Pearson BTEC Level 4 Higher Nationals in Engineering (RQF)

Unit 22: Electronic Circuits and Devices

Unit Workbook 1

in a series of 4 for this unit

Learning Outcome 1

Operational Amplifiers

1.1 Power Amplifiers

The main purpose of power amplifiers is to enhance the magnitude of the signal that is put into it (i.e. speaker systems amplifying the audio signal to make the song louder). A typical loudspeaker will have a low impedance (~7Ω), and so will need to be able to supply high peak currents to operate the low impedance speaker.

Amplifiers are divided into specific classes, depending on their amplification signal, demonstrated by Fig.1.1. There are many amplifier classes that are available to technicians, but this unit will cover just three: A, B and AB. These amplifiers, and class C, produce analogue signal outputs, whereas other amplifiers (D, E, F, G, S, T) are known as switching amplifiers and will only have digital signal outputs.

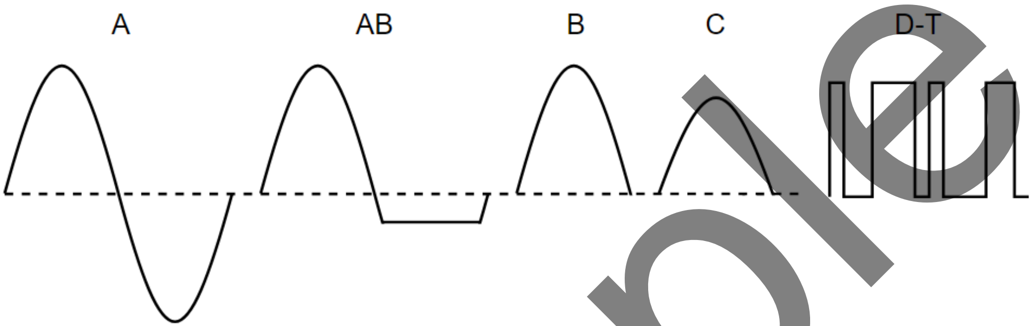


Fig.1.1: Outputs of amplifier classes

1.1.1 Class A Amplifiers

These amplifiers are the one of the simplest, and therefore the most common. The schematic of a class A amplifier is shown in Fig.1.2 and uses a common emitter configuration while for both halves of the waveform.

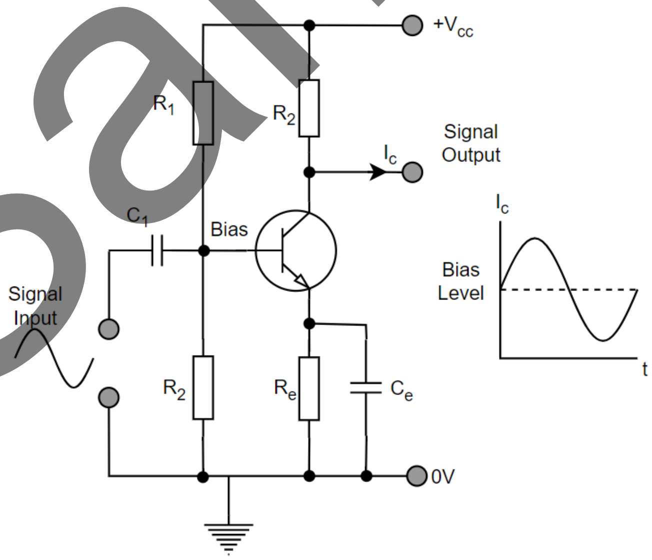


Fig.1.2: Class A amplifier schematic

As you can see by the schematic, the transistor will always have a current flowing through it and so the system will never turn off, even if there is no signal input. With this in mind, class A amplifiers are very inefficient, and generate a lot of heat even when there is no signal to be amplified. They are however, the most accurate amplifiers with low signal distortion.

1.1.2 Class B Amplifiers

Class B amplifiers were developed as a solution improve the efficiency and heat loss present in class A amplifiers. The simplest of class B amplifiers consists of two complimentary transistors that processes one half of the waveform each and create a "push-pull" arrangement. A schematic for a simple class B amplifier. A circuit diagram of a class B amplifier is shown in Fig.1.3.

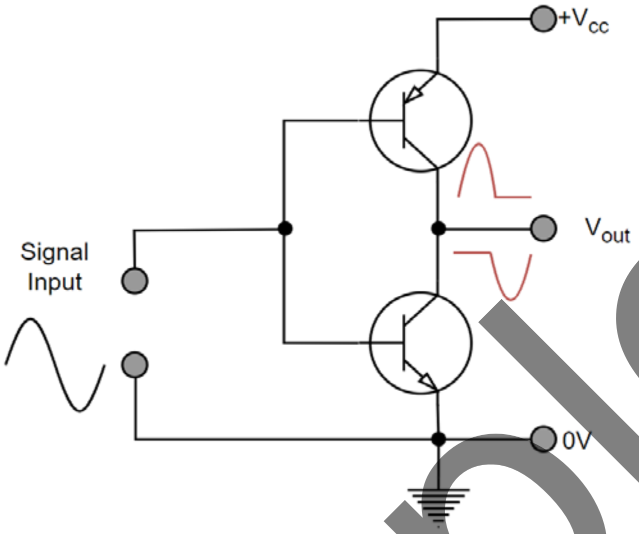


Fig.1.3: Class B Amplifier

When there is no input signal, then the gates of the transistors are not active, meaning that no current can flow between $+V_{CC}$ and $0V$, thus improving the overall efficiency of the system. V_{out} is shown in Fig.1.4. You will notice that this is *not* a perfect sine wave. Transistors have a dead band of input voltages between $\pm 0.7V$, so between these voltages, there is a "crossover distortion" because the transistor is not active.

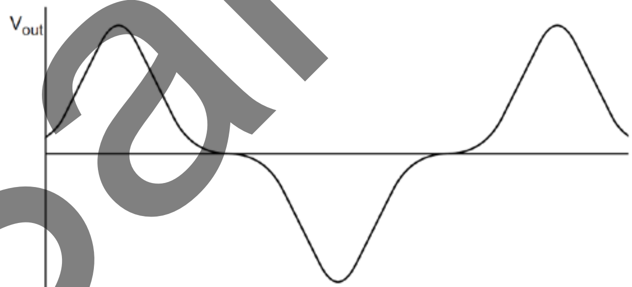


Fig.1.4: An output signal of a sine wave in a class B amplifier, exhibiting crossover distortion

1.1.3 Class AB Amplifier

In order to reduce the crossover distortion, class AB amplifiers were developed, essentially a hybrid of the class A and the class B. The class AB amplifiers introduce a small bias on each transistor, so that they are still switched on between $\pm 0.7V$, and eliminate the distortion exhibited by the class B. The AB amplifier is most commonly used in audio power amplification. By introducing a bias into the system, the transistors are active for more than half of the signal. Since the transistors are active for more of the cycle than they are in class B, they are less efficient, but still more efficient than having a class A in place. Fig.1.5 shows a circuit diagram of a class AB amplifier.

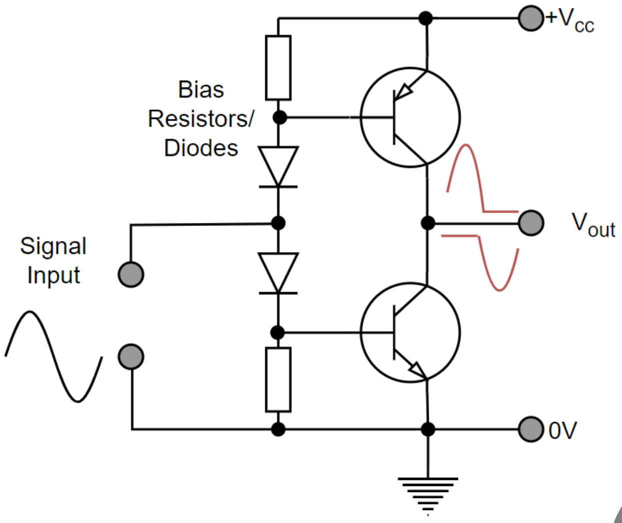


Fig.1.5: Class AB amplifier

1.1.4 The Ideal Amplifier

As with any aspect of engineering, the goal of a system is to be as closer to perfect as is physically possible. The characteristics of the ideal amplifier are:

- Infinite Bandwidth
- Infinite gain available
- Easily controllable gain
- Linear with no distortion
- Cheap
- Easy to convert functionality
- No Noise

While ideal does not exist, the closest we have at the moment is the Operational-Amplifier (Op-Amp), they are cheap to manufacture and have excellent performance characteristics. They are linear devices and can be used for mathematical operations, which will be discussed further in Section 1.4. The Op-Amp has two inputs: inverting and non-inverting, one output, and with a voltage across the internal circuitry that powers the electronics. A diagram of an Op-Amp can be seen in Fig.1.6, this is the drawing that is used to simplify circuit diagrams. The inner workings of an Op-Amp are complex, and in practice they are shaped just like any other integrated circuit.

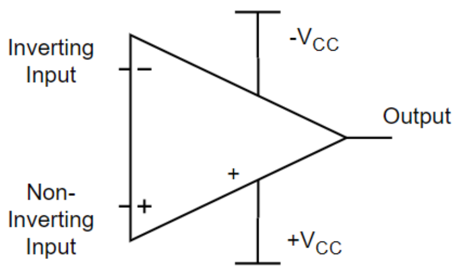


Fig.1.6: Op-Amp diagram.

1.2 Characteristics of Op-Amps

1.2.1 Impedance

The impedance is the ratio of voltage to current (essentially the resistance). ***For an ideal Op-Amp the input impedance is infinite***. Infinite input impedance implies no loading of sources connected to the input terminals of the Op-Amp, but realistically the impedance is not infinite and there will be some leakage current.

For an ideal Op-Amp the output impedance is zero. This makes sense because ideally, we would like the device to deliver high currents without reducing the output voltage. Typical values for actual devices are around 75Ω. Check device datasheets for actual values.

1.2.2 Bias

Although the ideal Op-Amp is assumed to have infinite input impedance and therefore zero current flowing into the input terminals, there is some current drawn in practical devices. The input currents to the Op-Amp are averaged to produce a figure for the input bias current***. An ideal Op-Amp will therefore have zero input bias current***.

The offset bias is the difference between the two input bias currents. Since the ideal Op-Amp has zero input bias current, it can also be stated that: ***The ideal Op-Amp has zero offset bias***.

Changes in temperature can cause Op-Amp parameters to “drift”. Bias current is particularly susceptible to drift with temperature. ***An ideal Op-Amp will have zero drift***.

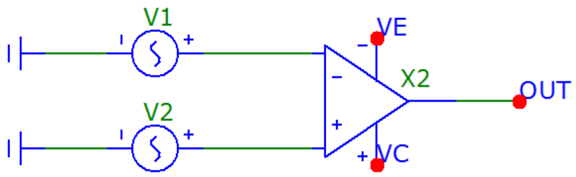
1.2.3 Voltage Gain

The voltage gain ($\mathrm{A_V}$) is the ratio of output voltage to the input voltage, expressed by Eq.1.1. The gain will vary on the configuration of the Op-Amp circuitry. ***For an open loop (no feedback resistor) ideal Op-Amp the voltage gain is infinity***.

$$\frac{V_{OUT}}{V_{IN}} = A_V \qquad \text{(Eq.1.1)}$$

1.2.4 Common Mode Rejection Ratio (CMRR)

Consider the two test circuits in Fig.1.7. The first circuit measures the differential voltage gain (A_D) of the Op-Amp. There is a separate signal presented to each of the Op-Amp inputs. An ideal Op-Amp should give an infinite differential voltage gain (i.e. maximum voltage at the output). The second circuit has the inputs shorted (common) so this will measure the common-mode voltage gain (A_{CM}) of the Op-Amp. An ideal Op-Amp will give zero voltage for this test.



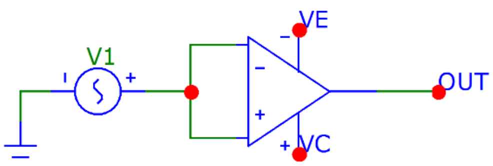


Fig.1.7: Two testing circuits Op-Amps.

Manufacturers commonly specify the Common Mode Rejection Ratio (CMRR) for Op-Amps. This is given as the ratio of the differential to common mode voltage gains, shown by Eq.1.2.

$$CMRR = \frac{A_D}{A_{CM}} \qquad \text{(Eq.1.2)}$$

An ideal Op-Amp will therefore have an infinite $CMRR$. Since A_{CM} would be zero. Typical values for actual devices are given in decibels.

1.2.5 Unity Gain Bandwidth

Bandwidth is the range of frequencies that the Op-Amp will operate at its optimal functionality. Outside of the bandwidth, the Op-Amp's gain will begin to drop off exponentially.

Unity gain bandwidth is when the Op-Amp has a gain of 1 (unity) then it will have infinite bandwidth (i.e. it will pass all frequencies equally). This is not possible in practical devices and a figure is quoted in Op-Amp datasheets. ***An ideal Op-Amp has infinite unity gain bandwidth***.

1.2.6 Slew Rate

Slew rate refers to how fast the output voltage of the Op-Amp can change in response to a changing input voltage. This is measured in volts per second. ***An ideal Op-Amp will have an infinite slew rate***.

There is also a range of frequencies at which slew rate does not occur whilst still achieving the rated output voltage of the Op-Amp, known as the full power bandwidth***. An ideal Op-Amp will have infinite full power bandwidth***.

1.2.7 Differential Input Range

This is the maximum difference in peak voltages tolerated by an Op-Amp. ***An ideal Op-Amp will have an infinite differential input range***.

1.2.8 Constant-Current Source

Inside an Op-Amp there is a differential amplifier consisting of two transistors with a shared emitter resistor. It is the combination of the negative supply voltage (V_E in the circuit diagrams here) and this emitter resistor which produces a constant current source. ***In an ideal Op-Amp the constant current generator does not vary***.

1.4 Op-Amp Uses

1.4.1 Summing

We can also expand on the circuitry shown in Fig.1.8 and Fig.1.9 to develop systems that can calculate mathematical functions. The circuit in Fig.1.10 shows a summing operator, with three different voltages and resistances feeding into the inverting input of the Op-Amp.

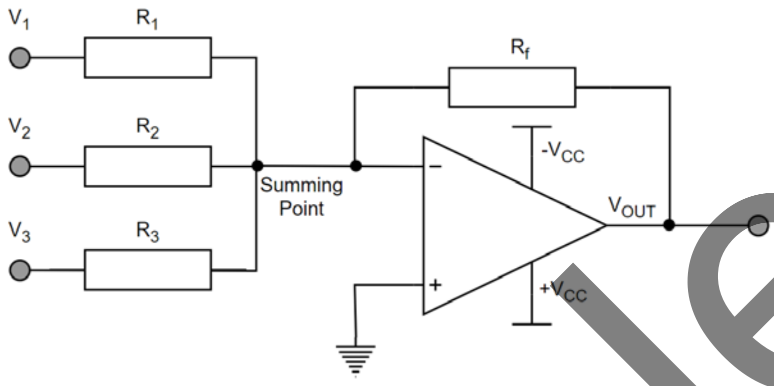


Fig.1.10: Summing Operator

Using what we know about inverting amplifiers, we can once again use Kirchhoff's current law to find the point where the input voltages add up at the summing point.

$$\frac{V_{OUT}}{R_f} = -\left[\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right]$$

$$V_{OUT} = -R_f\left[\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right]$$

Which, if all input resistances are the same $R_1 = R_2 = R_3$, then the equation simplifies to Eq.1.5

$$V_{OUT} = -\frac{R_f}{R_1}[V_1 + V_2 + V_3] \qquad \text{(Eq.1.5)}$$

1.4.2 Differential

While Op-Amps can be used for the summation of voltages, we can also use them for finding the difference in voltages. Fig.1.11 shows such a device, as you can see there is input at the inverter, and one at the non-inverter. Using Ohm's law, we can see that:

$$I_1 = \frac{V_1 - V_a}{R_1}, \qquad I_2 = \frac{V_2 - V_b}{R_2}, \qquad I_f = \frac{V_a - V_{OUT}}{R_3}$$

The summing point gives us:

$$V_a = V_b$$

And V_b can be calculated by:

$$V_b = V_2\left(\frac{R_4}{R_2 + R_4}\right)$$

If $V_2 = 0$, then:

$$V_{OUT(a)} = -V_1\left(\frac{R_3}{R_1}\right)$$

If $V_1 = 0$, then:

$$V_{OUT(b)} = V_2\left(\frac{R_4}{R_2 + R_4}\right)\left(\frac{R_1 + R_3}{R_1}\right)$$

$$V_{OUT} = -V_{OUT(a)} + V_{OUT(b)}$$

Meaning we can express the V_{OUT} as Eq.1.6.

$$V_{OUT} = -V_1\left(\frac{R_3}{R_1}\right) + V_2\left(\frac{R_4}{R_2+R_4}\right)\left(\frac{R_1+R_3}{R_1}\right) \qquad \text{(Eq.1.6)}$$

If $R_1 = R_2$ and $R_3 = R_4$, then we can simplify Eq.1.6 into Eq.1.7

$$V_{OUT} = \frac{R_3}{R_1}(V_2 - V_1) \qquad \text{(Eq.1.7)}$$

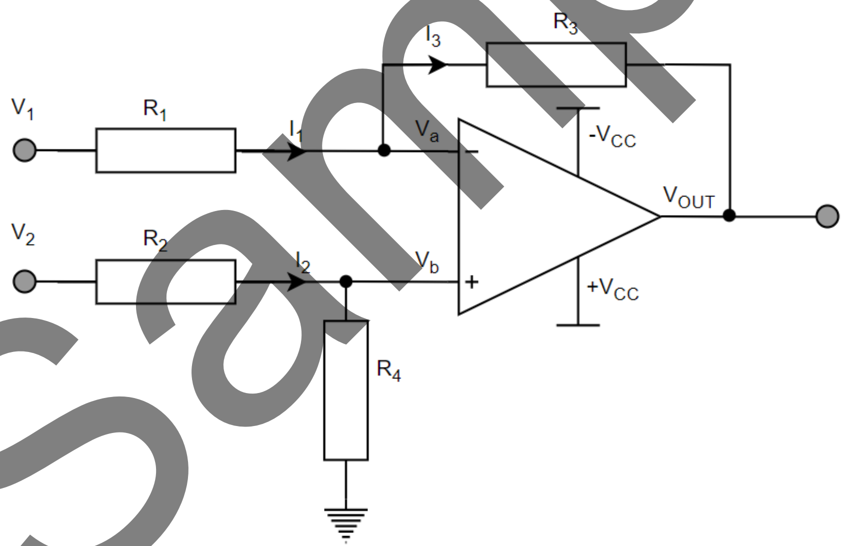


Fig.1.11: Differential Operator

1.4.3 Integrator

The integrator circuit creates an integration function with the Op-Amp, this is done by incorporating a capacitor into the system, demonstrated by Fig.1.12. You will notice that this is a small adjustment to the inverting amplifier. This now also means that the circuit incorporates a new variable, time, and must therefore be considered when calculating V_{OUT}.

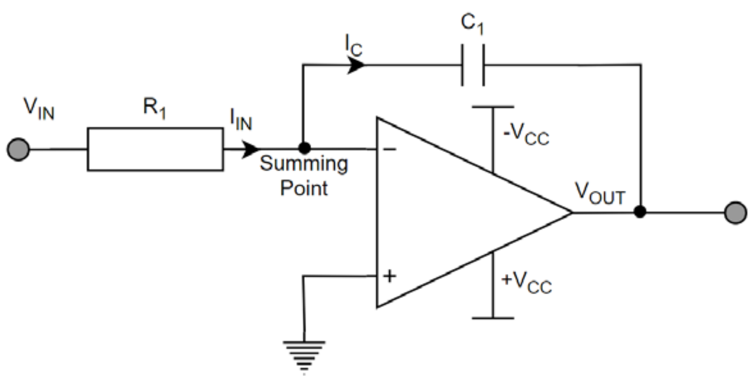


Fig.1.12: Integrator

We know that the current flowing into the summing point can be given as:

$$I_{IN} = \frac{V_{IN}}{R_1}$$

And that the current flowing through the capacitor is given as:

$$I_C = -C_1\frac{dV_{OUT}}{dt} = -C_1\frac{dQ}{C_1 dt} = -\frac{dQ}{dt}$$

Assuming no current flows into the inverting terminal (ideal Op-Amp – infinite resistance) we can once again use Kirchhoff's current law.

$$I_{IN} = I_C = \frac{V_{IN}}{R_1} = -\frac{dV_{OUT} \cdot C}{dt}$$

Rearranging this gives the Op-Amp Integrator function calculated as Eq.1.8:

$$V_{OUT} = -\frac{1}{R_1 C_1}\int_0^t V_{IN}\,dt \quad \text{(Eq.1.8)}$$

By changing the resistance or capacitance in the circuit, it is possible to change the gradient of the slope.

1.4.4 Differentiator

The differentiator is similar to the integrator circuit, however, the input to the summing point is now the capacitor, with a feedback resistor, a circuit diagram of which can be seen in Fig.1.13. The differentiator works more effectively at low frequencies, but this does produce a low voltage gain but if the frequency is too high, then the circuit is unstable and will oscillate. It is also worth noting that the differentiator is very susceptible to noise and distortion. Kirchhoff's current law gives the summing point of the currents as:

$$I_{IN} = I_F, \qquad I_f = -\frac{V_{OUT}}{R_1}$$

The charge on the capacitor is also given as:

$$Q = C_1 \cdot V_{IN}$$

The charge rate of the capacitor is:

$$\frac{dQ}{dt} = C\frac{dV_{IN}}{dt}$$

And since $\frac{dQ}{dt} = I_{IN}$ we can then state:

$$-\frac{V_{OUT}}{R_F} = C\frac{dV_{IN}}{dt}$$

$$V_{OUT} = -R_F C\frac{dV_{IN}}{dt} \qquad \text{(Eq1.9)}$$

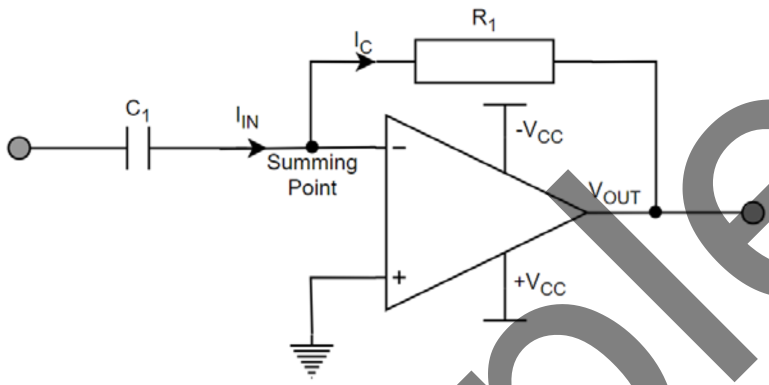


Fig.1.13: Differentiator

1.4.5 Schmitt Trigger

Schmitt Triggers are used to convert irregular input signals into much simpler square waves, a circuit diagram can be seen in Fig.1.14. The resistor R_3 is determined by the parallel resistance of R_1 and R_2. The circuit provides regenerative feedback in order to swing the output voltage to its positive saturation level when the input reaches a threshold negative level. Conversely, the circuit provides regenerative feedback in order to swing the output voltage to its negative saturation level when the input reaches a threshold positive level.

In the case of Fig.1.14, the value of R_3 is:

$$\frac{1}{R_3} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{1 \cdot 10^3} + \frac{1}{10 \cdot 10^3}$$

$$\frac{1}{R_3} = \frac{11}{10 \cdot 10^3}$$

$$R_3 = 909\Omega$$

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