## 4.1 Signal Conditioner

The measurand, which is basically a physical quantity as is detected by the first stage of the instrumentation system. The quantity is detected and is transduced into an electrical form in most of the cases. The output of the first stage has to be modified before it becomes usable and satisfactory to drive the signal presentation stage. This is where *signal conditioner* has its role.

*Signal conditioner* takes the output from the primary sensing element and makes it into a suitable form so that the signal can be processed by the rest of the system. These may include linear processes (amplification, attenuation, integration, differentiation, addition, and subtraction) and/or non-linear processes (modulation, demodulation, sampling, filtering, clipping and clamping, squaring, etc.) performed on the signal to bring it to the desired form to be accepted by the next stage of the measurement system.

In the case of the thermocouple, the signal conditioner may be an amplifier to make the emf big enough, with processing then being used to transform the voltage into a temperature reading on a meter. In the case of the resistance thermometer, there might be a Wheatstone bridge which transforms the resistance change into a voltage change and then an amplifier to make the voltage big enough for display, with processing then being used to convert the voltage into a reading on a meter of temperature. Examples of signal conditioners are Wheatstone bridges which convert resistance changes into voltage changes, amplifiers which are used to make signals bigger, and oscillators which convert an impedance change into a variable frequency.

## 4.2 Operational Amplifier

An *operational amplifier* is an example of signal conditioning element. The operational amplifier is a versatile device that can be used to amplify dc as well as ac input signals and was originally designed for performing mathematical operations in analog computers such as addition, subtraction, multiplication, and integration. Thus, the name "operational amplifier" stems from its original use for these mathematical operations and is abbreviated to op-amp. With the addition of suitable external feedback components, the modern day op-amp can be used for a variety of applications such as ac and dc signal amplification, active filters, oscillators, comparators, regulators, displays, testing and measuring systems, and others.

A typical op-amp is made up of three types of amplifier circuit: a differential amplifier, a voltage amplifier, and a push-pull amplifier as shown in figure below.

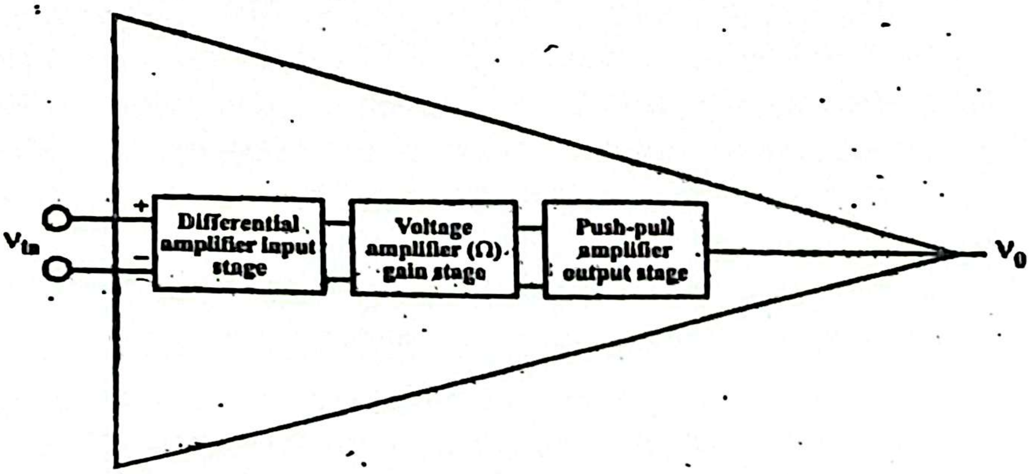


*Figure 4.1 Internal block diagram of an op-amp.*

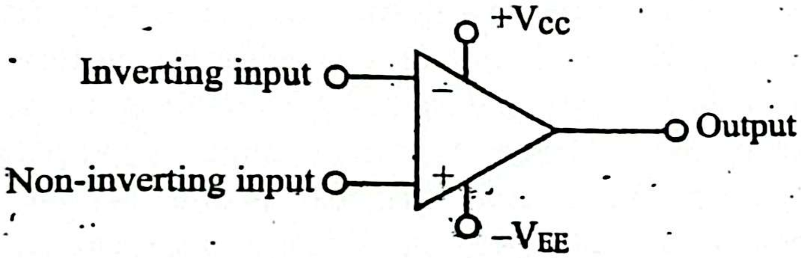


*Figure 4.2 Op-amp circuit symbol.*

An ideal op-amp would exhibit the following electrical characteristics:

1. **Infinite voltage gain, $A_o$.**
2. **Infinite input resistance, $R_i$** so that almost any signal source can drive it and there is no loading of the preceding stage.

3. **Zero output resistance, $R_o$** so that the output can drive an infinite number of other devices.

4. Zero output voltage when input voltage is zero.

5. **Infinite bandwidth** so that any frequency signal from 0 to $\infty$ Hz can be amplified without attenuation.

6. **Infinite common-mode rejection ratio** so that the output common-mode noise voltage is zero.

7. **Infinite slew rate** so that output voltage changes occur simultaneously with input voltage changes.

## 4.3 Modes of Operation of an Op-amp

There are two modes of operation of an op-amp:

i. Non-inverting mode

ii. Inverting mode

### i. Non-inverting mode

The circuit configuration of an op-amp working in the non-inverting mode is shown in the Figure 4.3. Input signal $v_i$ is applied to the non-inverting terminal i.e., +ve pin of op-amp. Let $v_o$ be the output voltage.

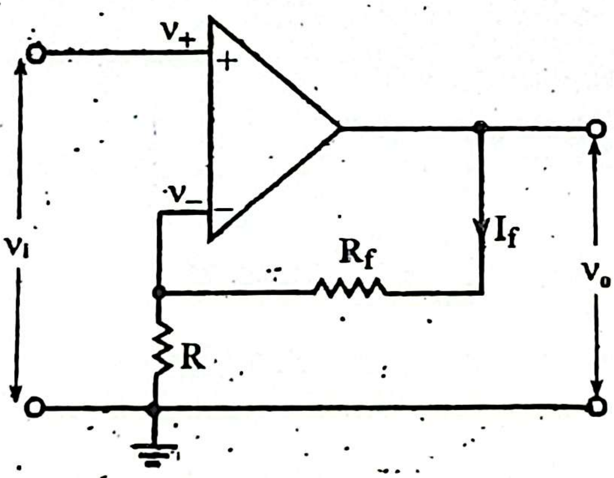


*Figure 4.3 Op-amp used in non-inverting mode.*

$v_+ = v_i$ .............(1)

$v_- = I_f R$ .............(2)

Also, $v_o = I_f (R_f + R)$

or, $I_f = \dfrac{v_o}{R_f + R}$ .............(3)

From equations (2) and (3),

$$v_- = \frac{v_o}{R_f + R} R \quad \text{.................(4)}$$

As we know,

$$v_o = A_{vol}(v_+ - v_-)$$

$$\text{or, } v_o = A_{vol}\left(v_i - \frac{v_o}{R_f + R} R\right)$$

$$\text{or, } \frac{v_o}{A_{vol}} = v_i - \frac{v_o}{R_l + R} R \quad \text{.............(5)}$$

As the output from operational amplifier is no more than 15 V and its open-loop voltage gain (i.e., the ratio of $v_o$ to $v_i$ with no feedback applied) is infinite, we have

$$\frac{v_o}{A_{vol}} = 0 \quad \text{...............(6)}$$

From equations (5) and (6), we get

$$0 = v_i - \frac{v_o}{R_f + R} R$$

$$\text{or, } \frac{v_o}{v_i} = \frac{R_f + R}{R}$$

$$\therefore A = \frac{v_o}{v_i} = 1 + \frac{R_f}{R} \quad \text{..............(7)}$$

where A is the closed-loop gain of the amplifier.

From equation (7),

$$v_o = \left(1 + \frac{R_f}{R}\right) v_i \quad \text{..............(8)}$$

**Voltage Follower or Buffer**

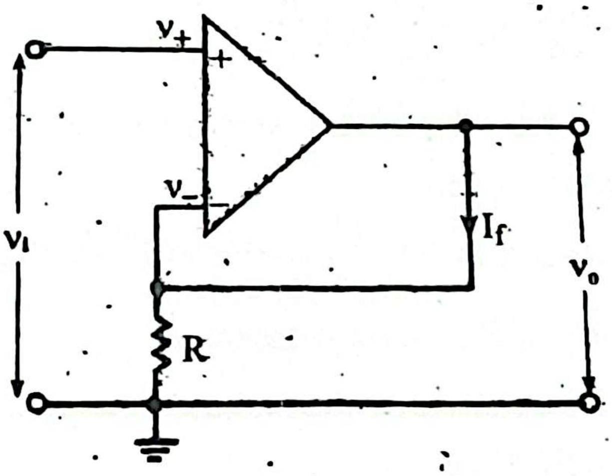


*Figure 4.4 Voltage follower.*

If $R_f = 0$ as shown in the Figure 4.4, then from equation (7),

$$A = \frac{v_o}{v_i} = 1$$

or, $v_o = v_i$

This shows that the output exactly tracks the input voltage in sign and magnitude. Therefore, this circuit is known as *voltage follower* or *buffer*.

ii. **Inverting Mode**

In this configuration, input signal $v_i$ is applied to the inverting terminal i.e., -ve pin of op-amp. The non-inverting terminal is grounded.

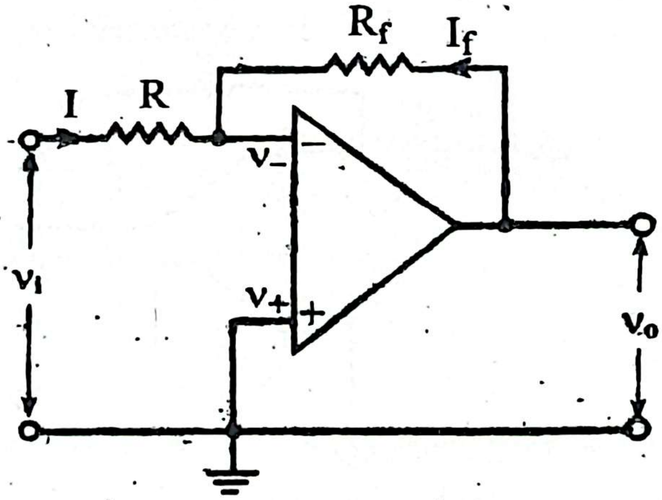


*Figure 4.5 Op-amp working in inverting mode.*

$v_+ = 0$

As we know,

$v_+ - v_- \cong 0$

$\therefore\ v_- = v_+ = 0$

KCL at terminal $v_-$ gives

$I + I_f = 0$

$$\text{or, } \frac{v_i - v_-}{R} + \frac{v_o - v_-}{R_f} = 0$$

$$\text{or, } \frac{v_o}{R_f} = \frac{-v_i}{R}$$

or, $A = \frac{v_o}{v_i} = \frac{-R_f}{R}$ which is the expression for closed-loop voltage gain of the amplifier.

Rewriting above equation,

$$v_o = \frac{-R_f}{R} v_i$$

## 4.4 Applications of Op-amp

There are large applications of op-amps in instrumentation/ measurement system. Some of the commonly used operational amplifier circuits are described below:

**i. Inverter**

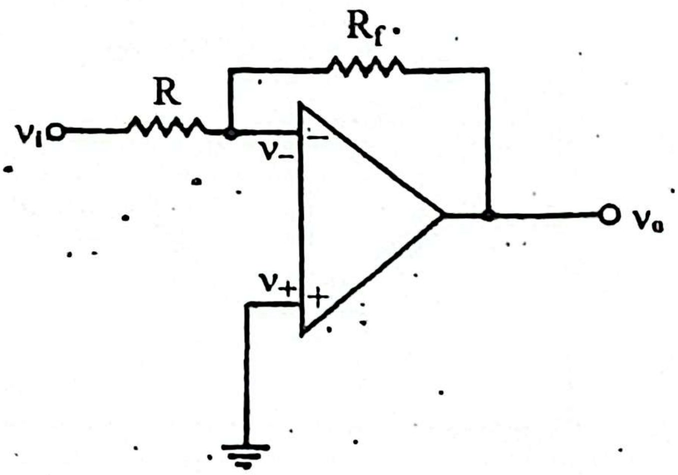


*Figure 4.6 Op-amp as an inverter.*

The closed-loop voltage gain of the amplifier in inverting configuration is given by

$$A = \frac{v_o}{v_i} = \frac{-R_f}{R}$$

If $R_f = R$, then $v_o = -v_i$

This clarifies the output voltage is 180° out of phase with the input voltage.

**ii. Adder**

The circuit that performs the addition of signals with amplification (if desired) is known as *adder*.

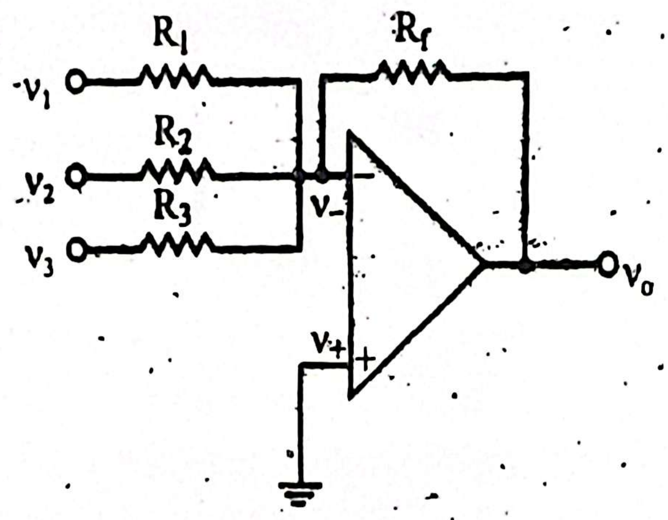


*Figure 4.7 Op-amp as an adder.*

If only $v_1$ is applied, then output is given by

$$v_{o1} = \frac{-R_f}{R_1} v_1$$

If only $v_2$ is applied, then output is given by

$$v_{o2} = \frac{-R_f}{R_2} v_2$$

If only $v_3$ is applied, then output is given by

$$v_{o3} = \frac{-R_f}{R_3} v_3$$

If all three signals are applied together, then the output can be obtained by superposition theorem as

$$v_o = v_{o1} + v_{o2} + v_{o3}$$

$$\text{or, } v_o = -\left(\frac{R_f}{R_1} v_1 + \frac{R_f}{R_2} v_2 + \frac{R_f}{R_3} v_3\right)$$

If $R_f = R_1 = R_2 = R_3$, then

$$v_o = -(v_1 + v_2 + v_3)$$

Thus, the output signal is the sum of all the input signals.

iii. **Subtractor (Differential Amplifier)**

The circuit that performs the subtraction of two input signals is known as *subtractor*.

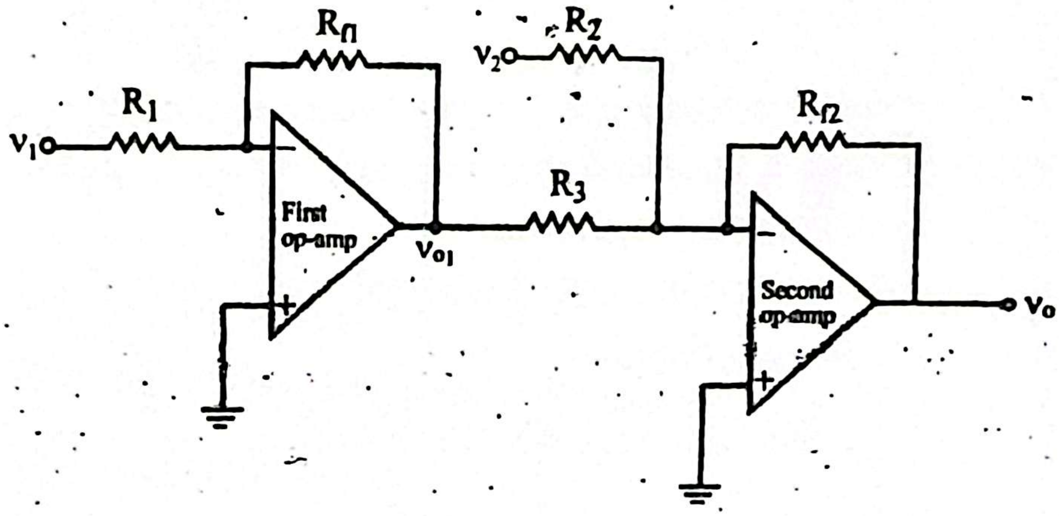


*Figure 4.8 Op-amp as a subtractor.*

The output from first operational amplifier is given by

$$v_{o1} = \frac{-R_{f1}}{R_1} v_1 \quad \text{...............(1)}$$

The output from second op-amp is given by

$$v_o = -\left(\frac{R_{f2}}{R_2} v_2 + \frac{R_{f2}}{R_3} v_{o1}\right)$$

$$\text{or, } v_o = -\left[\frac{R_{f2}}{R_2} v_2 + \left(\frac{R_{f2}}{R_3}\right)\left(\frac{-R_{f1}}{R_1}\right) v_1\right]$$

If $R_{f1} = R_{f2} = R_1 = R_2 = R_3$, then

$$v_o = -(v_2 - v_1) = v_1 - v_2$$

This expression shows that the output signal is the difference of two input signals.

**Alternative method:**

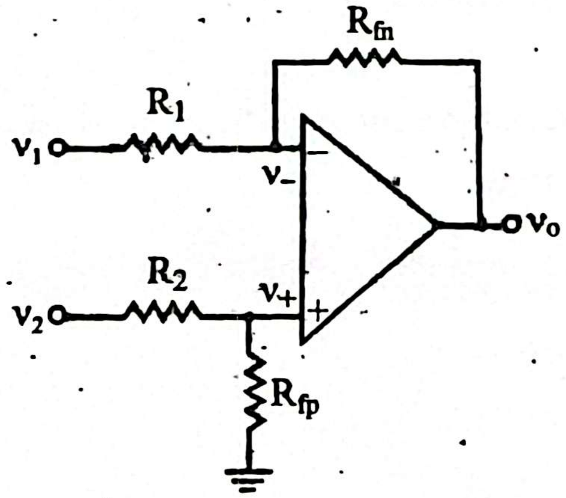


*Figure 4.9 Op-amp as a subtractor.*

- If only $v_1$ is applied, then the output is given by

$$v_{o1} = \frac{-R_{fn}}{R_1} v_1 \qquad \text{.................(1)}$$

- If only $v_2$ is applied, then the output is given by

$$v_{o2} = \left(1 + \frac{R_{fn}}{R_1}\right) v_+ \qquad \text{..............(2)}$$

But, $v_+ = \dfrac{R_{fp}}{R_{fp} + R_2} v_2$ .................(3)

From equations (2) and (3),

$$v_{o2} = \left(1 + \frac{R_{fn}}{R_1}\right) \left(\frac{R_{fp}}{R_{fp} + R_2} v_2\right) \text{............(4)}$$

If both signals are applied together, then output voltage is given by superposition theorem as

$$v_o = v_{o1} + v_{o2}$$

$$\text{or, } v_o = \frac{-R_{fn}}{R_1} v_1 + \left(1 + \frac{R_{fn}}{R_1}\right) \left(\frac{R_{fp}}{R_{fp} + R_2} v_2\right)$$

If $R_{fn} = R_{fp} = R_1 = R_2$, then

$$v_o = v_2 - v_1$$

**iv. Integrator**

A circuit that performs the mathematical integration of input signal is an *integrator*. For example, if the input to the integrator is a square wave, the output will be a triangular wave.

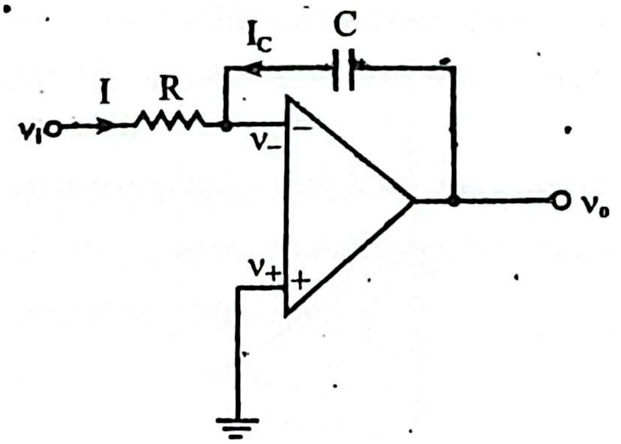


*Figure 4.10 Op-amp as an integrator.*

$v_+ = 0$

As we know,

$v_+ - v_- \cong 0$

$\therefore\ v_- = v_+ = 0$

KCL at terminal $v_-$ gives

$I + I_c = 0$

or, $\dfrac{v_i - v_-}{R} + C\dfrac{d(v_o - v_-)}{dt} = 0$

or, $C\dfrac{dv_o}{dt} = \dfrac{-v_i}{R}$

or, $dv_o = \dfrac{-1}{RC} v_i\, dt$

or, $\int dv_o = \dfrac{-1}{RC}\int v_i\, dt$

or, $v_o = \dfrac{-1}{RC}\int v_i\, dt = \dfrac{-1}{\tau}\int v_i\, dt$

Let $v_i = 10$ V dc

$v_o = \dfrac{-1}{RC}\int 10\, dt$

or, $v_o = \dfrac{-10}{RC} t$.

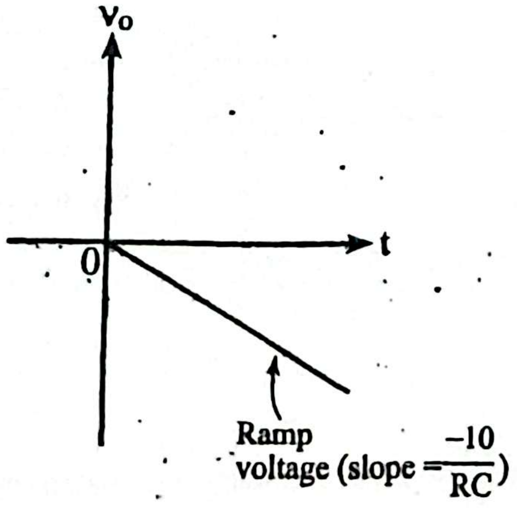


*Figure 4.11 Output voltage of an integrator when input voltage is dc.*

Thus, if dc voltage is applied to an integrator, it gives a ramp voltage at the output terminal.

Ramp function is given as

$$f(t) = 0 \text{ if } t < 0$$

$$= \pm mt \text{ if } t \geq 0$$

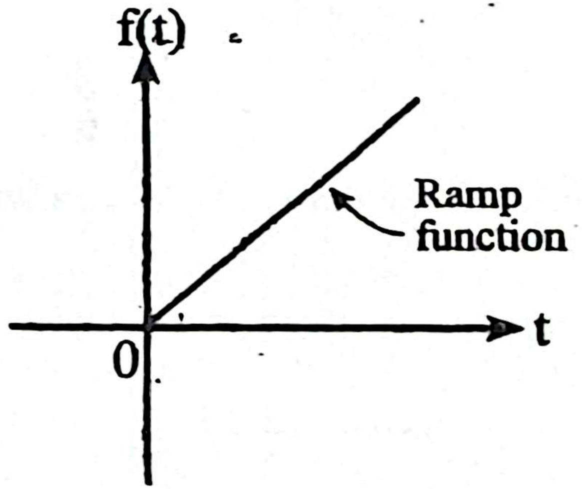


*Figure 4.12 Ramp function.*

$$\text{or, } \frac{v_o}{t} = \frac{-10}{RC} \text{ V/s} \quad \text{..................(1)}$$

$$\text{Given, } \frac{v_o}{t} = -10 \text{ V/ms}$$

$$= \frac{-10 \text{ V}}{10^{-3} \text{ s}} = -10 \times 10^3 \text{ V/s} \quad \text{............(2)}$$

From equations (1) and (2), we get

$$\frac{-10}{RC} = -10 \times 10^3$$

$$\text{or, } RC = 10^{-3} \quad \text{.............(3)}$$

Let $R = 1 \text{ k}\Omega = 10^3 \,\Omega$

$\therefore C = 10^{-6} \text{ F} = 1 \,\mu\text{F}$

The values of R and C should be chosen 1 kΩ and 1 μF respectively.

v. **Differentiator**

A circuit that performs the mathematical differentiation of input signal is called a *differentiator*. For example, if the input to the differentiator is a triangular wave, the output will be a square wave.

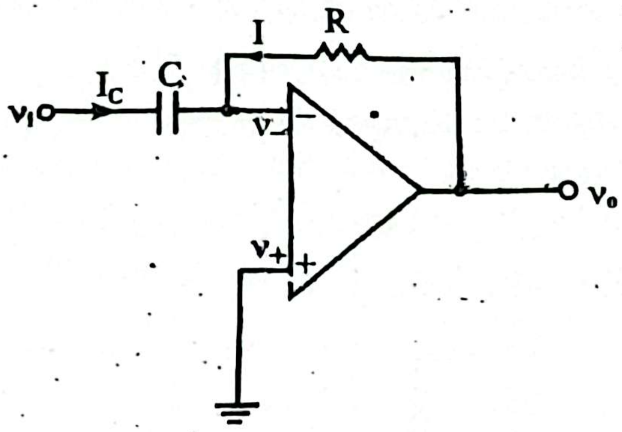


*Figure 4.13 Op-amp as a differentiator*

$v_+ = 0$

As $v_+ - v_- \cong 0$

$\therefore v_- = v_+ = 0$

KCL at terminal $v_-$ gives

$$I_C + I = 0$$

$$\text{or, } C\frac{d(v_i - v_-)}{dt} + \frac{v_o - v_-}{R} = 0$$

$$\therefore v_o = -RC\frac{dv_i}{dt} = -\tau\frac{dv_i}{dt}$$

### vi. Instrumentation Amplifier

The *instrumentation amplifier* is a dedicated differential amplifier with extremely high input impedance. Its gain can be precisely set by a single internal or external resistor. The high common-mode rejection ratio makes this amplifier very useful in recovering small signals buried in large common-mode offsets and noise.

The instrumentation amplifier (IA) is a closed loop device with carefully set gain. The op-amp itself is an open loop device with some very large (but variable) gain. This allows the instrumentation amplifier to be optimized for its role as signal conditioner of low level (often dc) signals in large amounts of noise. The op-amp in contrast, can be used to build a wide variety of circuits but does not make as good as a difference amplifier as does an instrumentation amplifier.

The instrumentation amplifier is superior than other amplifiers because of the following features:

i. Selectable gain with high gain accuracy and gain linearity.

ii. Differential input capability with high common-mode rejection ratio.

iii. High stability of gain with low temperature coefficient.

iv. Low dc offset and drift errors referred to input.

v. Low output impedance

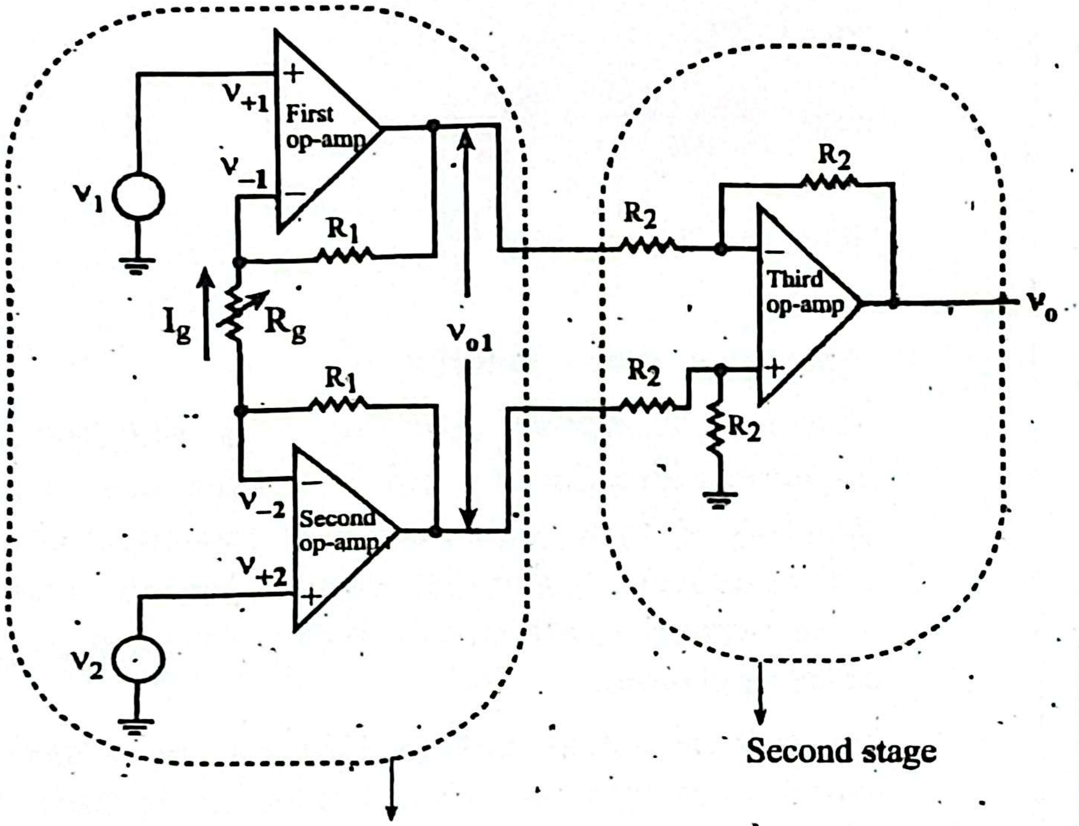


*Figure 4.14 Circuit diagram of an instrumentation amplifier.*

Instrumentation amplifier consists of two stages. The first stage consists of two carefully matched op-amps. The two inputs $v_1$ and $v_2$ are applied to non-inverting terminals of op-amp 1 and op-amp 2 respectively. The output from the first stage, $v_{o1}$ is taken through string of resistors ($R_1$, $R_g$, and R). The two resistors each $R_1$ are connected internal to the integrated circuit whereas $R_g$ is connected externally. By changing the value of $R_g$, the gain of instrumentation amplifier can be changed. So, $R_g$ is known as gain setting resistance..

The second stage of the instrumentation amplifier is a unity gain differential amplifier.

$v_{+1} = v_1$

As we know,

$v_{+1} - v_{-1} \cong 0$

$\therefore\ v_{-1} = v_{+1} = v_1$

Similarly,

$v_{-2} = v_{+2} = v_2$

Now, $I_g = \dfrac{v_{-2} - v_{-1}}{R_g} = \dfrac{v_2 - v_1}{R_g}$.

The output from the first stage is given by

$v_{o1} = I_g (R_1 + R_1 + R_g) = I_g (2R_1 + R_g)$

or, $v_{o1} = \left(\dfrac{v_2 - v_1}{R_g}\right) (2R_1 + R_g)$

or, $v_{o1} = (v_2 - v_1)\left(1 + \dfrac{2R_1}{R_g}\right)$

As the second stage is a unity gain differential amplifier, output from the second stage is given by

$v_o = -v_{o1}$

or, $v_o = -(v_2 - v_1)\left(1 + \dfrac{2R_1}{R_g}\right)$

or, $\dfrac{v_o}{v_2 - v_1} = -\left(1 + \dfrac{2R_1}{R_g}\right)$

$\therefore A = \dfrac{v_o}{v_2 - v_1} = -\left(1 + \dfrac{2R_1}{R_g}\right)$

Thus, by changing the value of $R_g$, the gain of instrumentation amplifier can be changed. For high value of $R_g$, gain will be low and vice-versa.

### Aperture time ($T_a$)

Suppose the sample and hold circuit is in sample mode, and a zero voltage is applied to the gate. Ideally, then, the circuit must go in hold mode instantaneously. But in actual practice, there is certain delay in time known as *aperture time.*

### Acquisition time

Suppose the sample and hold circuit is in hold mode, and a positive voltage is applied to the gate. Ideally, then, the circuit must go in sample mode instantaneously. But in actual practice, there is certain delay in time known as *acquisition time.*

## 6.5 Data Acquisition System (DAS)

The term *data acquisition system* is used for that part of a measurement system that quantifies and stores the data. Processing then involves manipulating the data to obtain the required result. While the system could be a scientist or engineer reading data from instruments, recording it in a notebook, and then manipulating the data to calculate the required quantity, the term is generally used for automated data acquisition involving microprocessors or computers for the data processing.

Data acquisition systems is a measurement system by means of which data can be obtained in desired form more economically and efficiently. Data acquisition systems are used to measure and record signals obtained in basically two ways:

a. Signals originating from direct measurement of electrical quantities (dc and ac voltages, frequency, or resistance)

b. Signals originating from transducers.

The data can be acquired/obtained either in analog form or in digital form. So, there are two types of DAS:

1. Analog DAS
2. Digital DAS

Data acquisition systems are used in a large and ever-increasing number of applications in a variety of industrial and scientific areas, such as biomedical, aerospace, and telemetry industries.

The objectives of data acquisition systems are:

i. It must acquire the necessary data at correct speed and at correct time.

ii. It must use all data efficiently to inform the operator about the state of the plant.

iii. To maintain on-line optimum and safe operations, it must monitor the complete plant operation.

iv. For diagnosis of operation and record purpose, it must be able to collect, summarize, and store the data.

v. It must be reliable, flexible, and capable of being expanded for further requirements.

vi. It must provide an effective human communication system and be able to identify problem areas, thereby minimizing unit availability and maximizing unit through point at minimum cost.

## 1. Analog DAS

In *analog data acquisition system*, the data is obtained in analog form. In general, analog data systems are used when wide bandwidth is required or when lower accuracy can be tolerated.

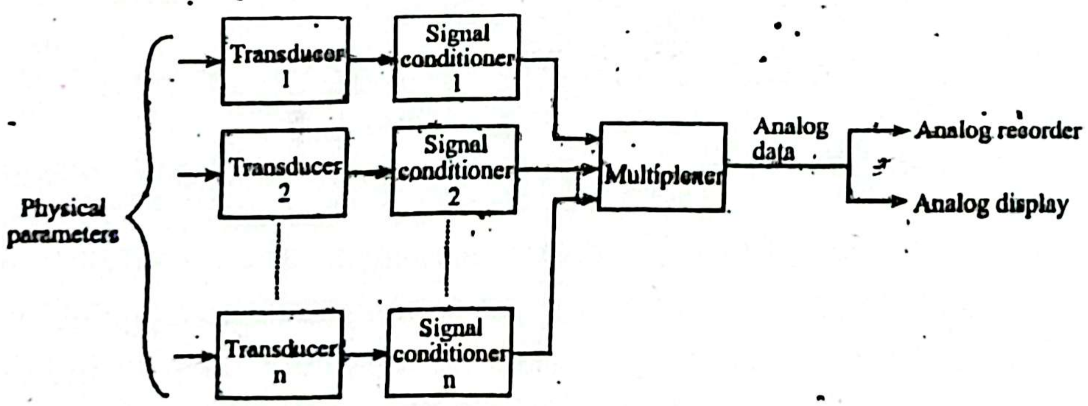


*Figure 6.9 Block diagram of an analog data acquisition system*

An analog data acquisition system typically consists of the following elements:

i. **Transducers**

A *transducer* translates physical parameters to electrical signals acceptable by the acquisition system. Some typical parameters include temperature, pressure, acceleration, weight displacement, and velocity. Electrical quantities such as voltage, resistance, or frequency also may be measured directly.

ii. **Signal conditioner**

*Signal conditioner* includes any equipment that assists in transforming the output of transducer to the desired magnitude or form required by the next stage of the data acquisition system. It also produces the required conditions in the transducers so that they work properly.

Signal conditioners may include devices for amplifying, refining, or selecting certain portions of these signals.

Examples of signal conditioning equipment include known constant voltage sources for strain gauge bridges, zero bridge balance devices for strain gauge circuits, temperature control devices for thermocouple junctions, voltage amplifiers, and servo-systems.

iii. **Multiplexer (scanner)**

A *multiplexer* or *scanner* accepts multiple analog inputs and connects them sequentially to one measuring output. Multiplexing is the process of sharing a single channel with more than one input. Thus, multiplexing enables usage of same transmission channel for transmitting more than one quantity. Multiplexing becomes necessary in measurement system when the distance between the transmitting and receiving point is large and many quantities are to be measured and transmitted. If separate channel is used for each quantity, the cost of installation, maintenance, and periodic replacement becomes very difficult.

Examples of analog recorder includes strip chart recorder, x-y recorder, etc.

2. **Digital DAS**

*Digital data acquisition systems* are used when the physical process being monitored is slowly varying (narrow bandwidth) and when accuracy and low per-channel cost is required. Digital data acquisition systems range in complexity from single-channel dc voltage measuring and recording systems to sophisticated automatic multichannel systems that measure a large number of input parameters, compare against preset limits or conditions, and perform computations and decisions on the input signal. Digital acquisition systems are in general more complex than analog systems, both in terms of the instrumentation involved and the volume and complexity of input data they can handle.

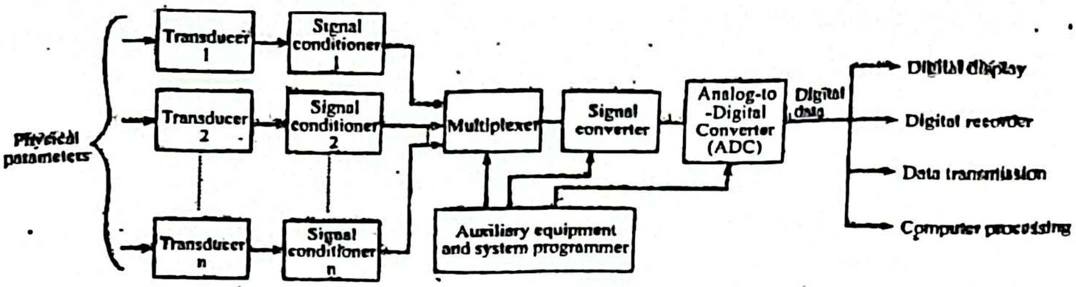


*Figure 6.10 Block diagram of a digital data acquisition system.*

A digital data acquisition system typically consists of the following elements:

i. **Transducer**

ii. **Signal conditioner**

iii. **Multiplexer**

iv. **Signal converter**

   Signal converter translates the analog signals to a form acceptable by the analog-to-digital converter (ADC). An example of a signal converter is an amplifier for amplifying low-level voltages produced by transducers.

v. **Auxiliary equipment**

   This contains devices for system programming functions and digital data processing. Some of the typical functions done by the auxiliary equipments are linearization and limit comparison of signals.

vi. **Analog-to-digital (A/D) converter**

   It converts the analog voltage to its equivalent digital form.