EEE118: Electronic Devices and Circuits

Lecture XVII

James E. Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

Review

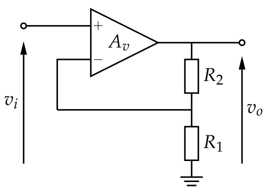
- Looked (again) at Feedback for signals and for DC (quiescent) conditions in a one transistor amplifier with and without emitter decoupling
- The situation where $R_L = R_E$ is called a "phase splitter".
- Looked at the small signal equivalent circuit of a BJT in terms of a one transistor amplifier
- Gave an example of a performance evaluation
- Noted that the value of the small signal circuit is to show which device and circuit affect the gain, not to give a numerical value (although this is possible.)
- Introduced the idea of an "analogue building block" - opamp
- presented the opamp as an implementation of a classical feedback system.
- Derived the opamp equation and presented a circuit symbol for an opamp.

Outline

Opamp Circuits - Non Inverting

The most common opamp circuits are the "non-inverting amplifier" and the "inverting amplifier".

It is usual to assume initially that $A_v \to \infty$. This means that the circuit behaviour is completely controlled by the feedback. If $A_v = \infty$, for finite v_o then $v^+ \approx v^-$ and this makes the calculation quite straightforward.



$$v^- = v_o \frac{R_1}{R_1 + R_2} \quad (1)$$

$$v^+ = v_i \text{ and } v^+ = v^- = v_i \quad (2)$$

$$v_i = v_o \frac{R_1}{R_1 + R_2} \quad (3)$$

$$\frac{v_o}{v_i} = \frac{R_1 + R_2}{R_1} \quad (4)$$

Opamp Circuits - Inverting

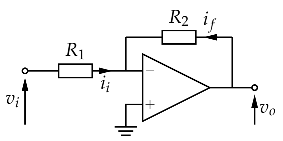
In the inverting amplifier v^+ is grounded and v_i is applied to R_1. If $A_v = \infty$, $v^+ = v^-$ and since v^+ is connected to ground v^- must be very close to ground. It is often called a virtual earth. The potential is always close to zero but the node is *not* actually connected to zero. To obtain the gain sum currents at the v^- node.

$$i_i + i_f = 0 \quad (5)$$

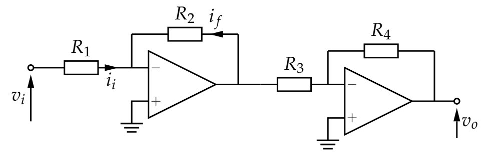
$$\frac{v_i - v^-}{R_1} + \frac{v_o - v^-}{R_2} = 0 \quad (6)$$

$$v^- = 0 \text{ so } \frac{v_i}{R_1} + \frac{v_o}{R_2} = 0 \quad (7)$$

$$\frac{v_o}{v_i} = -\frac{R_2}{R_1} \quad (8)$$



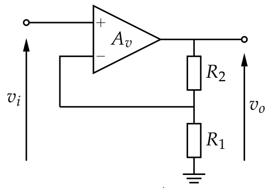
- Notice the "-" sign in the inverting gain formula. This means that the signal is *inverted* i.e. phase shifted by 180° as well as being amplified.
- Two inverting amplifiers in series would give rise to an overall non-inverting amplifier. The first stage would invert the signal and the second would invert it back to its original phase.



Effects of Finite Gain

Occasionally it is necessary to consider the effect of finite A_v on the overall gain of the circuit. When considering the effects of finite gain the approximation $v^+ \approx v^-$ does not hold.

As before, using potential division at the output,



$$v^- = v_o \frac{R_1}{R_1 + R_2} \quad (9)$$

$$v^+ = v_i \quad (10)$$

But now the opamp equation must be used to relate v^+, v^- and v_o,

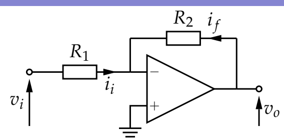
$$v_o = A_v \left(v^+ - v^-\right) = A_v \left(v_i - v_o \frac{R_1}{R_1 + R_2}\right) \quad (11)$$

$$\text{or, } v_o \left[\frac{1}{A_v} + \frac{R_1}{R_1 + R_2}\right] = v_i \quad (12)$$

$$\text{or, } \frac{v_o}{v_i} = \frac{1}{\frac{1}{A_v} + \frac{R_1}{R_1 + R_2}} \quad (13)$$

- Note if $A_v \to \infty$, $\frac{1}{A_v}$ becomes very small and (13) becomes (4).
- A_v is equivalent to G in the classical feedback system.
- It is between several thousand and several hundred thousand in most opamps.
- A_v is actually frequency dependent, but the frequency dependence of A_v is not covered in this course.

For the inverting case start as before, by summing currents at the v^- node,



$$i_i + i_f = 0 \text{ or } \frac{v_i - v^-}{R_1} + \frac{v_o - v^-}{R_2} = 0 \quad (14)$$

which can be transposed to yield,

$$v^- = v_i \frac{R_2}{R_1 + R_2} + v_o \frac{R_1}{R_1 + R_2} \quad (15)$$

$$\text{and } v^+ = 0 \quad (16)$$

Using the opamp equation

$$v_o = A_v \left(0 - \left[v_i \frac{R_2}{R_1 + R_2} + v_o \frac{R_1}{R_1 + R_2}\right]\right) \quad (17)$$

$$\text{or } v_o \left[\frac{1}{A_v} + \frac{R_1}{R_1 + R_2}\right] = -v_i \frac{R_2}{R_1 + R_2} \quad (18)$$

$$\text{or } \frac{v_o}{v_i} = \frac{-\frac{R_2}{R_1 + R_2}}{\frac{1}{A_v} + \frac{R_1}{R_1 + R_2}} \quad (19)$$

If $A_v \to \infty$, $\frac{v_o}{v_i}$ reduces to (8).

- Frequency dependent amplifiers (filters) can be produced by using frequency dependent passive components (inductors and, more usually, capacitors) in place of the resistors.
- R_1 and R_2 can become Z_1 and Z_2 and may be arbitrarily complex passive circuits.
- Particular arrangements of resistors and capacitors in opamp circuits can be used to produce circuits which perform mathematical functions such as integration and differentiation.

Input Resistance

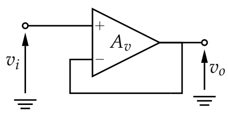
- The input to the non inverting circuit goes directly to the opamp so the circuit input resistance is the same as the opamp - very large ($\sim 10^9$).
- The inverting circuit is slightly different. Taking the $A_v \to \infty$ case, an input current, i_i, of $\frac{v_i}{R_1}$ flows from the source.
- Input resistance is the ratio of the applied signal voltage to the current drawn, i.e. $\frac{v_i}{i_i} = R_1$.
- This is typically a few kΩ which makes inverting amplifiers unsuitable as amplifiers of signals derived from sources with a large thévenin resistance.

Unity Gain Buffer

The unity gain buffer is a special case of the non inverting amplifier, in which $R_2 = 0$ and $R_1 = \infty$. Here $v^- = v_o$ so the opamp equation becomes,

$$v_o = A_v \left(v^+ - v^-\right) = A_v \left(v_i - v_o\right) \quad (20)$$

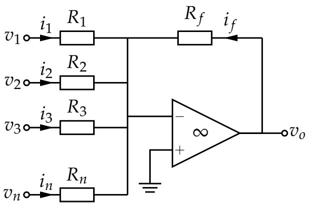
$$\text{or } \frac{v_o}{v_i} = \frac{1}{\frac{1}{A_v} + 1} = \frac{A_v}{1 + A_v} \quad (21)$$



If A_v is large, $\frac{v_o}{v_i}$ is very close to unity. This circuit is used to isolate high impedance sources from low impedance loads; i.e. it has a high power gain.

Summing Amplifier

Assume $A_v \to \infty$ so $v^- \to$ virtual earth (i.e. 0 V)



$$i_f + i_1 + i_2 + i_3 + i_n = 0$$

$$\frac{v_o}{R_f} + \frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3} + \frac{v_n}{R_n} = 0$$

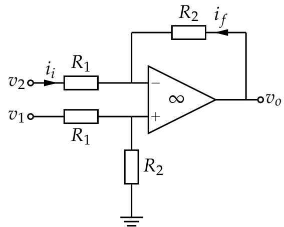
or,

$$v_o = -\left[v_1\frac{R_f}{R_1} + v_2\frac{R_f}{R_2} + v_3\frac{R_f}{R_3} + v_n\frac{R_f}{R_n}\right]$$

Many audio "mixers" use this circuit.

Subtracting Amplifier

Several avenues of solution are available for this circuit. Assume $A_v = \infty$ and so $v^+ = v^-$.



One approach is to work out v^+ and v^- and then equate them to get v_o in terms of v_1 and v_2. Summing currents at the v^- node,

$$i_i + i_f = 0 \text{ or } \frac{v_2 - v^-}{R_1} + \frac{v_o - v^-}{R_2} = 0 \qquad (22)$$

This can be transposed to give,

$$v^- = v_2\frac{R_2}{R1 + R_2} + v_o\frac{R_1}{R_1 + R_2} \qquad (23)$$

v^+ is a potentially divided version of v_1

$$v^+ = v_1\frac{R_2}{R_1 + R_2} \qquad (24)$$

equating v^+ and v^-,

$$v_2\frac{R_2}{R_1 + R_2} + v_o\frac{R_1}{R_1 + R_2} = v_1\frac{R_2}{R_1 + R_2} \qquad (25)$$

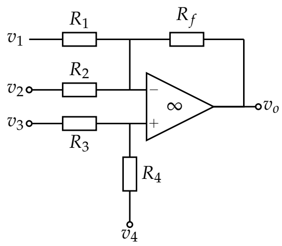
$$\text{or } v_o\frac{R_1}{R_1 + R_2} = v_1\frac{R_2}{R_1 + R_2} - v_2\frac{R_2}{R_1 + R_2} \qquad (26)$$

$$\text{or } v_o = \frac{R_2}{R_1}(v_1 - v_2) \qquad (27)$$

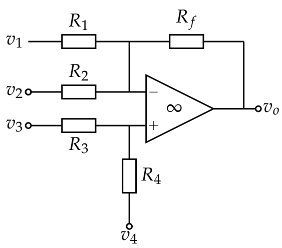
Note that the accuracy of the subtraction depends upon matching the the two R_1's and R_2's.

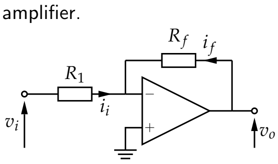
A General Multiple Input Circuit

The subtractor circuit can be generalised to allow more than two inputs. Such a circuit could be analysed by find v^+ and v^- and equating them, or by using the principle of superposition. Superposition has the advantage that at each stage the circuit is reduced to a much simpler single input circuit. For example,



Consider first the output due to v_1. v_2, v_3 and v_4 are grounded. The circuit becomes an inverting amplifier.





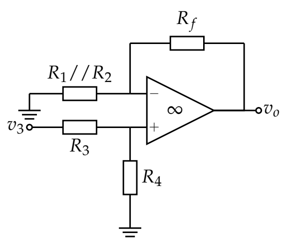
Since both v_3 and v_4 are zero v^+ is zero and v^- is a virtual earth. No current flows through R_2 so it has no effect on the circuit.

$$v_o|_{v_1} = v_1\left(\frac{-R_f}{R_1}\right) \qquad (28)$$

By changing the variable names the output voltage due to v_2 can be found,

$$v_o|_{v_2} = v_2\left(\frac{-R_f}{R_2}\right) \qquad (29)$$

The output due to v_3 leads to a more complex circuit however.



Here v_1 and v_2 are grounded so R_1 is effectively in parallel with R_2. v^+ is a potentially divided version of v_3. So,

$$\frac{v_o}{v^+} = \frac{R_f + R_1//R_2}{R_1//R_2} \qquad (30)$$

$$\frac{v_o}{v_3} = \frac{R_4}{R_3 + R_4} \qquad (31)$$

$$\therefore \frac{v_o}{v_3} = \frac{v_o}{v^+} \cdot \frac{v^+}{v_3} = \frac{R_4}{R_3 + R_4} \cdot \frac{R_f + R_1//R_2}{R_1//R_2} \quad (32)$$

$$\text{or } v_+|_{v_3} = v_3 \frac{R_4}{R_3 + R_4} \cdot \frac{R_f + R_1//R_2}{R_1//R_2} \quad (33)$$

By a similar argument,

$$v_o|_{v_4} = v_4 \frac{R_3}{R_3 + R_4} \cdot \frac{R_f + R_1//R_2}{R_1//R_2} \quad (34)$$

$$v_{o_{\text{total}}} = \frac{v_o}{v_1} + \frac{v_o}{v_2} + \frac{v_o}{v_3} + \frac{v_o}{v_4} \quad (35)$$

Note: if any of the inputs have both a DC and AC component, superposition allows them to be treated separately.

Homework 5

It should be possible to fully attempt the Homework 5 now. It is not due in, but, if you submit it and it is a good attempt and for some reason you do badly on the exam I will be more inclined to help you if I can than if you have made no meaningfull attempts at homework.

It should also be possible to fully attempt the Operational Amplifiers problem sheet.

Review

Considered circuit diagrams for a common set of opamp circuits and derived results for the output voltage due to one or more inputs:

- Non inverting amplifier with $A_v = \infty$
- Inverting amplifier with $A_v = \infty$
- Non inverting amplifier with $A_v \neq \infty$
- Inverting amplifier with $A_v \neq \infty$
- Unity gain buffer
- Multiple input circuits
  - Summing Amplifier
  - Difference Amplifier (Subtractor)
- General multiple input opamp circuit

http://hercules.shef.ac.uk/eee/teach/resources/eee118/eee118.html