

EEE118: Electronic Devices and Circuits

Lecture XVII

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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.

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Outline

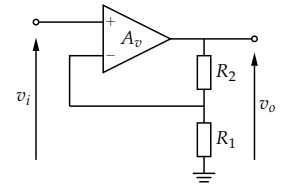
- Opamp Circuits
 - $A_v \rightarrow \infty$: Non-Inverting
 - $A_v \rightarrow \infty$: Inverting
 - $A_v \neq \infty$ Non-Inverting
 - $A_v \neq \infty$ Inverting
- Special Case: Unity Gain Buffer
- Circuits with Multiple Inputs
 - Summing Amplifier
 - Subtractor or Difference Amplifier
- A General Multiple Input Circuit
- Homework 5
- Review
- Bear

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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 $A_v \rightarrow \infty$. 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.



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

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

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

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

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Opamp Circuits - Inverting

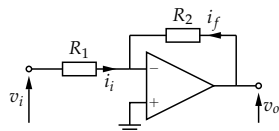
In the inverting amplifier v^+ is grounded and v_i is applied to R_1 . If $A_v = \infty$, $v^+ = v^-$ and since v^+ is connected to ground v^- must be very close to ground. It is often called a **virtual earth**. The potential is always close to zero but the node is *not* actually connected to zero.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

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

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

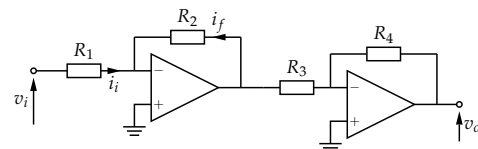
$$v^- = 0 \text{ so } \frac{v_i}{R_1} + \frac{v_o}{R_2} = 0 \quad (7)$$

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



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- 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.



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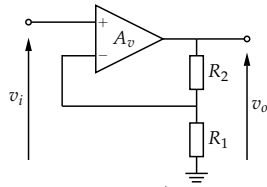
Effects of Finite Gain

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⁺ ≈ 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,

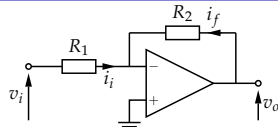
$$v_o = A_v (v^+ - v^-) = A_v \left(v_i - v_o \frac{R_1}{R_1 + R_2} \right) \quad (11)$$

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

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

- Note if A_v → ∞, 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 → ∞, 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.
- R₁ and R₂ can become Z₁ and Z₂ 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

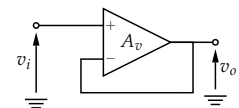
- The input to the non inverting circuit goes directly to the opamp so the circuit input resistance is the same as the opamp - very large (~ 10⁹).
- The inverting circuit is slightly different. Taking the A_v → ∞ case, an input current, i_i, of v_i/R₁ flows from the source.
- Input resistance is the ratio of the applied signal voltage to the current drawn, i.e. v_i/i_i = R₁.
- 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 R₂ = 0 and R₁ = ∞. Here v⁻ = v_o so the opamp equation becomes,

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

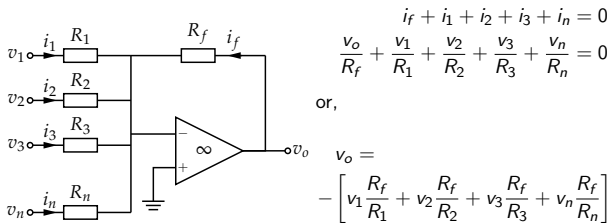
$$\text{or } \frac{v_o}{v_i} = \frac{1}{\frac{1}{A_v} + 1} = \frac{A_v}{1 + A_v} \quad (21)$$



If A_v is large, 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 $A_v \rightarrow \infty$ so $v^- \rightarrow$ virtual earth (i.e. 0 V)



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

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

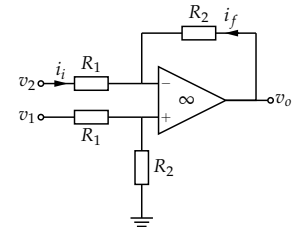
or,

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

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,

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

This can be transposed to give,

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

v^+ is a potentially divided version of v_1

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

equating v^+ and v^- ,

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

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

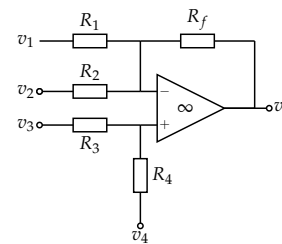
$$\text{or } v_o = \frac{R_2}{R_1} (v_1 - v_2) \quad (27)$$

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

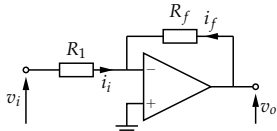
A General Multiple Input Circuit

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.



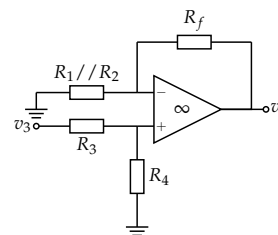
Since both v_3 and v_4 are zero v^+ is zero and v^- is a virtual earth. No current flows through R_2 so it has no effect on the circuit.

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

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

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

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,

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

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

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

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

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 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

