier configuration.

The gain of this configuration is:

$$\boxed{\frac{v_o}{v_i} = -\frac{R_2}{R_1}}$$

It is recommended, that in order to keep the CMRR (common mode rejection ratio) as high as possible, the resistor R_3 connected to the non-inverting terminal be equal to the parallel combination of resistors R_1 and R_2.

$$R_3 = R_1 \| R_2 = \frac{R_1 \times R_2}{R_1 + R_2}$$

Note that the sign $\|$ denotes the parallel connection of two resistors.

3.2 Non-Inverting Amplifier

Another important configuration is the non-inverting connection. In this configuration, a portion of the output signal is fed back into the inverting terminal, via a potential divider formed by the two resistors R_1 and R_2. The input signal is connected to the non-inverting input, via a resistor R_3. The only purpose of resistor R_3 is to equalise the resistance connected to the inverting and non-inverting terminals.

The gain of the non-inverting configuration is:

$$\boxed{Closed\ loop\ gain = \frac{1}{H} = \frac{R_2 + R_1}{R_1} = 1 + \frac{R_2}{R_1}}$$

The connection of the amplifier is shown in Figure 3.

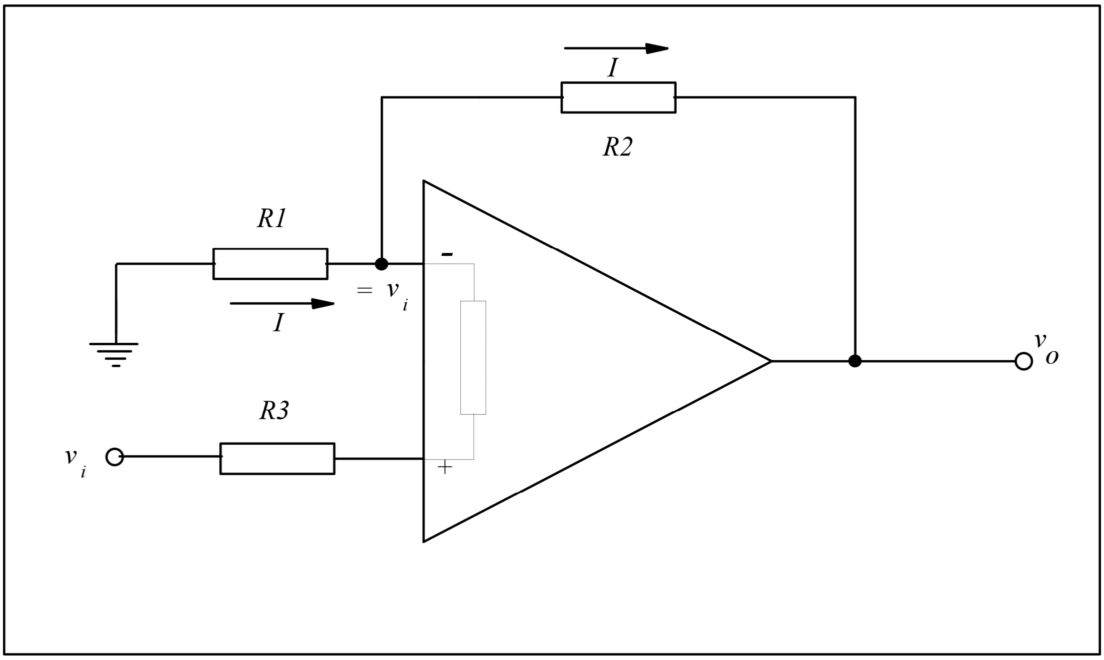


Figure 3: Non-inverting amplifier configuration.

3.3 Summing Amplifier

The summing amplifier, as the name implies, is used to add a number of signals. The principle is the same as that of the operation of the inverting amplifier. If the values of all resistors are selected such that R_1=R_2=R_3=R_4, then the output is equal:

$$v_o = -\left(v_{i2} + v_{i3} + v_{i4}\right)$$

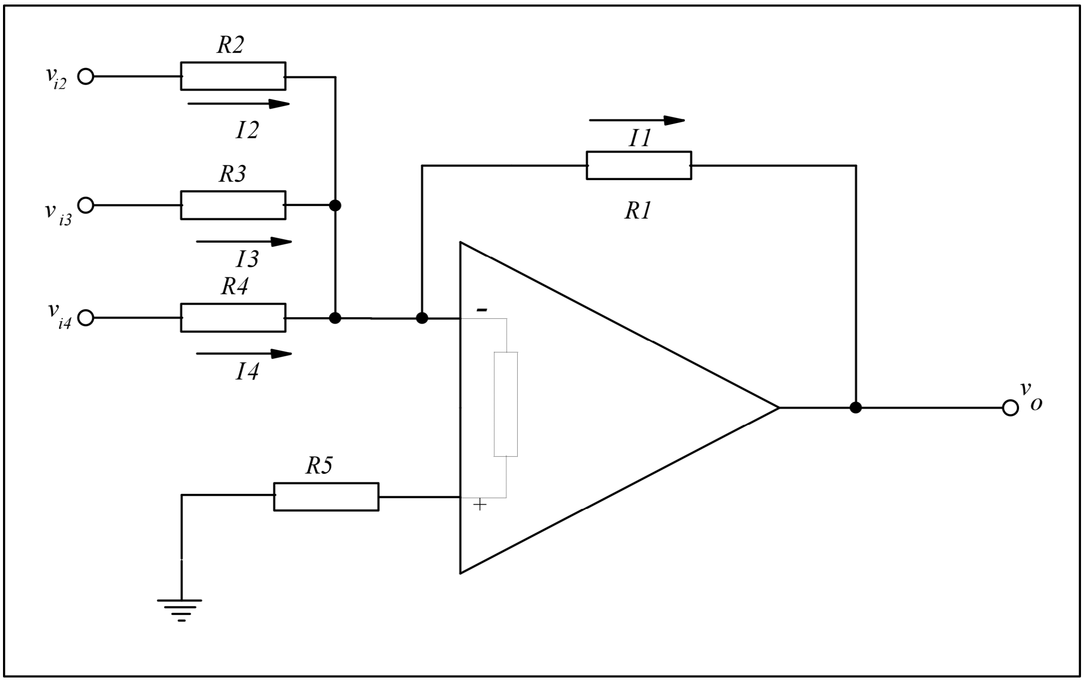


Figure 4: Summing amplifier configuration.

3.4 Subtracting amplifier

The op-amp can be used to subtract two signals. This is done by feeding one signal into the inverting terminal and the other into the non-inverting terminal. However, because the gain for each signal is different from the other, it is necessary to modify the configuration as shown in the Figure 5.

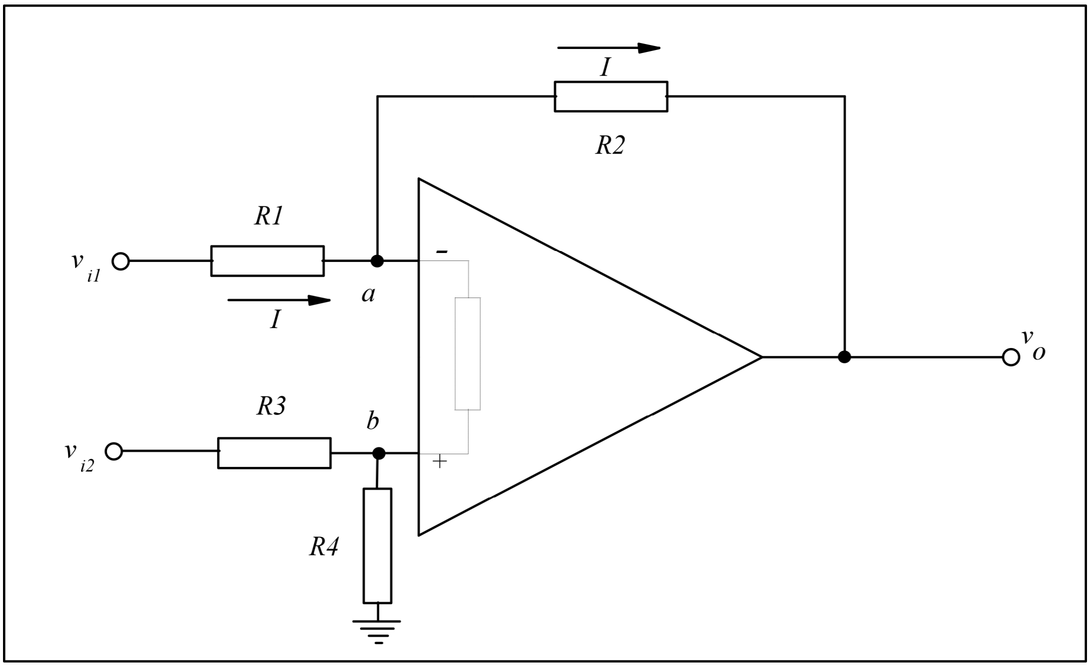


Figure 5: A subtracting amplifier configuration.

In order to calculate the output voltage, the method of superposition is used. This entails calculating the output caused by one signal, with the other kept at zero volts; and then calculating the effect of the other input with the first input set to zero. The final output is the sum of the effect of the two inputs. By adding the two results:

$$v_o = v_{i1} \times \left(-\frac{R_2}{R_1} \right) + v_{i2} \times \left(\frac{R_2}{R_1} \right) = \left(v_{i2} - v_{i1} \right) \times \left(\frac{R_2}{R_1} \right)$$

If we set, $R_1 = R_2$, then the output voltage becomes:

$$\boxed{v_o = \left(v_{i2} - v_{i1} \right)}$$

Where this shows how this set-up works as a subtractor. This, can be achieved by having $R_1 = R_2 = R_3 = R_4$.

3.5 Comparator

A comparator could be built by using a subtracting amplifier, with a very high gain. However, one problem with such a set-up, is when such a comparator is attempting to compare two signals which are nearly equal, the output of the op-amp might fluctuate between the positive rail voltage and the negative rail voltage. This is solved by using the circuit in the next sub-section.

3.6 Schmitt Trigger Amplifier

When attempting to process noisy signals, or slowly changing signals in order to decide whether the signal is below or above a certain level, there is a risk that the output of the op-amp will fluctuate between the positive and negative rail. To avoid this effect, some hysteresis can be introduced into the circuit. This is achieved by a circuit called a Schmitt Trigger amplifier.

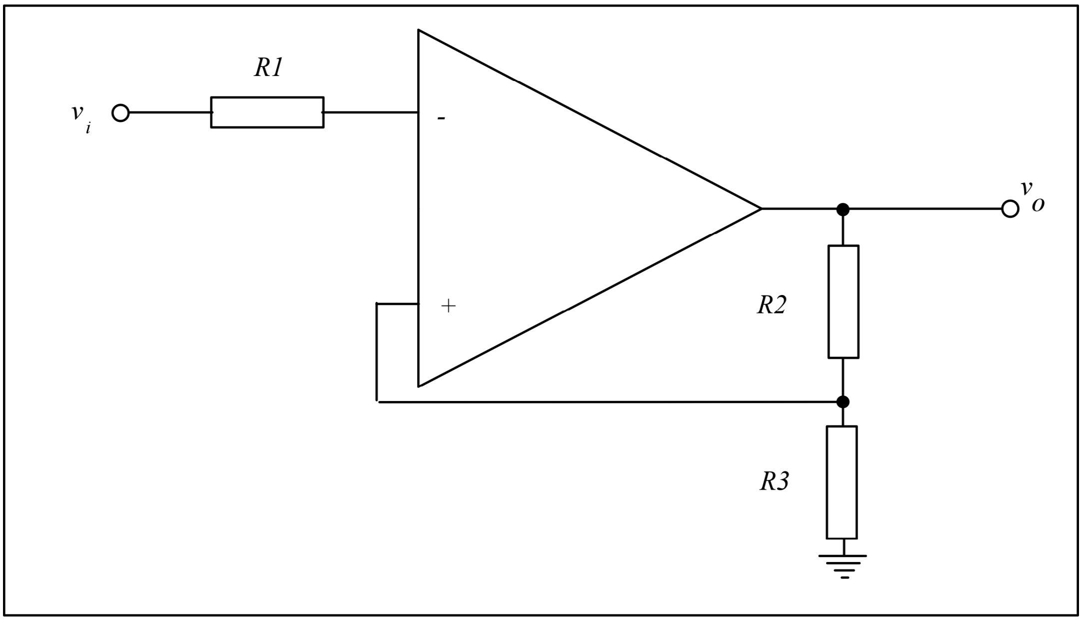


Figure 6: Schmitt trigger circuit.

Positive feedback is used to achieve this effect. A portion of the output signal is fed back to the non-inverting input. This introduces a dead-band zone.

The total dead-band zone, V_d, is equal to:

$$V_d = V_s \times \frac{R_3}{R_3 + R_2} \times 2$$

The characteristic of this circuit is shown in Figure 7, which shows how the output changes with respect to the input. When the input is rising, the output does not switch over until the input passes a certain positive voltage level. However, if the input starts dropping again, the output does not switch back at the same level, but only switches back if the input drops back to zero and to a negative voltage below zero. This ensures that if the input is fluctuating just around a certain value, the output does not keep changing between the two extreme levels.

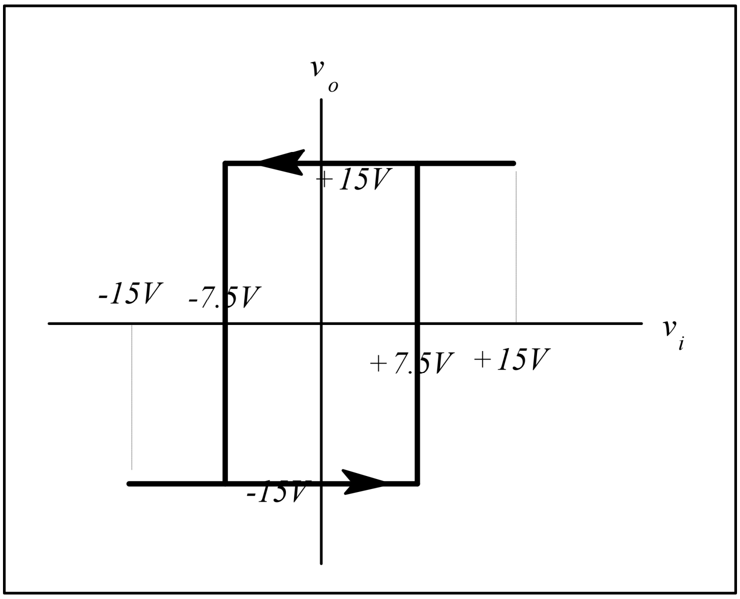


Figure 7: Schmitt trigger input/output characteristic showing dead-band zone.

4. Integrators and Differentiators

All the configurations discussed up to now have only used resistors. This section discusses the use of capacitors to achieve integration and differentiation.

4.1 Integrating Amplifier

An integrating amplifier employs a capacitor in the feedback path, as shown in Figure 8. The input voltage develops across resistor R_1, and thus a current proportional to the input voltage. This current charges the capacitor, and thus the voltage developing across the capacitor (which is equal to the voltage at the output) is proportional to the integral of the input voltage.

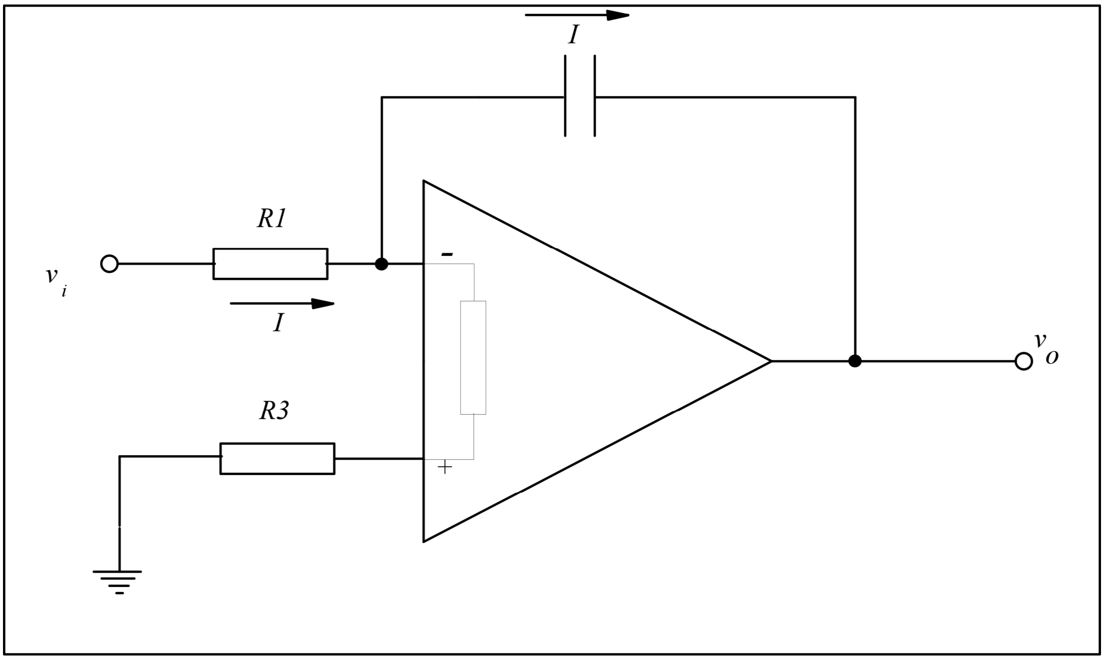
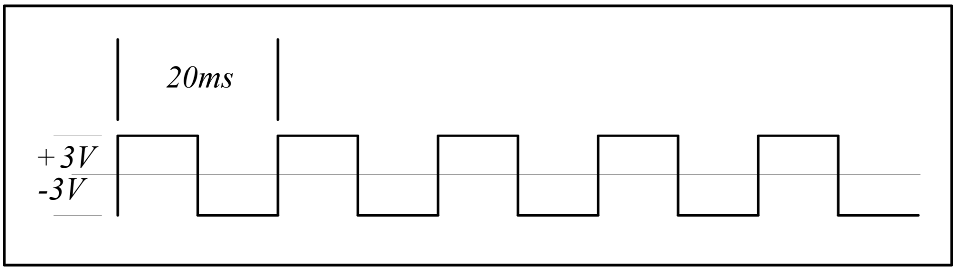


Figure 8: Integrating configuration.

Example 1

Design an integrator to convert a square wave which has a frequency of 50 Hz into a triangular waveform. Plot the output integrated waveform.



Solution

As the time period of the input waveform is 20 ms, then the time constant of the integrator should be at least equal to this value, or 20 ms. If we select a value of capacitance of 2.2 μF, then the required value of resistance is around 9.1 kΩ. Although this is not a preferred value of resistance, it can be achieve by the parallel combination of a 10kΩ and a 100kΩ.

$$\left(\frac{10{,}000\times 100{,}000}{110{,}000}=9{,}100=9.1\,k\Omega\right).$$

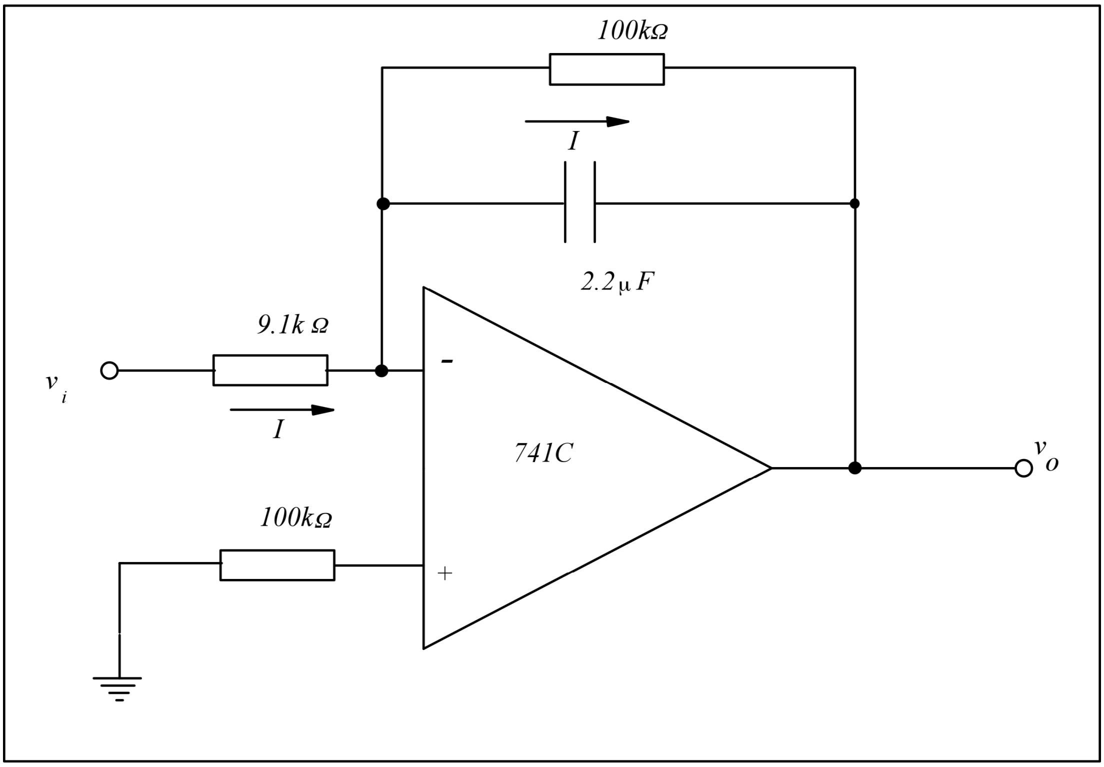
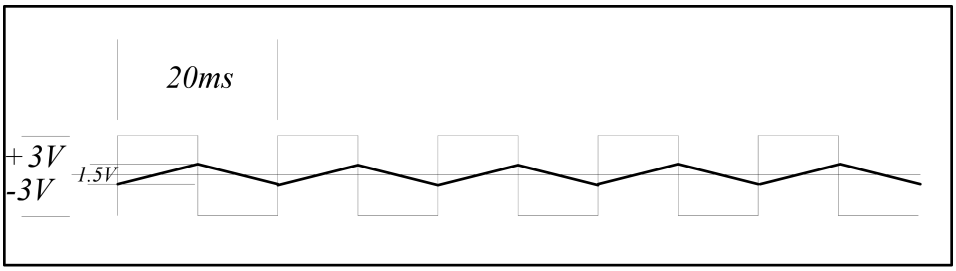


Figure 9: Solution to example 1.

[Correction to solution in figure above: The resistor connected to the non-inverting input should be equal to the parallel combination of 9.1 k and 100 k).]

The value of the charging current will be $\frac{3V}{9.1k\Omega} = 330\,\mu A$. When charging a capacitor for 20 ms, the total charge is $330\,\mu A \times 20\,ms = 6.6 \times 10^{-6}\,C$. This will achieve a final voltage of $V = \frac{Q}{C} = \frac{6.6 \times 10^{-6}}{2.2 \times 10^{-6}} = 3\,V$. This will be the peak to peak voltage. Thus the final waveform is shown below. It has an average value of zero. ■



4.2 Differentiating Amplifier

By interchanging the positions of the capacitor and the resistor in the integrator circuit, a differentiator is obtained. The input voltage develops across the capacitor, and thus the current flowing though the capacitor is proportional to the derivative of the input voltage. This current flows into the feedback resistor, and thus develops an output voltage proportional to the differential of the input voltage. The set-up is shown in Figure 10.

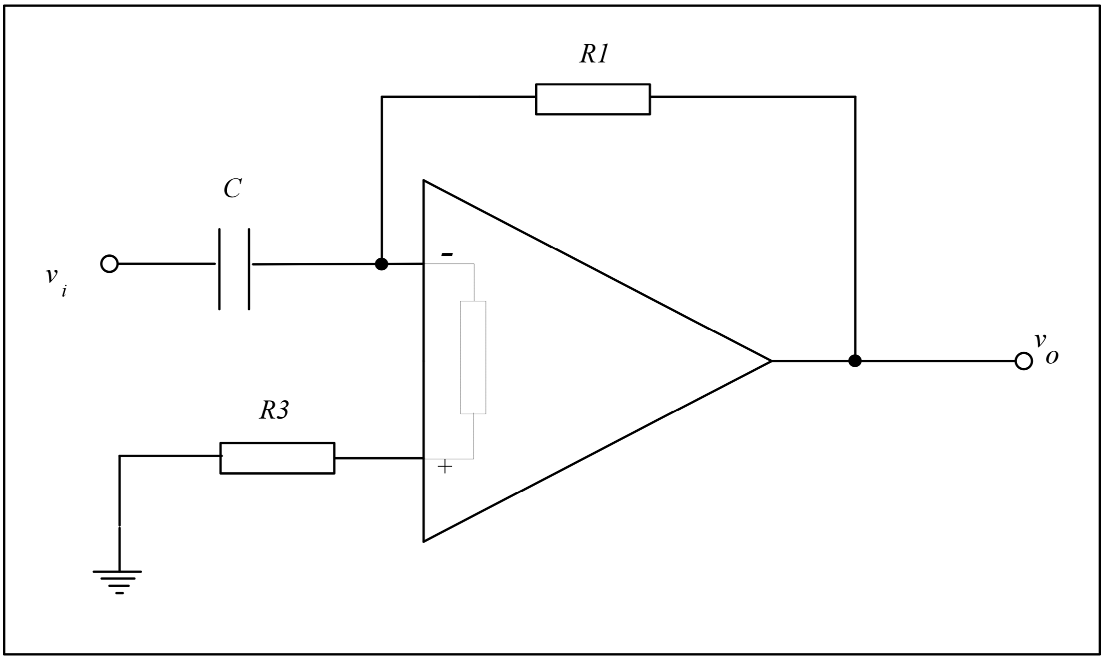


Figure 10: Differentiating amplifier set-up.

5. Difference Amplifier

One of the simplest methods of amplification is to amplify the difference between two signals. This is especially necessary in amplifying biomedical signals [3]. A difference amplifier is used. This is shown in Figure 11 below.

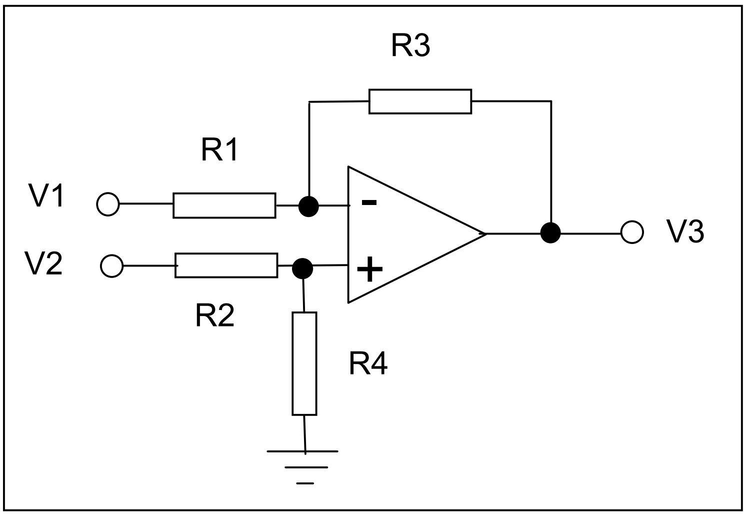


Figure 11: Difference amplifier.

The relationship between the inputs and output can be derived as follows. Setting V2 to zero, we can find the effect of V1 on the output as follows:

$$V3\big|_{V2=0} = V1\cdot\left(\frac{R3}{R1}\right)$$

Setting V1 to zero, we can find the effect of V2 on the output as follows:

$$V3\big|_{V1=0} = V2\cdot\left(\frac{R4}{R2+R4}\right)\cdot\left(1+\frac{R3}{R1}\right)$$

Using superposition, V3 can be found as follows:

$$V3 = V3\big|_{V1=0} + V3\big|_{V2=0} = V2\cdot\left(\frac{R4}{R2+R4}\right)\cdot\left(1+\frac{R3}{R1}\right) - V1\cdot\left(\frac{R3}{R1}\right)$$

By setting R1=R2, and R3=R4, gives:

$$V3 = V2\cdot\left(\frac{R3}{R1+R3}\right)\cdot\left(1+\frac{R3}{R1}\right) - V1\cdot\left(\frac{R3}{R1}\right) = \left((V2-V1)\cdot\left(\frac{R3}{R1}\right)\right) \text{..........(1)}$$

So this difference amplifier amplifies the difference between V2 and V1 and amplifies it by the ratio of R3 to R1.

However this amplifier suffers from two main disadvantages:

1. It has relatively low input impedance (which is equal to the sum of R3 and R1). This could load the sensor that is feeding this amplifier and consequent distortion of the signal.

2. In order to achieve a high value of CMRR (common mode rejection ratio), the values of the resistors have to be exactly matched.

6. Instrumentation Amplifier

Ideally, the amplifier used to amplify the weak signal coming out of the sensor needs to have the following characteristics [4]:

1. Have high input impedance so that it does not load the sensor (and to provide the conditions for maximum voltage transfer).

2. Have a high common mode rejection ratio (CMRR). The CMRR is the ratio of the difference mode gain to the common mode gain. The difference mode gain is the amplification factor for the difference between the two inputs. The common mode gain is the amplification factor of the average of the two inputs. Thus if the common mode gain is zero, then the CMRR is infinite. In practice however, this is not possible, and some of the average value of the two input signals will be amplified.

3. Ability to amplify weak signal mixed with noise.

4. Consistent bandwidth over a large range of gains.

The schematic diagram of a typical instrumentation amplifier is shown below.

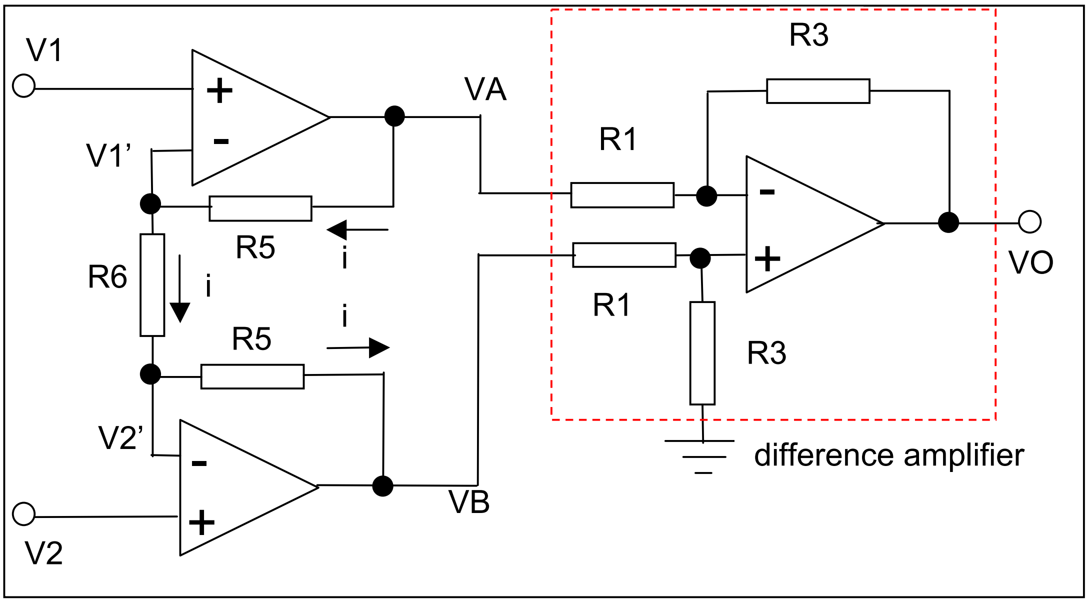


Figure 12: Instrumentation amplifier.

First we note that by the definition of the op-amp, V1'=V1 and V2'=V2. Considering VA and V1, we note that:

$$VA - V1 = i \cdot R5 \text{..........(2)}$$

Considering VB and V2, we note that:

$$V2 - VB = i \cdot R5 \text{..........(3)}$$

And considering V1 and V2, we note that:

$$V1 - V2 = i \cdot R6 \Rightarrow i = \frac{V1 - V2}{R6} \text{..........(4)}$$

Substituting (4) in (2) gives:

$$VA - V1 = \frac{V1 - V2}{R6} \cdot R5 \Rightarrow VA = V1 \cdot \left(1 + \frac{R5}{R6}\right) - V2 \cdot \frac{R5}{R6} \text{..........(5)}$$

Substituting (4) in (3) gives:

$$V2 - VB = \frac{V1 - V2}{R6} \cdot R5 \Rightarrow VB = V2.\left(1 + \frac{R5}{R6}\right) - V1 \cdot \frac{R5}{R6} \text{..........(6)}$$

But for the difference amplifier stage we have:

$$VO = (VB - VA) \cdot \frac{R3}{R1} \text{..........(7)}$$

Substituting (5) and (6) in (7) gives:

$$VO = \left(\left(V2 \cdot \left(1 + \frac{R5}{R6} \right) - V1 \cdot \frac{R5}{R6} \right) - \left(V1 \cdot \left(1 + \frac{R5}{R6} \right) - V2 \cdot \frac{R5}{R6} \right) \right) \cdot \frac{R3}{R1}$$

Rearranging:

$$VO = (V2 - V1) \left(1 + 2 \cdot \frac{R5}{R6} \right) \cdot \left(\frac{R3}{R1} \right) \text{..........(8)}$$

The gain depends on the value of R6 and can be made large by making R6 very small.

We have assumed that the six resistors denoted as R5, R3 and R1 (two of each) are perfectly matched. This is very difficult to achieve with discrete components. The only way to ensure that they are matched is to implement this amplifier as an integrated circuit, where the resistors can be laser etched. Examples of commercially available instrumentation amplifiers are AD623 [5] and INA114 [6]. R6 can be externally connected to the IC to set the required gain (it is usually referred to as RG, from gain).

7. Precise Rectifier

When dealing with very small signals, it is not possible to use the conventional approach of rectification using diodes or full wave bridges, as this take away 0.7 V of the signal (and if the signal has amplitude less than 0.7 V, it would not appear at the output). In such cases, it is important to use a precise rectifier.

A precise rectifier uses an operational amplifier with a diode in order to rectify the signal with no loss. An example of a precise rectifier is shown in Figure 13 below. It is built in two halves: one half deals with the positive part and the other deals with the negative half. Note that the diodes are fitted between the output of the operational amplifier and the output signal. Thus the point V_1 is 0.7 V higher than the output signal, but the output signal is equal to the input signal (via the virtual connection between the inverting and non-inverting inputs of the operational amplifier (0.7 V assumes a silicon diode). The same argument applies to the V_2.

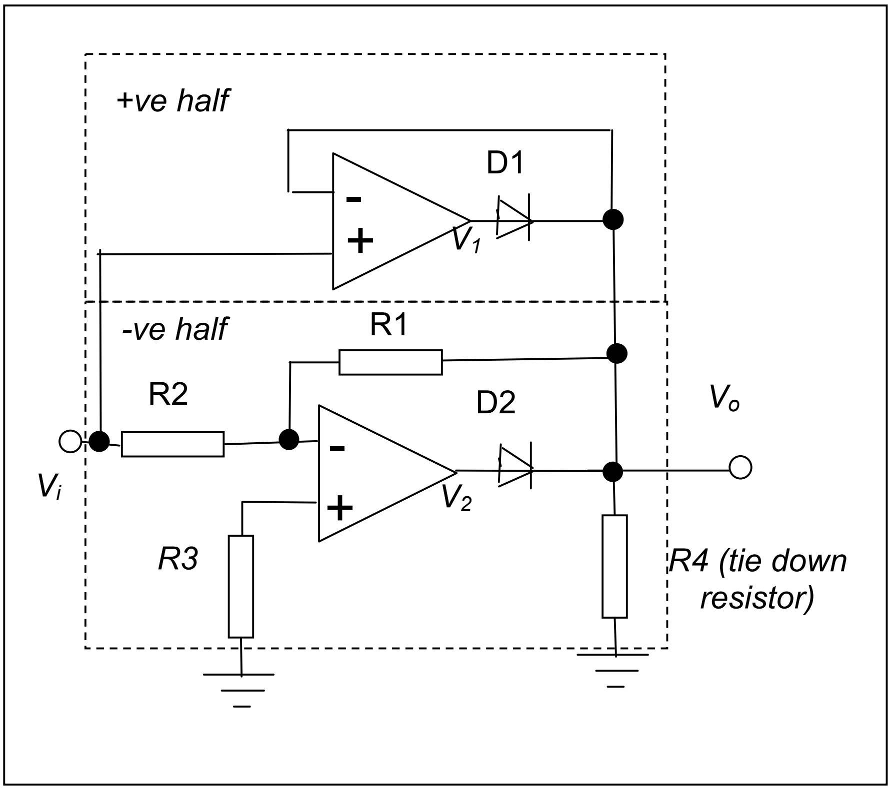


Figure 13: Precise Rectifier.

8. Sample & Hold Circuit

In many applications there is a need to sample the value of a signal at a certain point in time for further processing or storage. The best example is A to D converters (analogue to digital converters). Basically, a sample and hold circuit consists of capacitor to hold the charge and an operational amplifier to buffer the capacitor and prevent fast discharge (as shown in Figure 14). The capacitor used is a low leakage capacitor (usually of the polystyrene or polypropylene type) rather than electrolytic (as it suffers from high leakage and would thus leads to the rapid loss of the charge).

At the required sample time switch SW1 will momentarily close and charge the capacitor to the value of the input voltage. The capacitor will hold this value and the value will appear at the output of the voltage following operational amplifier arrangement.

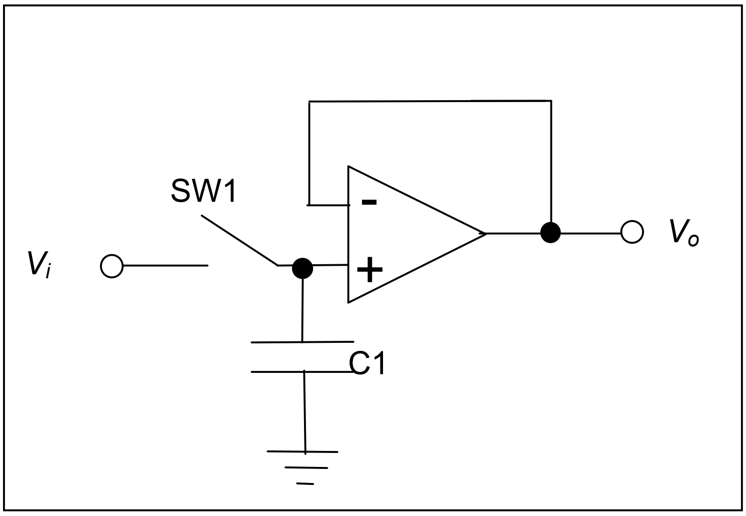


Figure 14: Sample & Hold circuit.

9. Filters

In many instances the signal to be measured gets contaminated by noise. If there is a clear separation between the frequency content of the signal and the frequency content of the noise, then filtering can be used to remove the noise from the signal.

The behaviour of any filter can be best described by the magnitude Bode plot of its frequency response. Taking for example, a low pass filter, it will have a flat zero attenuation frequency response below its so called cut-off frequency and a line sloping at 20 dB per decade (as shown in Figure 15). Each filter has a cut-off frequency. The cut-off frequency is the frequency at which the gain drops 3 dB below the pass-band gain.

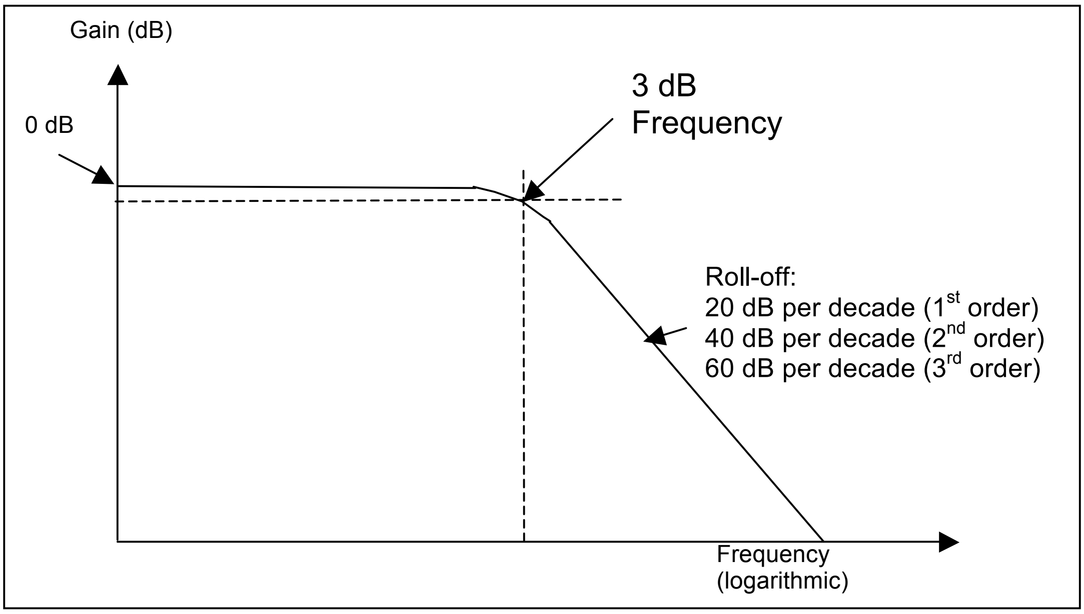


Figure 15: Frequency response of a low pass filter showing the 3 dB point.

There are effectively four types of filter:

1. Low pass: A low pass filter attenuates the frequencies above the cut-off frequency and passes the frequencies below the cut off frequency unchanged.

2. High pass: A high pass filter attenuates the frequencies below the cut-off frequency and passes the frequencies above the cut off frequency unchanged.

3. Band pass filter: A band-pass filter will attenuate the frequencies outside band-pass range and pass the frequencies within the band-pass unchanged. In effect a band pass filter can be thought of as a series combination of a low pass filter and a high pass filter, whereby the cutoff frequency of the high pass filter is *lower* than the cutoff frequency of the low pass filter.

4. Band stop filter: A band-stop filter will attenuate the frequencies inside the band stop and pass all other frequencies unchanged. In effect a band pass filter can be thought of as a series combination of a low pass filter and a high pass filter, whereby the cutoff frequency of the high pass filter is *higher* than the cutoff frequency of the low pass filter.

Any filter can also be classified in accordance with its design and in accordance with its order (1^{st} order, 2^{nd} order…). The most widely used designs are the Butterworth filter and the Chebychev filter. The Butterworth has a flat frequency response in the pass-band range, while the Chebychev has ripple in the frequency response of the pass-band. The higher the order of the filter, the steeper is the roll-off line in the frequency response. As a general rule for Butterworth filters, the slope of the line separating the pass-band and the stop-band is equal to $n \cdot 20$ dB per decade, where n is the order of the filter. As the line must have a finite roll-off rate, it is impossible to design a filter that has a vertical roll-off line (it will have to be infinite order!).

A simple example of a low pass filter is the simple first order RC network, shown below in Figure 16.

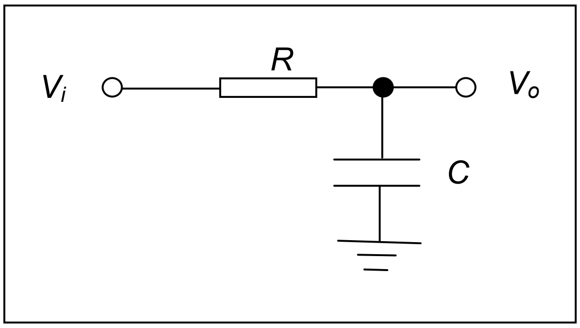


Figure 16: Simple RC low pass filter.

Its transfer function can be found as follows:

$$F(s) = \frac{\dfrac{1}{j \cdot \omega \cdot C}}{R + \dfrac{1}{j \cdot \omega \cdot C}} = \frac{1}{1 + j \cdot \omega \cdot R \cdot C}$$

The magnitude of the transfer function is:

$$\left| F(j \cdot \omega) \right| = \left| \frac{1}{1 + j \cdot \omega \cdot R \cdot C} \right| = \frac{1}{\sqrt{1 + \omega^2 \cdot R^2 \cdot C^2}}$$

At the 3 dB frequency:

$$20 \cdot \log\left(\frac{V_o}{V_i} \right) = -3\ dB$$

$$\frac{V_o}{V_i} = \frac{1}{\sqrt{2}} = \frac{1}{\sqrt{1 + \omega^2 \cdot R^2 \cdot C^2}}$$

$$2 = 1 + \omega^2 \cdot R^2 \cdot C^2$$

$$\omega^2 \cdot R^2 \cdot C^2 = 1$$

$$f_{-3dB} = \frac{1}{2 \cdot \pi \cdot R \cdot C}$$

This allows us to decide the value of the resistor and capacitor to set the cutoff frequency of the filter.

A special case of the band-stop filter is the Twin-T notch filter. This is useful in rejecting a specific strong noise signal that is concentrated at a specific frequency (e.g., 50 Hz noise signal from the mains). It is called Twin-T because it is effectively made of two T networks connected in parallel, one acting as a low pass filter and the other acting as a high pass filter.

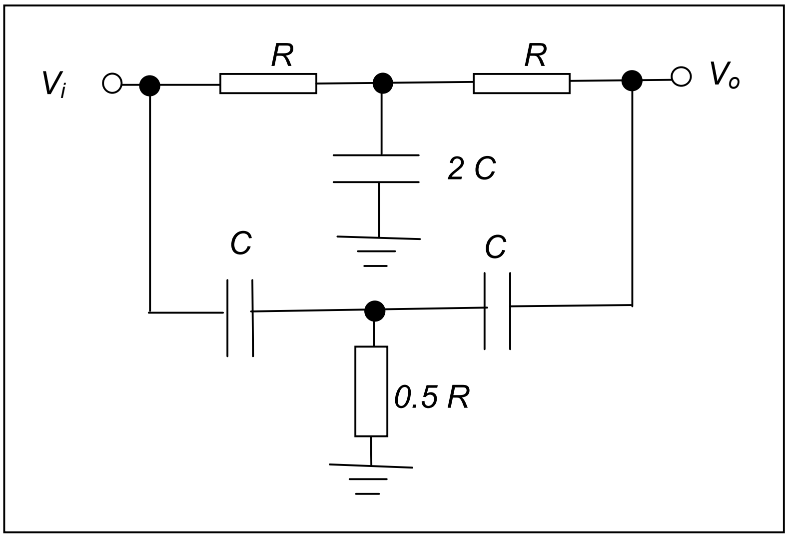


Figure 17: Twin-T notch filter.

The notch frequency can be found as follows:

$$f_{notch} = \frac{1}{2 \cdot \pi \cdot R \cdot C}$$

A widely used type of low pass Butterworth filter is the Sallen & Key, which is a 2nd order low pass filter, shown in below.

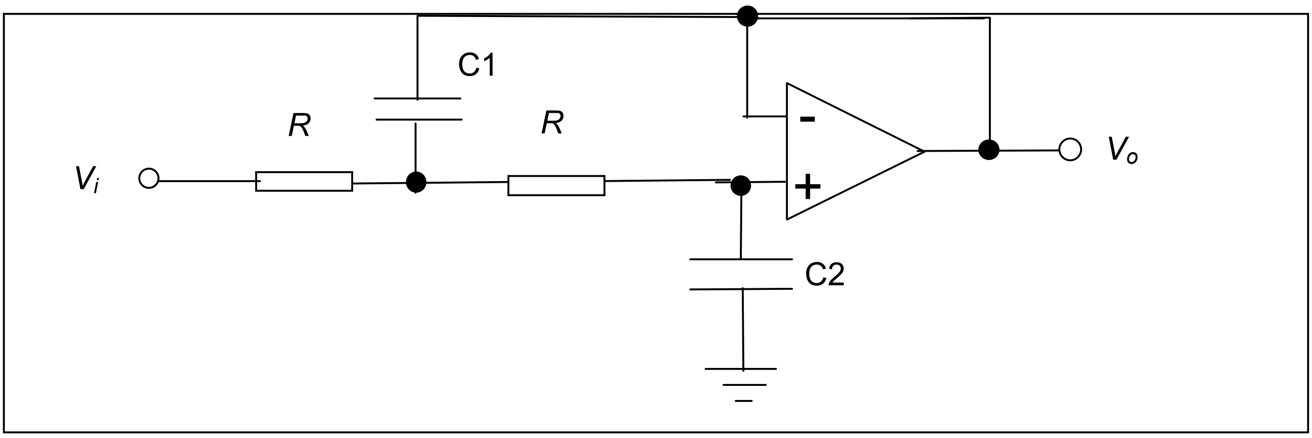


Figure 18: Sallen and Key low pass filter.

Its -3 dB cutoff frequency is:

$$f_{-3dB} = \frac{1}{2 \cdot \pi \cdot R \cdot \sqrt{C_1 \cdot C_2}}$$

References

[1] "Measurement & Instrumentation Principles", Alan S. Morris, Elsevier, 2001.

[2] “Principles of Measurement Systems”, John P. Bentley, Pearson Prentice Hall, 2005.
[3] “Medical Instrumentation: Application and Design”, John G. Webster, Editor, Third Edition, Wiley.
[4] “Introduction to Mechatronics and Measurement Systems”, David G. Alciatore and Michael B. Histand, Third Edition, McGraw Hill International Edition, 2007.
[5] Analogue Devices, “AD623: Single supply, Rail to Rail, low cost instrumentation amplifier”.
[6] Burr-Brown, “INA114: Precision instrumentation amplifier”.

Further Reading

[7] Millman, J., 1979, “*Microelectronics: Digital and analogue circuits and systems*”, McGraw Hill, International Student Edition. [A formal approach to general electronic components and systems.]
[8] Bohlman, K.J., 1993, “*Electronics Servicing, Vol. 2: Analogue and digital core studies and science background*”, Dickson Price Publishing. [A practical approach with many examples.]

Problems

1- Implement the block diagram shown below, using op-amps, resistors and capacitors. Show all values. Select preferred resistor values. Assume a signal frequency of 10 Hz.

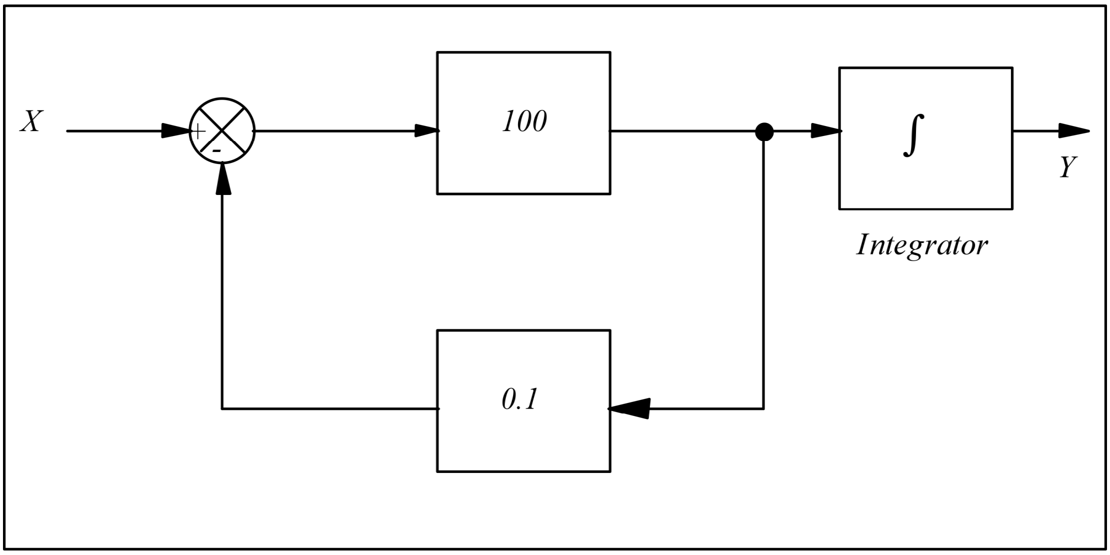


Figure 19: Block diagram for problem 1.

2- Design a Schmitt trigger inverter to convert the noisy signal shown below, into a rectangular waveform. Design for a total dead-band zone of 4 V (+/- 2V). Sketch the output waveform.

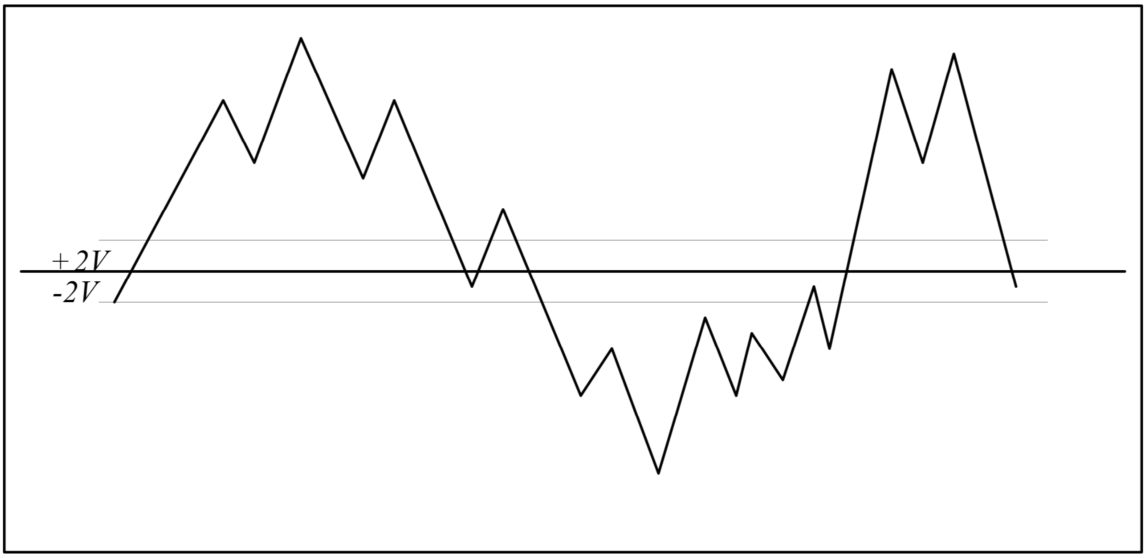


Figure 20: Diagram for problem 2.

3- What are the ideal characteristics of an op-amp?

4- What is the Common Mode Rejection Ration (CMRR)?

5- Design an inverting amplifier, to provide an amplification of 100 times for a sinusoidal signal which has a frequency of 7kHz. What is the minimum required gain-bandwidth product required for this op-amp?