Equipment usage note

Integrating amplifier

June 19, 2023

Op Amps and the Integrating amplifier

Summary

An integrating amplifier is an example application of the Operational Amplifier (Op Amp), one of the most versatile components for constructing analogue circuits. It is therefore instructive to know the conceptual and practical bases for op amps, and look at their application to signal processing.

Common pitfalls

Common issues encountered whilst using the device:

- **The measured output voltage is** $\pm 15\,\mathrm{V}$
  - Discharge the capacitor (reset the voltage to zero) by hitting the `Reset` button
  - If the voltage increases (decreases) rapidly to $\pm 15\,\mathrm{V}$, then the offset will need to be adjusted. Continue to reset the device and change the offset until the rate of increase (decrease) slows, and with careful adjustment can be completely removed
- **The measured output voltage does not increase or decrease, even with a large offset**
  - The grounding is not correct: ensure that one of the inputs is connected to ground

In all cases of troubleshooting, the recipe outlined below for configuring the oscilloscope should be followed in order to obtain a high-quality measurement.

The device

The Op Amp is ubiquitous in analogue circuits due in large part to being able to be tune the amplifier characteristics using *external* components. In practice, this means the things one cares about when building an amplifier such as gain, impedance, and bandwidth can be well controlled with minimal dependence on the amplifier properties. The device traces its origin to analogue computers, where they typically performed mathematical operations, hence the name, and why they are commonplace in physics laboratories.

How does it function?

Like many electronic components, the details of how they actually work are surprisingly complex and are marvellous examples of clever electrical engineering, At their heart, they are essentially collections of transistors, the inner workings of which are saved for any introductory solid-state physics course. For our purposes, we can consider an Op Amp a device which takes a difference between input terminals (V_+ and V_-)and provides an output voltage which is given by

$$V_{out} = A_{OL}(V_+ - V_-) \tag{1}$$

where A_{OL} is the *open-loop* gain, as compared to the *closed-loop* gain as we shall see below. Op Amps are typically treated as *ideal* devices, meaning that they have well-defined and well-behaved characteristics. These include:

- Infinite open-loop gain
- Infinite bandwidth
- Infinite input impedance
- Zero output impedance
- Zero noise

which are obviously not physical, but for most intents and purposes, they suffice to produce accurate models of amplification. Importantly, they give rise to the *Golden Rules* of Op Amps:

1. In a **closed loop** the output does whatever is necessary to make the voltage difference between the inputs zero
2. The inputs draw zero current

which are key to understanding the functioning of various Op Amp circuit designs. It is worth noting that we can make minor modifications to the model of an Op Amp to increase the realism, which are depicted in a cartoon circuit shown in figure 1. The notable differences from the ideal case are the inclusion of both input and output impedance, along with a finite gain of A_{OL}; however, for analysis of any circuit, the golden rules should still be followed.

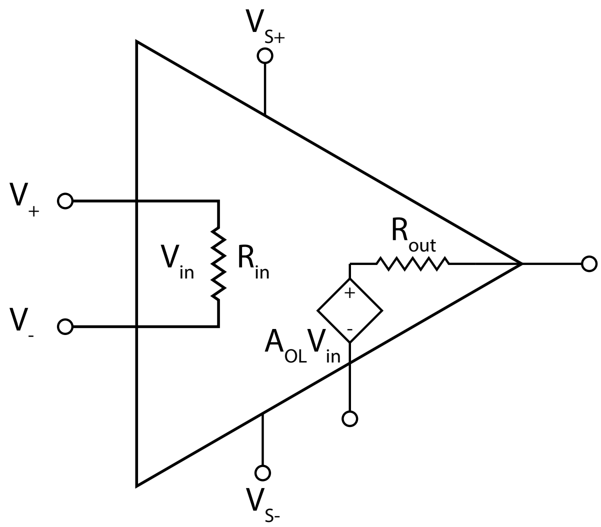

Figure 1: A cartoon schematic of an operational amplifier

If one operates and Op Amp in an open-loop configuration, the typical values for A_{OL} are 10^5 or larger, which will result commonly result in distortion of the input signal, and variability of circuit performance due to variation of A_{OL} between chips. Consequently, Op Amps are most commonly used in a *closed-loop* configuration, whereby a portion of the output voltage is fed back to the input. The result of this is a dramatic decrease in the gain of the amplifier, but with a dramatic increase in predictability of the amplification. Figure 2 shows an Op Amp in a closed-loop configuration, with negative feedback used to tame the gain of the device, and importantly, have the gain properties of the circuit determined by the external components.

To analyse the circuit shown in figure 2, we use the golden rules of Op Amps. If the amplifier acts to ensure the input potential is zero, at the inverting $(-)$ input we can say the voltage will be V_{in} and thus

$$I = \frac{V_{in}}{R_g}. \tag{2}$$

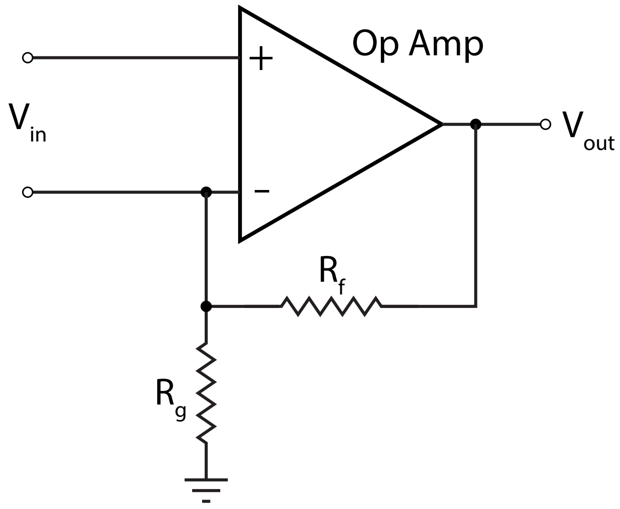

Figure 2: An closed-loop configuration of an Op Amp producing a non-inverting amplifier (negative feedback)

At the lower node, we use Kirchhoff's law, which states that the sum of currents at a node is zero, to infer that the same current I must flow through the resistor R_f. We then have

$$\begin{aligned} V_{out} &= V_{in} + IR_f \\ &= V_in + \frac{V_{in}}{R_g} R_f \\ &= V_in \left(1 + \frac{R_f}{R_g}\right) \end{aligned}$$

from which we can identify the *closed-loop* gain $A_{CL} = 1 + R_f/R_g$. Our gain is thus independent of the Op Amp, which simply exists in the circuit to mediate this process by abiding by the golden rules. By using more elaborate configurations of resistors, one can construct more elaborate amplifiers, for example a differential amplifier, or one could include reactive components to accomplish other tasks, such as integrating, and figure 3 shows such a configuration.

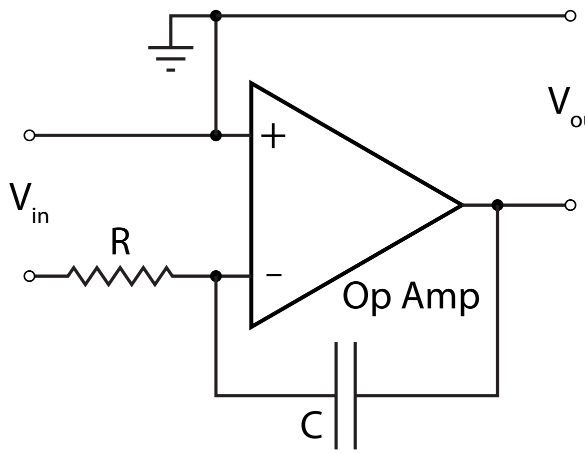

Figure 3: A closed-loop Op Amp configuration for an inverting amplifier

Exercise 1

Apply the golden rules of Op Amps to show the amplifier shown in figure 3 is an integrator, and find the closed-loop gain for the system.

How does one drive it?

The particular implementation of integrating amplifier that you have will depend on the experiment that you are undertaking, but common to all integrating amplifiers that you will find at UTAS is the LM301AN Op Amp chip at the heart of the amplifier, along with two adjustment controls. These controls serve two proposes, namely to restart the integration, and to ensure we remove any offset on our signal. To reset the integrator, we simply need to discharge the capacitor, which can be done manually by shorting the capacitor, or much more conveniently with the button labelled `Reset`. The offset is controlled using a trimmer potentiometer, which allows a voltage to be added or subtracted from the input voltage to ensure that the output voltage is the integral of the input signal and not some systematic background value. Necessarily, this offset adjustment is sensitive, so patience when adjusting will be required.

1. Short the input signal, and ensure to properly ground the input
2. Power on the $\pm 15\,\mathrm{V}$ required to operate the amplifier
3. Monitor the output voltage, it is likely that the voltage will rush towards either $+15\,\mathrm{V}$ or $-15\,\mathrm{V}$ and the remain at this value. Use the reset button to restart the integration; however, if the value does anything other than remain at zero, this indicates that the offset is incorrectly set
4. Adjust the offset, noting that an larger offset from zero will result in hitting $\pm 15\,\mathrm{V}$ more quickly, so if this behaviour is observed, reverse direction. With a combination of resetting and fine adjustments, it should be possible to get a mostly constant integration voltage, at which point the system is well adjusted.
5. If you are struggling to make sense of the offset, adjust the offset such that when the integrator is reset, the voltage *decreases*. Verify the direction of offset by continuing in the direction which causes the voltage to decrease more quickly. Know you know that to make the voltage increase, you must change the offset in the other direction. Continue to do so until you witness the voltage *increase*. By the intermediate value theorem, you have just passed the optimum position of the offset: if the voltage was decreasing, and now is increasing, there must be an offset where it remains the same.
6. If you cannot get your system to rail to either $\pm 15\,\mathrm{V}$ with offset adjustment, it is likely the system is wired up incorrectly

Additional resources

- POLUS is a resource for all things related to experimental physics at UTAS