Newcomers' Notebook

Simple explanation without complex mathematics

The Ins and Outs of op-amps

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The operational amplifier – or op-amp – is one of the most versatile electronic devices available. Applications using op-amps are widespread in both the analogue and digital arenas.

Invention of the vacuum tube op-amp is attributed to Karl Dale Swartzel Jr (1907 – 1998) when he was working on analogue computer applications in 1941 while at Bell Laboratories in the US.

Looking at the op-amp as a black box, there are usually five connections. The symbol for the op-amp is a sideways triangle, as in **Figure 1**, which shows two inputs, an output, and two power supply connections. In some drawings, the power connections are not shown, but implied.

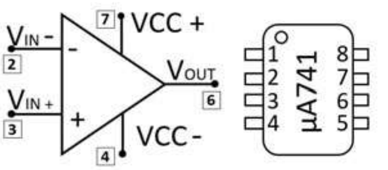

Figure 1. The general op-amp symbol at left highlights the two inputs – inverting [–] and non-inverting [+], plus the output and supply connections. The package outline of the widely-used uA741 op-amp is at right.

Offset

Unavoidable mismatches in op-amp internal circuitry can cause the device to output a signal when there is no input signal.

These mismatches can be compensated as per the datasheet for the op-amp in use, usually by applying an offset voltage to pins identified as "Offset N1" and/or "Offset N2". Guidance is often given in product application notes from the manufacturer.

Configurations

Open Loop – In open loop configuration (that is, with no feedback), an op-amps gain can be so great it is not effective as an analogue amplifier. This configuration is ideal for using an op-amp as a comparator (comparing voltages at the inputs) or a switch.

Closed Loop – The closed loop amplifier has feedback applied from the output to the input. The feedback components control the gain and frequency response of the amplifier.

Ideal characteristics

Open Loop Gain (Avol) – The ideal op-amp has high gain of between 20,000 and 200,000. Feedback is applied to control the gain.

Input resistance (r_i) – The input resistance is the ratio of input voltage to input current and is assumed to be infinite (i.e, no current flows at the input when a voltage is applied).

Output resistance (r_0) – The output resistance of the ideal operational amplifier is assumed to be zero; in reality, it is generally in the 100 ohms to 2000 ohms range.

Bandwidth (BW) – An ideal op-amp has infinite frequency response from DC to daylight, so it said to have infinite bandwidth! In real op-amps, the bandwidth is limited by the Gain-Bandwidth product (GBP), which is that frequency where its gain becomes one.

Common Mode Rejection Ratio (CMRR) – CMRR is the ability of the op-amp to reject the same signal on both inputs. This is important for the attenuation of noise common to both inputs.

Offset Voltage (V_{I0}) – The ideal op-amp's output is zero when the voltage difference between the inverting and the non-inverting inputs is zero. Real op-amps have some (small) amount of output offset voltage.

These ideal characteristics can be summarized by the two very important Golden Rules:

1. In a closed loop configuration, the output drives the V_{IN}+ and V_{IN}– to be equal.
2. The inputs draw no current.

A 'typical' op-amp

A very common op-amp is the uA741 (Figure 1). Here are a few interesting figures from the uA741 data sheet that make it a versatile device.

- V_{CC+} Supply maximum +15 V
- V_{CC-} Supply maximum –15 V
- Vom Output voltage swing, typically +/– 14 V
- I_{CC} No load supply current 3.3 mA
- T_A Operating free-air temp. max. 70 deg.C
- CMRR Typically 90 dB
- r_i Input resistance, typically 2 Mohms
- r_o Output resistance, typically 75 ohms

Basic op-amp circuits

There are many circuits using an op-amp as the primary component. I have selected 10 types to provide examples.

1. The *voltage follower*, also known as a unity gain amplifier, buffer amplifier, or isolation amplifier. This circuit is used as a buffer as it draws very little current because of the high input impedance of the amplifier that eliminates loading effects on the preceding input circuit. In **Figure 2**, the op-amp has a gain of one (1) so the output is the same as the input. Tip: Review the Golden Rules.

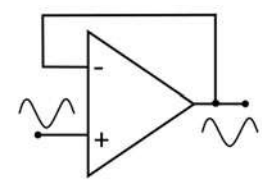

Figure 2. The voltage follower.

2. The *inverting amplifier* changes the signal phase by 180 degrees. In **Figure 3**, the gain of the amplifier is determined by the ratio of R2 to R1.

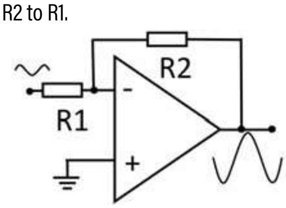

Figure 3. The inverting amplifier.

3. The *non-inverting amplifier*, **Figure 4**, is used where the input and output need to be in phase. Again, the gain of the amplifier is determined by the ratio of R2 to R1 (but there's a formula involved!).

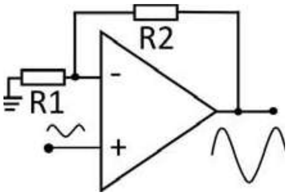

Figure 4. The non-Inverting amplifier.

4. The *non-inverting summing amplifier* is used to combine the voltages present on two or more inputs into a single output voltage, as in Figure 5. As it is non-inverting, the output will be in phase with the input. The gain of the circuit is set by the ratio of R2 to R1 in a formula.

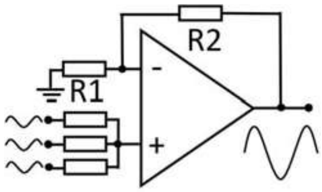

Figure 5. The non-inverting summing amplifier.

5. The *differential amplifier* is a circuit that amplifies the difference between two input voltages, but suppresses any voltage common to the two inputs. The **Figure 6** circuit has two inputs – the output is proportional to the difference between the two voltages.

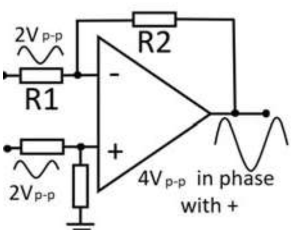

Figure 6. The differential amplifier.

6. The *integrator* op-amp performs integration with respect to time. In **Figure 7**, the output is proportional to the input voltage integrated over time governed by the values of R1 and C1.

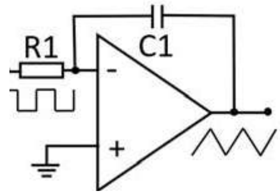

Figure 7. The integrator.

7. The *differentiator* is designed so that the output of the circuit is proportional to the rate of change to the input. In **Figure 8**, The rate of change is governed by the values of C1 and R1.

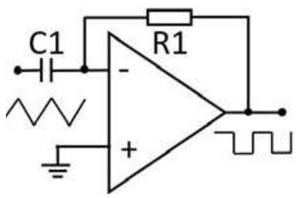

Figure 8. The differentiator.

8. The *high-pass filter* circuit in **Figure 9** is a unity gain amplifier passing the frequencies higher than that determined by the values of R1 and C1. This design frequency is known as "the break point" or cutoff frequency.

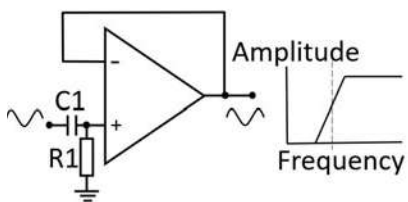

Figure 9. The general high-pass filter circuit.

9. The *low-pass filter* circuit in **Figure 10** is a unity gain amplifier passing the frequencies lower than "the break point" as determined by the values of R1 and C1.

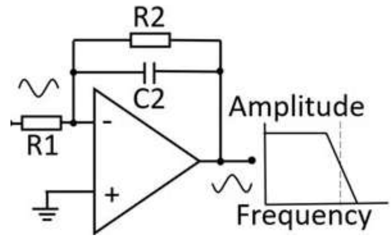

Figure 10. The general low-pass filter circuit.

10. The band-pass filter of **Figure 11** is a unity gain amplifier with two break point frequencies, one high and one lower. The values of R1 and C1 determine the high-pass cutoff while the values of R2 and C2 determine the low-pass cutoff.

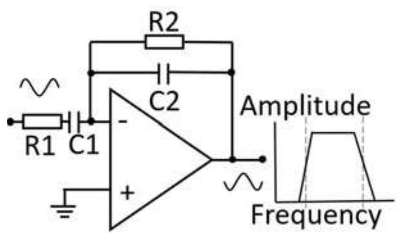

Figure 11. The general circuit of a band-pass filter.

If you have a topic you would like to nominate to be covered in a future instalment of Newcomers' Notebook, email Jules at jp.bqt@bigpond.net.au.

Have fun and stay safe.

Error last issue: Figure 2, p47, for 50 dB, the Power value should be 100,000.