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C10T (Analog Systems and Applications)

Topic – Amplifiers (Part – 6)

We have already discussed part 5 of this e-report.

Now let us continue part 6 of it.

Sub Topic – Applications of Op-Amps

Introduction:

We have already discussed that the name operational amplifier (or Op-Amp) has come into play, since it was designed to perform a few mathematical operations such as addition, subtraction, integration and differentiation. Because of its versatile nature, an Op-Amp has many practical applications. It can be connected in a large number of circuits to provide various operating characteristics. In this e-report, we shall discuss some important applications of Op-Amps.

1. Inverting Amplifier:

An operational amplifier can be operated as an *inverting amplifier* as shown in Fig. 1. An input signal v_{in} is applied through input resistor R_i to the inverting input. The output is fed back to the same inverting input through feedback resistor R_f. The non-inverting input is grounded. We should note that the resistor R_f provides the negative feedback. Since the input signal is applied to the inverting input (–), the output will be inverted (i.e. 180^0 out of phase) as compared to the input. Hence the name inverting amplifier.

Voltage gain. An Op-amp has an infinite input impedance. This means that there is zero current at the inverting input. If there is zero current through the input impedance, then there must be no voltage drop between the inverting and non-inverting inputs. This means that voltage at the inverting input (–) is zero (at point A) because the other input (+) is grounded. The 0 V at the inverting input terminal (point A) is popularly referred to as *virtual ground*. This condition is illustrated in Fig. 1. The point A is said to be at virtual ground because it is at 0V (i.e. $V_A = 0$ V), but is not physically connected to the ground.

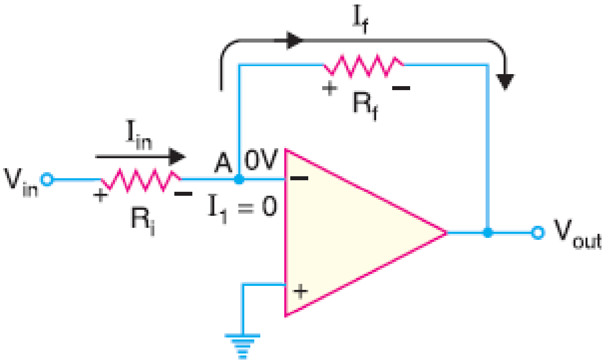

Fig. 1

The current I_1 to the inverting input is zero. Therefore, current I_{in} flowing through R_i entirely flows through feedback resistor R_f. In other words, $I_f = I_{in}$.

Now $I_{in} = \frac{v_{in} - V_A}{R_i} = \frac{v_{in}}{R_i}$, since $V_A = 0$ V for virtual ground. Using the same argument, we also can write $I_f = \frac{V_A - v_{out}}{R_f} = -\frac{v_{out}}{R_f}$.

Therefore, $\frac{v_{in}}{R_i} = -\frac{v_{out}}{R_f}$. Finally we can write closed-loop voltage gain $A_{CL} = \frac{v_{out}}{v_{in}} = -\frac{R_f}{R_i}$. The negative sign indicates that output signal is inverted as compared to the input signal. The inverting amplifier can also be designed for *unity gain buffer*. Thus if $R_f = R_i$, then voltage gain, $A_{CL} = -1$. Therefore, the circuit provides a unity voltage gain with 180^0 phase inversion.

2. Non-Inverting Amplifier:

There are times when we wish to have an output signal of the same polarity as the input signal. In this case, the Op-Amp is connected as *non-inverting amplifier* as shown in Fig. 2. The input signal is applied to the non-inverting input (+). The output is applied back to the input through the feedback circuit formed by feedback resistor R_f and input resistor R_i. It is important to note that resistors R_f and R_i form a voltage divider at the inverting input (–). This produces negative feedback in the circuit. R_i is grounded. Since the input signal is applied to the non-inverting input (+), the output signal will be non-inverted i.e., the output signal will be in phase with the input signal. Hence, the name non-inverting amplifier.

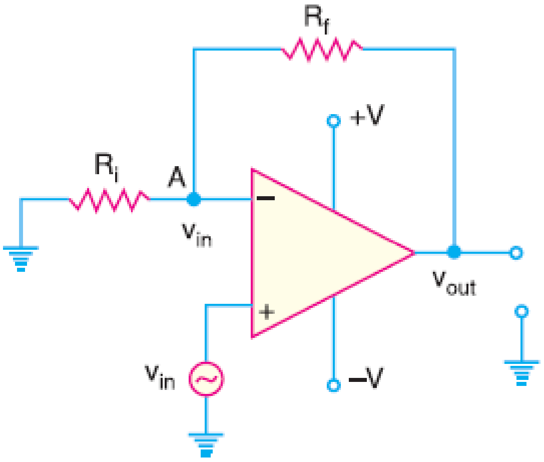

Fig. 2

Voltage gain. If we assume that we are not at saturation, the potential at point A is the same as v_{in}. Since the input impedance of Op-Amp is very high, all of the current that flows through R_f also flows through R_i. Current through R_f is $\frac{v_{out}-V_A}{R_f}=\frac{v_{out}-v_{in}}{R_f}$. Current through R_i is $\frac{V_A}{R_i}=\frac{v_{in}}{R_i}$. Therefore, $\frac{v_{in}}{R_i}=\frac{v_{out}-v_{in}}{R_f}$. So, we can write closed-loop voltage gain $A_{CL}=\frac{v_{out}}{v_{in}}=1+\frac{R_f}{R_i}$.

The voltage gain is always positive. This is not surprising because output signal is in phase with the input signal. The voltage gain of a non-inverting amplifier can be made equal to or greater than 1.

3. Summing Amplifier (Adder):

A *summing amplifier* or *adder* is an inverted Op-Amp that can accept two or more inputs. The output voltage of a summing amplifier is proportional to the negative of the algebraic sum of its input voltages. Fig. 3 shows a three-input summing amplifier but any number of inputs can be used. Three voltages V_1, V_2 and V_3 are applied to the inputs and produce currents I_1, I_2 and I_3. Using the concepts of infinite impedance and virtual ground, we can see that inverting input of the Op-Amp is at virtual ground (0 V) and there is no current to the input. This means that the three input currents I_1, I_2 and I_3 combine at the summing point A and form the total current (I_f) which goes through R_f as shown in Fig. 3.

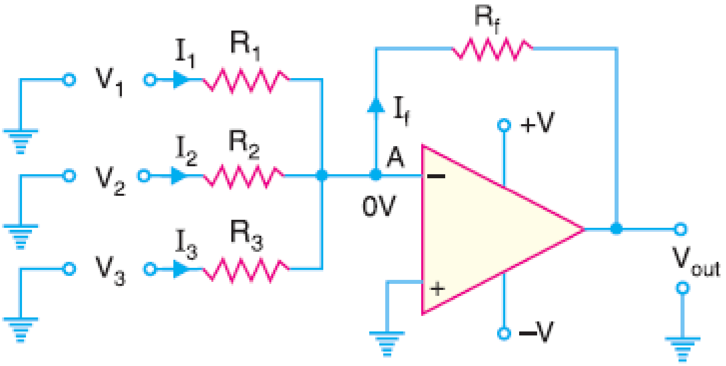

Fig. 3

When all the three inputs are applied, the output voltage is $v_{out} = -I_f R_f = -(I_1 + I_2 + I_3)R_f = -R_f(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3})$. We can see that the output voltage becomes a weighted sum of the input voltages.

If $R_1 = R_2 = R_3 = R$ we get $v_{out} = -\frac{R_f}{R}(V_1 + V_2 + V_3)$, the output becomes the algebraic sum of the input voltages.

This circuit can be used as a *subtractor* as well with two inputs, one of those being inverted by 180^0 phase.

4. Op-Amp Integrator:

An *integrator* is a circuit that performs integration of the input signal. The most popular application of an integrator is to produce a ramp output voltage (i.e. a linearly increasing or decreasing voltage). Fig. 4 shows the circuit of an Op-Amp integrator. It consists of an Op-Amp, input resistor R_i and feedback capacitor C_f. We note that the feedback component is a capacitor instead of a resistor. As we shall see, when a signal is applied to the input of this circuit, the output-signal waveform will be the integration of input-signal waveform.

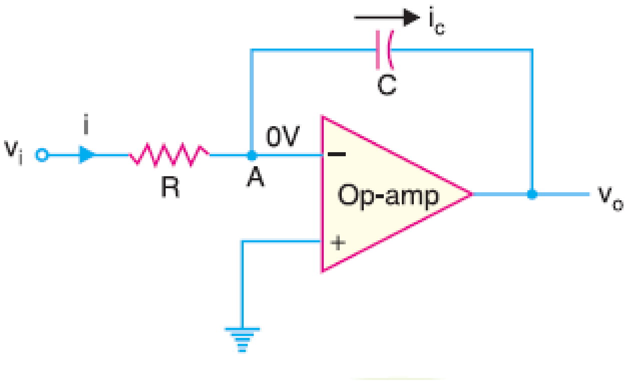

Fig. 4

Circuit Analysis. Since point A in Fig. 4 is at virtual ground and the Op-Amp has an infinite input impedance, all of the input current i flows through the capacitor i.e. $i = i_C = \frac{v_{in}-0}{R_i} = \frac{v_{in}}{R_i}$. Now voltage across the capacitor $v_C = 0 - v_{out} = -v_{out}$. So, $i_C = C_f \frac{dv_C}{dt}$ or $\frac{v_{in}}{R_i} = -C_f \frac{dv_{out}}{dt}$. So, we get $\frac{dv_{out}}{dt} = -\frac{1}{R_i C_f} v_{in}$.

Therefore, we finally get $v_{out} = -\frac{1}{R_i C_f}\int v_{in}dt$. This result shows that the output is the integral of the input with an inversion and scale multiplier of $-\frac{1}{R_i C_f}$.

5. Op-Amp Differentiator:

A *differentiator* is a circuit that performs differentiation of the input signal. In other words, a differentiator produces an output voltage that is proportional to the rate of change of the input voltage. Its important application is to produce a rectangular output from a ramp input. Fig. 5 shows the circuit of Op-Amp differentiator. It consists of an Op-Amp, an input capacitor C_i and feedback resistor R_f. We note how the placement of the capacitor and resistor differs from the integrator. The capacitor is now the input element.

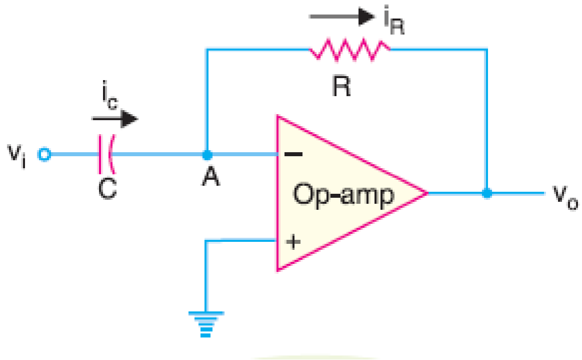

Fig. 5

Circuit Analysis. Because of virtual ground and infinite input impedance of Op-Amp, all the input current i_C flows through the feedback resistor R_f i.e. $i_C = i_R$. Now $i_R = \frac{0-v_{out}}{R_f} = -\frac{v_{out}}{R_f}$. We now can write $i_C = C_i\frac{dv_C}{dt} = C_i\frac{dv_{in}}{dt}$. Therefore $-\frac{v_{out}}{R_f} = C_i\frac{dv_{in}}{dt}$ or $v_{out} = -R_f C_i\frac{dv_{in}}{dt}$.

This equation shows that output is the differentiation of the input with an inversion and scale multiplier of $R_f C_i$.

6. Op-Amp Comparator:

Often we want to compare one voltage to another to see which is larger. In this situation, a *comparator* may be used. A comparator is an Op-Amp circuit without negative feedback and takes advantage of very high open-loop voltage gain of Op-Amp. A comparator has two input voltages (non-inverting and inverting) and one output voltage. Because of the high open-loop voltage gain of an Op-Amp, a very small difference voltage between the two inputs drives the amplifier to saturation. For example, consider an Op-Amp having $A_{OL} = 10^5$. A voltage difference of only 0.25 mV between the inputs will produce an output voltage of $(0.25$ mV$)$ (10^5) = 25 V. However, most of Op-Amps have output voltages of less than ± 15 V because of their DC supply voltages. Therefore, a very small differential input voltage will drive the Op-Amp to saturation. This is the key point in the working of comparator.

A comparator circuit has the following two characteristics:

(i) It uses no feedback so that the voltage gain is equal to the open-loop voltage gain (A_{OL}) of Op-Amp.

(ii) It is operated in a *non-linear mode*. These properties of a comparator permit it to perform many useful functions.

(a) As a zero-crossing detector. When one input of a comparator is connected to ground, it is known as *zero-crossing detector* because the output changes when the input crosses 0 V. The zero-crossing circuit is shown in Fig. 6. The input and output waveforms are also shown. When the input signal is positive-going, the output is driven to positive maximum value (i.e. $+V_{sat} = +13$ V). When the input crosses the zero mark and begins to go negative, the output is driven to negative maximum value (i.e. $-V_{sat} = -13$ V).

From the input/output waveforms, you can see that every time the input crosses 0 V going positive, the output jumps to +13 V. Similarly, every time the input crosses 0 V going negative, the output jumps to –13 V. Since the change (+13 V or –13 V) occurs every time the input crosses 0 V, we can tell when the input signal has crossed 0 V. Hence the name zero-crossing detector.

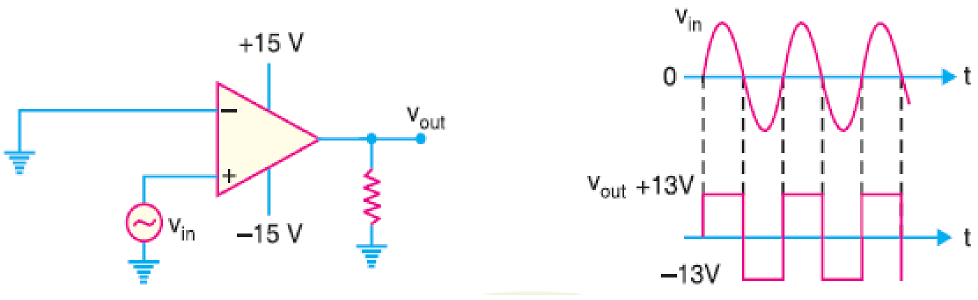

Fig. 6

(b) As a level detector. When a comparator is used to compare a signal amplitude to a fixed DC level (reference voltage), the circuit is referred to as a level detector. We can modify zero-crossing detector circuit to construct level detector. This can be done by connecting a fixed reference voltage V_{REF} to the inverting input.

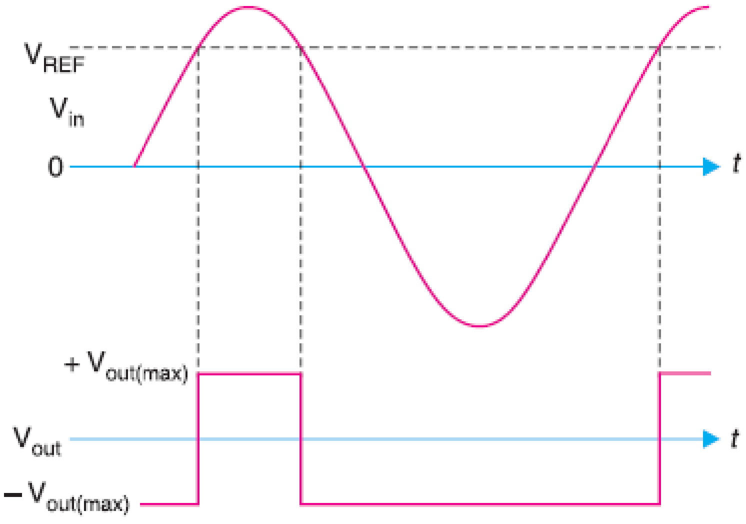

Fig. 7

The circuit action is as follows. Suppose the input signal v_{in} is a sine wave. When the input voltage is less than the reference voltage (i.e. $v_{in} < V_{REF}$), the output goes to maximum negative level. It remains here until v_{in} increases above V_{REF}. When the input voltage exceeds the reference voltage (i.e. $v_{in} > V_{REF}$), the output goes to its maximum positive state. It remains here until v_{in} decreases below V_{REF}. Fig. 7 shows the input/output waveforms.

(c) As a Schmitt trigger. Noise is any kind of unwanted signal that is not derived from or harmonically related to the input signal. Electric motors, neon signs, power lines, car ignitions, lightning, and so on produce electromagnetic fields that can induce noise voltages into electronic circuits. The standard solution for a noisy input is to use a comparator like the one shown in Fig. 8. The input voltage is applied to the inverting input. Because the feedback voltage at the non-inverting input is aiding the input voltage, the feedback is *positive.* A comparator using positive feedback like this is usually called a *Schmitt trigger*.

When the comparator is positively saturated, a positive voltage is fed back to the non-inverting input. This positive feedback voltage holds the output in the high state. Similarly, when the output voltage is negatively saturated, a negative voltage is fed back to the non-inverting input, holding the output in the low state. In either case, the positive feedback reinforces the existing output state.

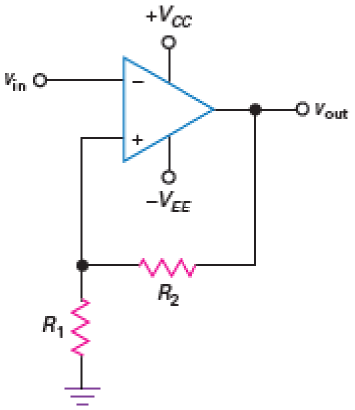

Fig. 8

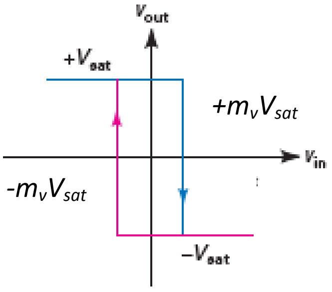

Fig. 9

Here the feedback fraction is given by $m_v = \frac{R_1}{R_1+R_2}$. When the output is positively saturated, the reference voltage applied to the non-inverting input is

$v_{REF} = +m_v V_{sat}$. When the output is negatively saturated, the reference voltage is $v_{REF} = -m_v V_{sat}$.

The output voltage will remain in a given state until the input voltage exceeds the reference voltage for that state. For instance, if the output is positively saturated, the reference voltage is $+m_v V_{sat}$. The input voltage must be increased to slightly more than $+m_v V_{sat}$ to switch the output voltage from positive to negative, as shown in Fig. 9. Once the output is in the negative state, it will remain there indefinitely until the input voltage becomes more negative than $-m_v V_{sat}$. Then, the output switches from negative to positive (Fig. 9). Overall, the $v_{in} - v_{out}$ sweep creates something called a *hysteresis curve*.

7. Wien-Bridge Oscillator:

The *Wien-Bridge Oscillator* is the standard sinusoidal oscillator circuit for low to moderate frequencies in the range of 5 Hz to about 1 MHz. It is often used in commercial audio generators and is usually preferred for other low-frequency applications.

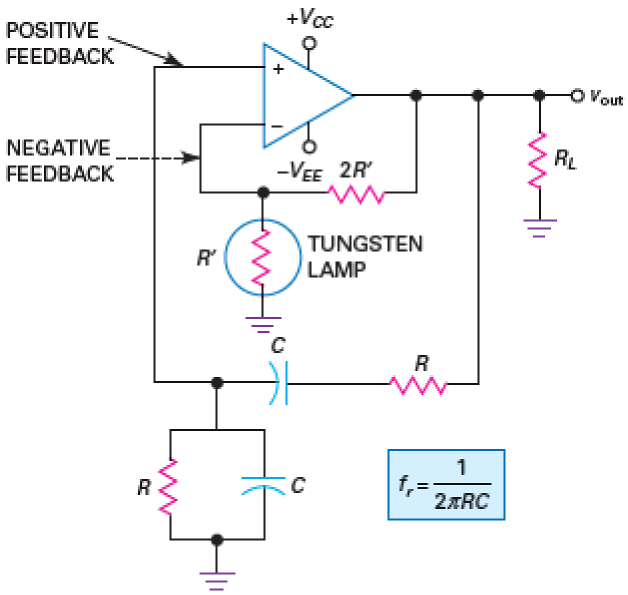

Fig. 10

Fig. 10 shows a Wien-Bridge Oscillator using Op-Amp in the circuit. It uses positive and negative feedback because there are two paths for feedback. There is a path for positive feedback from the output through the lead-lag circuit to the non-inverting input. There is also a path for negative feedback from the output through the voltage divider to the inverting input.

When the circuit is initially turned on, there is more positive feedback than negative feedback. This allows the oscillations to build up, with a resonant frequency $f_r = \frac{1}{2\pi RC}$. After the output signal reaches a desired level, the negative feedback becomes large enough to reduce loop gain $m_v A_v$ to 1.

Let's find out why $m_v A_v$ decreases to 1. At power-up, the tungsten lamp has a low resistance, and the negative feedback is small. For this reason, the loop gain is greater than 1, and the oscillations can build up at the resonant frequency. As the oscillations build up, the tungsten lamp heats slightly and its resistance increases. In most circuits, the current through the lamp is not enough to make the lamp glow, but it is enough to increase the resistance. At some high output level, the tungsten lamp has a resistance of exactly R'. At this point, the closed-loop voltage gain from the non-inverting input to the output decreases to $A_{CL} = 1 + \frac{R_f}{R_i} = 1 + \frac{2R'}{R'} = 3$. Since the lead-lag circuit has a m_v of $\frac{1}{3}$, the loop gain is $m_v A_{CL} = \frac{1}{3} \times 3 = 1$.

When the power is first turned on, the resistance of the tungsten lamp is less than R'. As a result, the closed-loop voltage gain from the non-inverting input to the output is greater than 3 and $m_v A_{CL}$ is greater than 1. As the oscillations build up, the peak-to-peak output becomes large enough to increase the resistance of the tungsten lamp. When its resistance equals R', the loop gain $m_v A_{CL}$ is exactly equal to 1. At this point, the oscillations become stable, and the output voltage has a constant peak-to-peak value.

This concludes part 6 of this e-report.

The discussion will be continuing in the part 7 of this e-report.

Reference(s):

Principles of Electronics, V.K. Mehta & Rohit Mehta, S. Chand & Company

Electronic Principles, Albert Malvino & David Bates, McGraw-Hill Education

(All the figures have been collected from the above mentioned references)