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C10T (Analog Systems and Applications)

Topic – Amplifiers (Part – 5)

We have already discussed part 4 of this e-report.

Now let us continue part 5 of it.

Sub Topic – Operational Amplifiers

Introduction:

Historically, an *operational amplifier* (or Op-Amp) was designed to perform a few mathematical operations such as addition, subtraction, integration and differentiation. Hence, the name operational amplifier has come into play. An operational amplifier is a multistage amplifier and consists of a differential amplifier stage, a high-gain CE amplifier stage and class *B* push-pull emitter follower. It is an integrated circuit and is widely used in computers, as video and audio amplifiers in communication electronics.

Because of their multi-purpose use, Op-Amps are used in all branches of electronics, both digital and linear circuits. In this e-report, we shall discuss the various aspects of operational amplifiers.

Features of an Op-Amp:

An operational amplifier (Op-Amp) is a circuit that can perform such mathematical operations as addition, subtraction, integration and differentiation.

Fig. 1 shows the block diagram of an operational amplifier. It is important to note that Op-Amp is a multistage amplifier. The three stages are differential amplifier input stage followed by a high-gain CE amplifier and finally the output stage. The key electronic circuit in an Op-Amp is the differential amplifier. A differential amplifier (DA) can accept two input signals and amplifies the difference between these two input signals.

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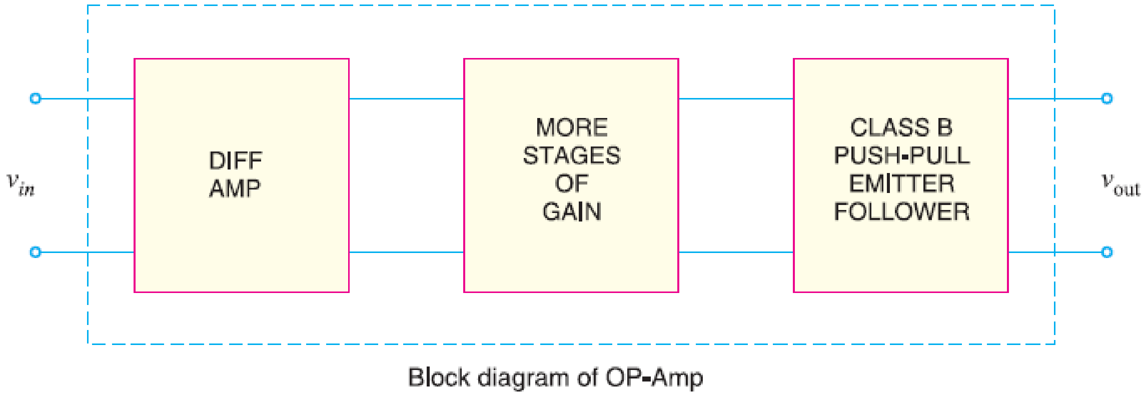

Fig. 1

The following points may be noted about Op-Amps.

(i) The input stage of an Op-Amp is a differential amplifier (DA) and the output stage is typically a class B push-pull emitter follower.

(ii) The internal stages of an Op-Amp are direct-coupled i.e. no coupling capacitors are used. The direct coupling allows an Op-Amp to amplify DC as well as AC signals.

(iii) An Op-Amp has very high input impedance Z_{in} (ideally infinite) and very low output impedance Z_{out} (ideally zero). The effect of high input impedance is that the amplifier will draw a very small current (ideally zero) from the signal source. The effect of very low output impedance is that the amplifier will provide a constant output voltage independent of current drawn from the source.

(iv) An Op-Amp has very high open-loop voltage gain (ideally infinite), typically $\sim 2 \times 10^5$.

(v) The Op-Amps are almost always operated with negative feedback. It is because the open-loop voltage gain of these amplifiers is very high and we can sacrifice the gain to achieve the advantages of negative feedback including large bandwidth and gain stability.

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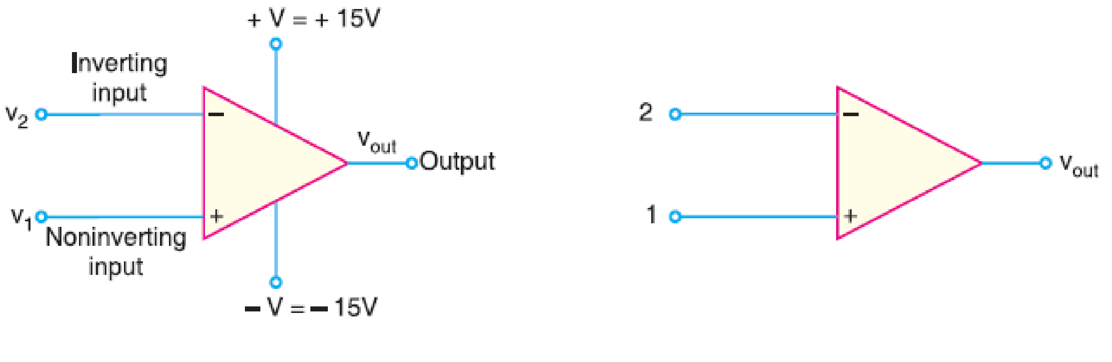

(*i*) (*ii*)

Fig. 2

Schematic Symbol of an Op-Amp:

Fig. 2(*i*) shows the schematic symbol of an operational amplifier. The following points are worth noting,

(i) The basic operational amplifier has five terminals; two terminals for supply voltages $+V$ and $-V$, two input terminals (inverting input and non-inverting input) and one output terminal.

(ii) Note that the input terminals are marked + and –. These are not polarity signs. The – sign indicates the inverting input while the + sign indicates the non-inverting input. A signal applied to + terminal will appear in the same phase at the output as at the input. A signal applied to the – terminal will be shifted in phase 180^0 at the output.

(iii) The voltages v_1, v_2 and v_{out} are node voltages. This means that they are always measured from the ground. The differential input v_{in} is the difference of two node voltages v_1 and v_2. We normally do not show the ground in the symbol.

(iv) For the sake of simplicity, $+V$ and $-V$ terminals are often omitted from the symbol as shown in Fig. 2(*ii*). The two input leads are always shown on the symbol regardless of whether they are both used.

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Differential Amplifier (DA):

Since *differential amplifier* (DA) is key to the operation of OP-Amp, we shall discuss this first before going into the detail. In conventional amplifiers, the signal (generally single input) is applied at the input terminals and amplified output is obtained at the output terminals. However, we can design an amplifier circuit that accepts two input signals and amplifies the difference between these two signals. Such an amplifier is called a differential amplifier (DA). Therefore, a differential amplifier is a circuit that can accept two input signals and amplify the *difference* between these two input signals.

The importance of a differential amplifier lies in the fact that the outputs are proportional to the difference between the two input signals. Thus the circuit can be used to amplify the difference between the two input signals or amplify only one input signal simply by grounding the other input.

The input signals to a DA are defined as (i) Common-mode signals and (ii) Differential-mode signals.

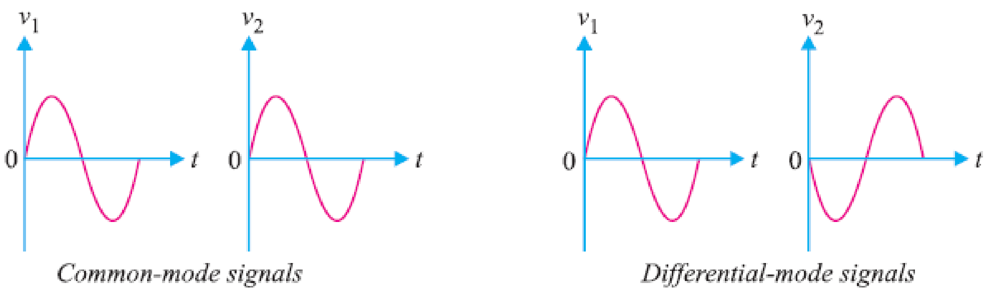

Fig. 3

(i) Common-mode signals. When the input signals to a DA are in phase and exactly equal in amplitude, they are called common-mode signals as shown in Fig. 3(*i*). The common-mode signals are rejected (and not amplified) by the differential amplifier. It is because a differential amplifier amplifies the difference between the two signals ($v_1 - v_2$) and for common-mode signals, this difference is zero. Note that for common-mode operations $v_1 = v_2$.

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(ii) Differential-mode signals. When the input signals to a DA are 180^0 out of phase and exactly equal in amplitude, they are called differential-mode signals as shown in Fig. 3(*ii*). The differential-mode signals are amplified by the differential amplifier. It is because the difference in the signals is twice the value of each signal. For differential-mode signals $v_1 = -v_2$.

Voltage Gains of DA, Common Mode Rejection Ratio (CMRR):

The voltage gain of a DA operating in differential mode is called differential-mode voltage gain and is denoted by A_{DM}. The voltage gain of DA operating in common-mode is called common-mode voltage gain and is denoted by A_{CM}.

Ideally, a DA provides a very high voltage gain for differential-mode signals and zero gain for common-mode signals. However practically, differential amplifiers do exhibit a very small common-mode gain (usually much less than 1) while providing a high differential voltage gain (usually several thousands). The higher the differential gain in comparison to the common-mode gain, the better the performance of the DA in terms of rejection of common-mode signals.

A differential amplifier should have high differential mode voltage gain (A_{DM}) and very low common mode voltage gain (A_{CM}). The common mode rejection ratio (CMRR) is defined as,

$$CMRR = \frac{A_{DM}}{A_{CM}}$$

Clearly, it is a dimensionless quantity. But very often, the CMRR is expressed in decibels (dB). The decibel measure for CMRR is given by, $CMRR$ (in dB) $= 20 \log_{10} \frac{A_{DM}}{A_{CM}} = 20 \log_{10} CMRR$.

For example, a CMRR of 10^5 corresponds to 100 in dB unit of CMRR.

Importance of CMRR. The CMRR is the ability of a DA to reject the common-mode signals. The larger the CMRR, the better the DA is at eliminating common-mode signals. Let us illustrate this point by an example.

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Let us assume that the differential amplifier has a differential voltage gain A_{DM} of 1500 and a common-mode gain A_{CM} of 0.01. This means that the output produced by a difference between the inputs would be 1.5×10^5 times as great as an output produced by a common-mode signal. The ability of the DA to reject common-mode signals is one of its main advantages. Common mode signals are usually *undesired signals* caused by external interference. For example, any RF signals picked up by the DA inputs would be considered undesirable. The CMRR indicates the DA's ability to reject such unwanted signals.

Output Voltage from Op-Amp:

The output voltage from an Op-Amp for a given pair of input voltages depends mainly on the following factors:

1. The voltage gain of Op-Amp,

2. The polarity relationship between v_1 and v_2 and

3. The values of supply voltages, $+V$ and $-V$

1. Voltage gain of Op-Amp. The maximum possible voltage gain from a given Op-Amp is called *open-loop voltage gain* and is denoted by the symbol A_{OL}. The value of A_{OL} for an Op-Amp is generally greater than 10000.

The term open-loop indicates a circuit condition where there is no feedback path from the output to the input of Op-Amp. The Op-Amps are almost always operated with negative feedback i.e., a part of the output signal is fed back in phase opposition to the input. Consequently, the voltage gain of the Op-Amp is reduced. When a feedback path is present, the resulting circuit gain is referred to as *closed-loop voltage gain* (A_{CL}). Value of A_{CL} depends on the circuit parameters.

2. Polarity relationship between v_1 and v_2. The polarity relationship between v_1 and v_2 will determine whether the Op-Amp output voltage polarity is

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positive or negative. There is an easy method for it. We know the differential input voltage v_{in} is given by $v_{in} = v_1 - v_2$.

When the result of this equation is positive, the Op-Amp output voltage will be positive. When the result of this equation is negative, the output voltage will be negative.

3. The values of supply voltages $+V$ and $-V$. The supply voltages for an Op-Amp are normally equal in magnitude and opposite in sign e.g., ± 15 V, ± 12 V, ± 18 V. These supply voltages determine the limits of output voltage of Op-Amp. These limits, known as *saturation voltages*, are generally given by,

$$+V_{sat} \approx +V_{supply} - 2$$

$$-V_{sat} \approx -V_{supply} + 2$$

If the differential input voltage v_{in} exceeds this value in an Op-Amp, it will be driven into saturation and the device will become non-linear.

Comparison between Practical Op-Amp and Ideal Op-Amp:

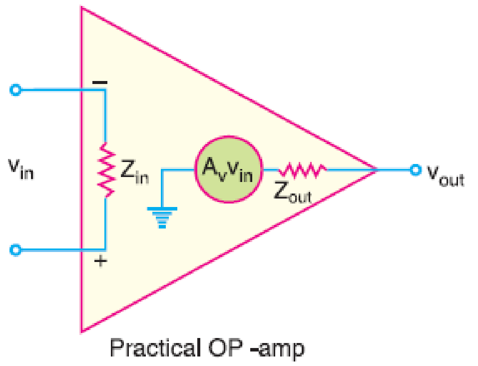

Fig. 4

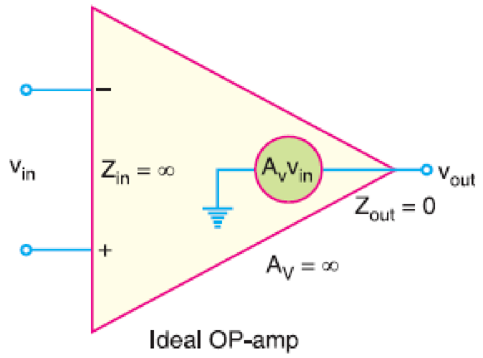

Fig. 5

The basic Op-Amp has two input terminals and one output terminal. The input terminals are labelled as + (non-inverting input) and – (inverting input). As discussed earlier, a signal applied to the non-inverting input will produce an output voltage that is in phase with the input voltage. However, a signal applied to the inverting input will produce an output voltage that is 180^0 out of phase with the input signal.

(i) Practical Op–Amp. Fig. 4 shows the AC equivalent circuit of a practical Op-Amp (IC 741). The characteristics of a practical Op-Amp are very high voltage gain, very high input impedance and very low output impedance. The input voltage v_{in} appears between the two input terminals and the output voltage is $A_{OL}v_{in}$ taken through the output impedance Z_{out}.

(ii) Ideal Op-Amp. Fig. 5 shows the AC equivalent circuit of an ideal Op-Amp. The characteristics of an ideal Op-Amp are infinite voltage gain, infinite input impedance Z_{in} and zero output impedance Z_{out}.

We can sum up the values of parameters of a practical Op-Amp and an ideal Op-Amp as under

	Practical Op-Amp	Ideal Op-Amp
Z_{in}	~2 MΩ	∞
A_{OL}	$\sim 10^5$	∞
Z_{out}	~100 Ω	0

Bandwidth of an Op-Amp:

All electronic devices work only over a limited range of frequencies. This range of frequencies is called bandwidth. Every Op-Amp has a bandwidth Δf i.e., the range of frequencies over which it will work properly. The bandwidth of an Op-Amp depends upon the closed-loop gain (A_{CL}) of the Op-Amp circuit. One important parameter is gain-bandwidth product (GBW). It is defined as follows.

$$A_{CL} \times f_2 = f_{unity} = GBW$$

where A_{CL} = closed-loop gain at frequency f_2

f_{unity} = frequency at which the closed-loop gain is unity

It can be proved that the gain-bandwidth product of an Op-Amp is constant. Since an Op-Amp is capable of operating as a DC amplifier, its bandwidth is $\Delta f = f_2 - 0 = f_2$. The gain-bandwidth product of an Op-Amp is an important parameter because it can be used to find two things,

(i) The maximum value of A_{CL} at a given value of f_2 and

(ii) The value of f_2 for a given value of A_{CL}.

Slew Rate and Frequency Response:

In a situation where the input voltage is changing very fast, the output voltage from an Op-Amp can't follow it. The *slew rate* (SR) of an Op-Amp is a measure of how fast the output voltage can change with time and is measured in volts per microsecond (Vμs^{-1}). If the slew rate of an Op-Amp is 0.5 Vμs^{-1}, it means that the output from the amplifier can change by 0.5 V every µs. Since frequency is a function of time, the slew rate (SR) can be used to determine the *maximum operating frequency* (f_{max}) of the Op-Amp as follows:

$$f_{max} = \frac{SR}{2\pi V_{pk}}$$

Here V_{pk} is the peak output voltage from the Op-Amp.

The operating frequency (f) has a significant effect on the operation of an Op-Amp. The following are the important points regarding the frequency response of an Op-Amp.

(i) The maximum operating frequency f_{max} of an Op-Amp can be calculated from the slew rate using the peak output voltage V_{pk}. Thus, the peak output voltage limits the maximum operating frequency.

(ii) When the maximum operating frequency of an Op-Amp is exceeded, the result is a distorted output waveform.

(iii) Increasing the operating frequency of an Op-Amp beyond a certain point will do the following,

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(a) Decrease the maximum output voltage swing,

(b) Decrease the open-loop voltage gain,

(c) Decrease the input impedance and

(d) Increase the output impedance.

This concludes part 5 of this e-report.

The discussion will be continuing in the part 6 of this e-report.

Reference:

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

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