EE285 - Electronics 1

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Tutorial: General Amplifiers and Operational Amplifiers

These questions are to help you to check yourself whether you understood the concepts.[1]

1 Amplifiers

1. What is the difference between small-signal amplifiers and large-signal amplifiers?
2. Explain the difference between the linear range and the saturation region of a simple voltage amplifier system.
3. A simple voltage amplifier system is shown in Figure 1.
   a) Derive an expression for the overall voltage gain v_o/v_s for the complete amplifier system.
   b) Derive expressions for the input resistance and output resistance of the amplifier.
      i. What are the ideal values you would like to have for them?
      ii. What benefits would those ideal values result in the system?

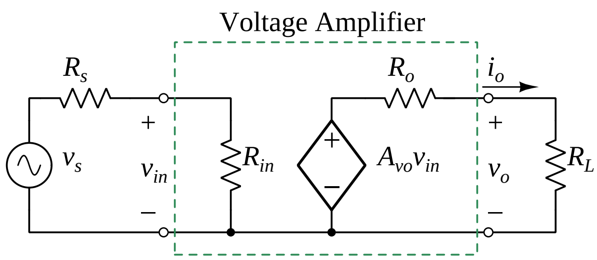

Figure 1: A simple voltage amplifier system

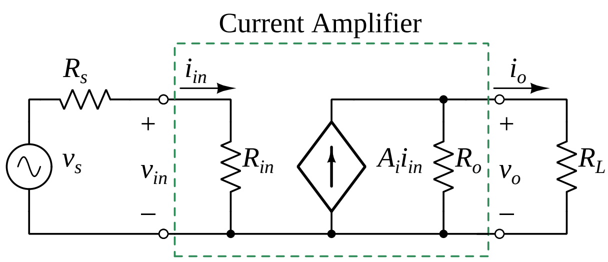

Figure 2: A simple current amplifier system

4. A simple current amplifier system is shown in Figure 2.
   a) Derive an expression for the overall current gain i_o/i_s for the complete amplifier system.
   b) Derive an expression for the overall voltage gain v_o/v_s for the complete amplifier system.
5. Consider the voltage amplifier system shown in Figure 1. The system has the following parameters: $v_s = 0.2\,sin(2\pi * 5000t)$ V, $R_s = 1$ kΩ, $R_o = 5$ Ω, $A_{vo} = 2$
   a) The signal source v_s can support only up to an output power of 5 µW. Calculate the minimum input impedance that the amplifier can have so that v_s is operating in the rated conditions.
      i. For the above calculated R_{in}, calculate the load current if $R_L$corresponds to an 8-Ω speaker.
      ii. Calculate the power dissipated in the load resistor.
6. Explain what is meant by the frequency response of an amplifier.

[1]Note: The tutorial is still in draft version. So there could be some errors: however, the structure of the questions should give you an idea about what you are expected to know. Please let me know if you find any errors by emailing me at nirmana@ee.pdn.ac.lk.

2 Operational Amplifiers

2.1 Concepts and Basic Circuit Analysis

1. The ideal op amp is a good enough approximation for most cases.
   a) Draw the basic differential amplifier model which incorporates a source and load.
   b) With necessary assumptions, obtain the ideal op amp model.
   c) Explain the two Golden Rules in ideal op amp analysis with a suitable circuit diagram.
   d) List important properties of ideal op amps.
2. An **Op Amp based Standard Inverting Amplifier** configuration is shown in Figure **??**. Assume ideal op amp operation.

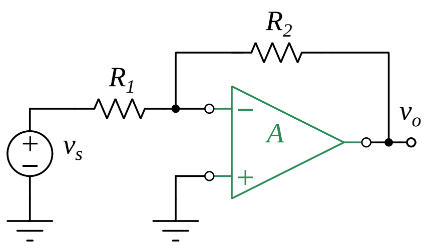

Figure 3: The op amp based standard Inverting Amplifier configuration

   a) What is the difference between the open-loop gain, A, and the closed-loop gain, A_v.
   b) Derive an expression for the closed-loop gain, A_v, of the amplifier configuration.
   c) With the aid of the derived result, state the important observations that can be observed in this amplifier system.
   d) What constitute the feedback branch?
   e) What kind of feedback is employed here?
   f) *Extra Work: Find the difference between negative and positive feedback and their corresponding effects and applications.*
   g) Derive results for input and output resistance of this ideal amplifier configuration.
3. An **Op Amp based Standard Non-Inverting Amplifier** configuration is shown in Figure 4. Assume an ideal op amp.

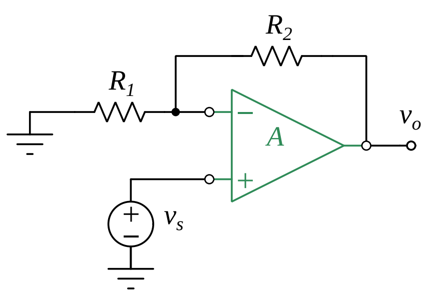

Figure 4: The op amp based standard Non-Inverting Amplifier configuration

   a) What topological differences can be observed between the two amplifier configurations shown in Figure 3 and Figure 4.
   b) Derive an expression for the closed-loop gain, A_v, for the non-inverting the amplifier configuration shown in Figure 4.
   c) What kind of feedback is employed here?
   d) Derive results for input and output resistance of this ideal amplifier configuration.

4. An op amp based **Weighted Summer** circuit is shown in Figure 5 . Derive an expression for the output voltage in terms of the input voltages and the resistances in the circuit.

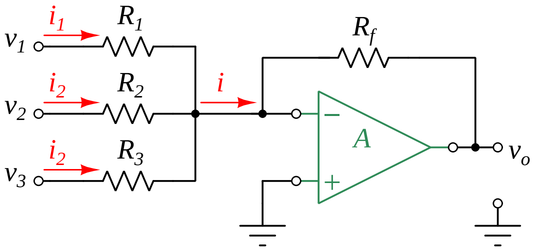

Figure 5: Weighted Summer circuit

5. An op amp based circuit with negative feedback is shown in Figure 6. Derive an expression for the overall gain v_o/v_s of the system. Clearly state your assumptions.

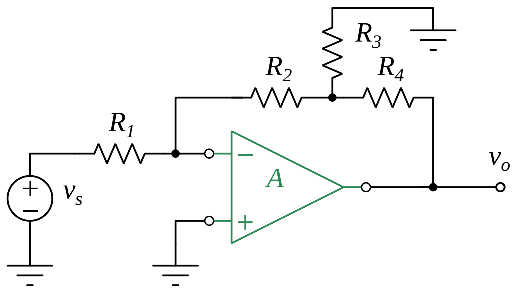

Figure 6: Op amp based circuit 1 for analysis

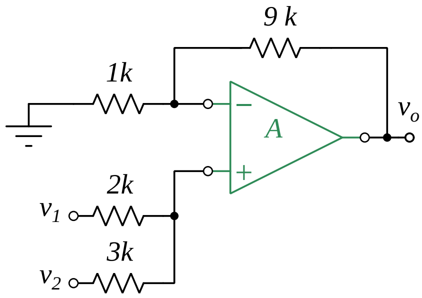

Figure 7: op amp based circuit 2 for analysis

6. An op amp based circuit with negative feedback is shown in Figure 7. Derive an expression for the output voltage. Clearly state your assumptions.

2.2 Practical Operation of Circuits Employing Ideal Op Amps

Here we consider op amp based circuits where the op amp is assumed to be ideal: i.e. it satisfies the two Golden Rules. However, please read each question carefully before you venture forth.

1. Consider an op amp based standard inverting amplifier unit. Assume an ideal op amp.
   a) Design the system to have a gain of 20 dB and an input resistance of $R_{in} = 25$ kΩ.
   b) The input source signal is given by $v_s = 250\,sin(\omega t)$ mV. Find the corresponding output signal. Assume zero source resistance.
   c) Calculate the peak value of the source current.
   d) Calculate the average power dissipated in the input resistance R_{in}.
   e) Calculate the maximum power dissipated in the input resistance R_{in}.
   f) *Extra work: What is meant by power rating of standard resistors? Find out commercially available power ratings and choose a suitable range for R_{in}.*

2. For standard inverting and non-inverting amplifier configurations with a load resistance R_L, show the following:
   a) The equivalent resistance seen by the output terminal is $R_{eq} = R_L \,/\!/\, R_2$ for the inverting case
   b) The equivalent resistance seen by the output terminal is $R_{eq} = R_L \,/\!/\, (R_1 + R_2)$ for the non-inverting case
   c) With the aid of above two results, comment on the op amp output current for the two configurations.

3. A standard non-inverting amplifier system has the following design parameters in usual notation. Assume ideal op amp operation for the calculations.

   $R_1 = 1.5\ \text{k}\Omega$, $R_2 = 18\ \text{k}\Omega$

   The source voltage is a dc voltage of 50 mV and there is no load connected at the output.

   a) Find the closed-loop voltage gain, A_v, of this amplifier.
   b) Calculate the output voltage, v_o.
   c) Calculate the output current, i_o. What is the relationship between the feedback current and the output current in this particular configuration.
   d) Calculate the average power dissipated in the feedback resistor R_2.

4. A standard non-inverting amplifier system with a load resistance is shown in Figure 8.

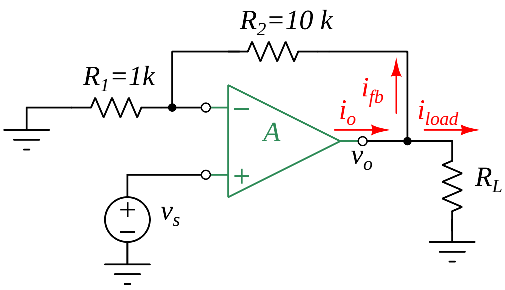

Figure 8: The standard op amp based Non-Inverting Amplifier configuration with a load resistance

   a) Assuming an ideal op amp, calculate the closed-loop gain of the amplifier system.
   b) If the input source signal is a perfect sinusoid with a magnitude of 100 mV and a frequency of 5 kHz.
      i. Find an expression for the output voltage, v_o, for the above system.
      ii. Write the relationship between i_o, i_{fb}, and i_{load}.
      iii. Find the corresponding output current, i_o if $R_L = 2.5\ \text{k}\Omega$. Also, find its RMS value.
      iv. Calculate the average power dissipated in the load R_L.

2.3 Operation of Practical Op Amp Circuits with Non-Idealities.

Here we consider op amp based circuits where the op amp is a real op amp with its practical limitations. However, depending upon the question, you can still use the two golden rules: therefore, you should be able to read the question and understand what kind of a scenario you are dealing with. ***Also, neglect the effects of input offset voltage and offset currents unless otherwise stated.***

1. Explain the effect of a finite value for the open-loop gain for a standard non-inverting amplifier system. Derive the closed-loop gain for an ideal non-inverting amplifier system using this result with the correct simplifications. Neglect the effect of frequency dependence of the open-loop gain.

2. For practical op amps, the open-loop gain is not only finite, but also frequency dependent: usually op amps are internally compensated so that they would have a Single Time Constant (STC) Low-Pass frequency response. This can be mathematically expressed as,

$$A = A(s) = \frac{A_0}{1 + \dfrac{s}{\omega_b}} \tag{1}$$

   where A_0 is the dc gain and $\omega_b = 2\pi f_b$ is the break frequency.

   a) Noting that for physical frequencies $s = j\omega$, and by deriving necessary mathematical results, plot the magnitude and phase plots of the open-loop gain A.
   b) Mark important parameters in the above plot.

c) op amp data-sheets state a parameter called the "Unity Gain Bandwidth", denoted by f_t Hz.

i. Explain the importance of this parameter.

ii. What is the relationship between $|A(j\omega)|$, the unity gain bandwidth and the actual operating frequency of the op amp?

iii. How does this help you to find the open-loop gain of a given op amp at difference frequencies?

d) With the aid of Equation (1), derive expressions for the closed-loop gain of standard inverting and non-inverting amplifier configurations. You may use the results you derived in question 1.

i. With the derived results, explain how a practical op amp based amplifier system would respond to different input signal frequencies.

3. An op amp (internally compensated) have a unity gain bandwidth of 3 MHz. Find its open-loop gain at $f = 50$ kHz. Express the value in dB scale as well. Assume that $f \gg f_b$.

4. An op amp (internally compensated) have an open-loop gain of 80 dB at $f = 50$ kHz. Assume that $f \gg f_b$.

a) Find the value of f_t.

b) Find the value of the dc-gain if $f_b = 10$ Hz.

5. An op amp (internally compensated) have a unity gain bandwidth of 2.5 MHz. The data-sheet also says it has a large-signal voltage gain of 200 V/mV.

a) Calculate the dc gain, A_0 of the op amp. Express the value in dB scale as well.

b) Calculate the break frequency (corner frequency), f_b in Hz.

c) Find the value of the open-loop gain of the op amp at $f = 5$ kHz and $f = 25$ kHz. State any assumption you made.

6. A standard non-inverting amplifier system has the following parameters:

$R_1 = 1\,\text{k}\Omega$, $R_2 = 19\,\text{k}\Omega$, op amp power supply of $+V_{CC}$ and $-V_{EE}$, an input source $v_s = V_s\, sin(\omega_0 t)$ V, and a load resistance R_L.

a) Draw the corresponding circuit diagram.

b) Calculate the closed-loop gain of the system. Assume that the op amp open-loop gain is large enough at ω_0 to neglect the effects of finite open-loop gain.

c) The data-sheet specifies the following parameters for the op amp.

- output short-circuit current: 25 mA
- output voltage swing: ± 14 V
- power consumption: 60 mW

i. For $V_s = 500$ mV, and no-load condition, calculate the output voltage and current.

ii. For $V_s = 500$ mV, and $R_L = 2$ kΩ, find the output voltage and plot the corresponding pattern. Also find the peak value of the output current.

iii. For $V_s = 800$ mV, and $R_L = 2$ kΩ, find the output voltage and plot the corresponding pattern. Also find the peak value of the output current.

iv. For $V_s = 250$ mV, find the minimum value of R_L that can be used without exceeding the recommended current ratings.

7. Consider the voltage follower circuit in Figure 9. The input voltage is given by $v_s = 2.5\, sin(2\pi \times 2000t)$ V and the op amp data sheet provides the following information:

- output short-circuit current: 20 mA
- output voltage swing: ± 10 V
- input resistance: 2 MΩ
- power consumption: 50 mW

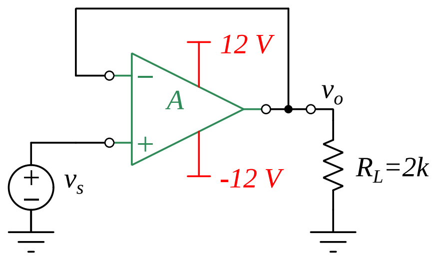

Figure 9: A voltage follower circuit

a) What is the maximum value the load current can have for proper op amp operation.

b) What is the power drawn from the signal source?

c) For $R_L = 5\ \mathrm{k}\Omega$;

  i. What is the dc power dissipation in the op amp?

  ii. Calculate the power consumed in the load?

  iii. Calculate the power drawn from the external dc supply.

  iv. Calculate the system efficiency.

8. An op amp used in a buffer configuration has the following limitations:
   - output voltage swing: ± 10 V
   - slew rate: 0.5 V/µs

   a) Calculate its full-power bandwidth.

   b) A triangular signal with a frequency of 100 kHz and a peak-peak value of ± 1 V is applied at the input.

     i. Can the op amp respond well enough? Explain your answer.

     ii. What is the maximum peak-to-peak value the input triangular signal can have at the same frequency that ensures full-amplitude output?

9. An op amp used in buffer configuration has the following limitations:
   - output voltage swing: ± 12 V
   - slew rate: 1 V/µs

   An input signal of $v_s = 0.5\, sin(2\pi \times 15000t)$ V is applied at the input (assume zero source resistance).

   a) Calculate the maximum rate of change of the input signal in V/µs.

   b) Is there any distortion at the output? Explain your answer.

10. Briefly explain the effects of input-offset voltage using a unity-gain buffer configuration (use the op amp model with input-offset voltage).

11. With the effect of input-offset voltage V_{OS}, derive an expression for the output voltage, v_O, using R_1, R_2, V_{OS} and the input source voltage v_s for inverting and non-inverting configurations.

    hint: *you may use the superposition to tackle this problem. Usually, we model the input offset voltage always at the non-inverting terminal. Then effect of that is always* $v_O = V_O = (1 + \frac{R_2}{R_1})V_{OS}$ *since its placed in non-inverting configuration: we name this as* v_{O1}. *Then the effect of input source voltage for inverting and non-inverting configurations can be separately derived assuming zero input-offset voltage: we name this as* v_{O2}. *Then using superposition, the output is equal to* $v_O = v_{O1} + v_{O2}$.

12. An op amps has the following parameters:
    - output voltage swing: ± 10 V
    - input offset-voltage: $+ 4$ mV

- dc voltage gain (A_0): 200 V/mV

Neglect the effects of offset currents for the following analysis.

a) What is the input differential voltage that should be applied across the two inputs of the op amp to have a zero output voltage?

b) Plot the transfer characteristics v_O vs v_{id} for this op amp, where v_O is the total output voltage.

13. An op amp based standard inverting amplifier configuration has $R_1 = 250$ kΩ and $R_2 = 5$ kΩ. The op amp has an input offset voltage $V_{OS} = 5$ mV and a output voltage swing of ±10 V. Neglect the effects of the input offset currents and any frequency dependencies of the open-loop gain.

    a) Find the output voltage at zero input source voltage ($v_s = 0$ V).

    b) If $v_s = V_s\,sin(2\pi \times 10000t)$, find the maximum value possible for V_s for the output to be not clipped.

    c) Draw the output voltage pattern for the above sinusoidal input.

14. Briefly explain the effects of input-offset current. What is input bias current?

15. A standard inverting amplifier configuration has a closed-loop gain of 100 (neglect the effect of frequency on the gain). The output voltage is +8.5 V with open inputs and +8.1 V with the input (the non-inverting input) grounded.

    a) Calculate the input bias current (I_B) of this op amp.

    b) Calculate the value of input-offset voltage for this op amp.

3 Non-Linear Applications of Op Amps

1. Explain the operation of a inverting integrator circuit built using an op amp. Draw the corresponding circuit diagram.

2. Explain the operation of the op amp differentiator circuit. Draw the corresponding circuit diagram.

3. Explain how an op amp comparator circuit can be used to compare two input signals. What is the nature of the output signal for comparator action?