Lecture 8 The Operational Amplifier
ECEL 301 ECE Laboratory I
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Preparation
- Read pp. 241-246, 250-254 in textbook
- Read through the week 8 experiment
- MATLAB commands to review
  - polyfit - curve fitting
  - xlsread - read data from Excel files
The Plan

- Introduce the OpAmp
- Derive the voltage gain
  - We can do this with KVL and KCL
    - Inverting amp
    - Non-inverting amp
- Discuss limitations
  - Offset voltage
  - Slew rate
- Describe the lab exercises
  - Distributing power supplies in PSpice

Background

- Why is this called an “operational” amplifier?
  - The device has this name because it can be used to perform mathematical operations. The OpAmp can be used in circuits which add, subtract, integrate or differentiate analog signals (voltages or currents). It forms the basis for the analog computer.
Background

Why is it important?

- Because of the OpAmp’s flexibility and low cost, it is an indispensable tool in the analog circuit designer’s “toolbox”. Digital designers can use it to interface to the analog world.

What can you do with it?

Common Operational Amplifier Circuits

- Integrator
- Filter
- Summing Amplifier
- Differentiator
- Sweep Generator
- Function Generator
- Oscillator
- Buffer Amplifier
- Analog-to-Digital Converter
- DC Amplifier
How Does it Work?

- The OpAmp is constructed using bipolar transistors, MOS transistors, or a mix of the two types (BiCMOS). Because it uses REAL components, the OpAmp does not have ideal behavior, but in many instances it comes close.

Characteristics of an Ideal Amplifier

- Infinite Input Impedance \((R_{in} = \infty)\)
  - The OpAmp circuit will not “load” the circuit that is driving it
- Zero Output Impedance \((R_{out} = 0)\)
  - The OpAmp circuit can provide as much current as needed
How Does it Work?

- Characteristics of an Ideal Amplifier
  - Infinite Gain
  - Infinite Bandwidth
    - The output gain does not depend on the frequency of the input signal, dc to gigahertz

The uA741 OpAmp

- Input resistance (typ) = 2 MΩ
- Output resistance (typ) = 75 Ω
- Output short circuit current (typ) = 25 mA
- Max open-loop gain = 200,000 V/V

Data from “EE Design Center”, www.questlink.com
Note the feedback loop from output to input through RF. Since this feedback goes through the inverting input, it is termed "negative feedback".

The Inverting Amplifier

- The open-loop gain of the OpAmp, or the gain if there were no feedback, is:

\[ A_{vo} = \frac{V_{out}}{V_d} \]

This gain is determined by the OpAmp circuit (chip) only.
When feedback is present, you are operating under closed-coop conditions, and have a new, closed-loop gain,

\[ A_v = \frac{V_{out}}{V_i} \]

We will derive the closed-loop gain for the inverting amplifier.

- The input resistance is \( V_{in} / I_i \)

Apply Kirchhoff’s Laws

1) \( V_{in} = I_i R_1 + V_d \), where \( V_d \) is the OpAmp input voltage
2) \( I_i = I_a + I_n \), where \( I_a \) is the OpAmp input current
3) \( V_d = I_f R_F + V_{out} \)
The Inverting Amplifier

- Solve for the closed-loop gain, $A_v$, assuming the OpAmp is ideal:
  
  Let open loop gain $A_v = \infty$, then $V_{out}/V_d = \infty$, or $V_d = 0$.
  
  And input resistance $R_{op} = \infty$, then $I_a = 0$, or $I_i = I_f$.

- The ideal OpAmp has zero input current, infinite input resistance, and zero differential input voltage, $V_d$.

The Inverting Amplifier

- The closed-loop gain (using $V_d = 0$) is

  $$4) \quad A_v = \frac{V_{out}}{V_{in}} = \frac{V_d - I_f R_F}{I_i R_1 + V_d} = \frac{-I_f R_F}{I_i R_1} = -\frac{R_F}{R_1}$$

- Note the important result: The gain is fixed by external components only, not by any property of the OpAmp itself.
The Inverting Amplifier

- The input resistance seen by the generator is

\[ R_{in} = \frac{V_{in}}{I_i} = \frac{I_i R_1 + V_d}{I_i} = R_1 \]
### The Non-Inverting Amplifier

\[ A_v = +\left(\frac{R_F + R_1}{R_1}\right) = 1 + \frac{R_F}{R_1} \]

### Voltage Transfer Curve

The voltage transfer curve for a non-inverting amplifier is shown below, where \( V_{in} \approx \pm V_{cc} \) and \( V_{out} \approx \pm V_{cc} \).
OpAmp Limitations

- **Offset Voltage**
  - Due to manufacturing and design limitations, the opamp may produce a small, non-zero output voltage when the input is grounded.
  - In devices like the uA741 the offset can be reduced or eliminated by using a potentiometer between the offset adj pins (pins 1 & 5).

The potentiometer is in the Breakout library.
OpAmp Limitations

- **Slew Rate**
  - Slew rate describes the maximum possible rate of change of the opamp’s output voltage
  - A slew rate slower than the rate of change of the input will cause distortion
  - We can test the slew rate by using a large, fast changing signal at the input, such as a square pulse.

\[
SR = \left. \frac{dV_{out}}{dt} \right|_{max}
\]

\[V_{in} \quad V_{out} \quad V_{out}\]

Slope = SR
The Experiment

- Simulate the inverting amplifier (uA741)
  - Save $V_{out} \text{ vs } V_{in}$ data to file
- Simulate the non-inverting amplifier (uA741)
  - Save $V_{out} \text{ vs } V_{in}$ data to file
- Run the analysis of Example 6.1 on both sets of simulated data
- Make slew rate measurements on two opamps (uA741 and TLC081A)
- Modify the analysis of Example 6.3, and run on each set of slew rate data

Simulate Performance

- For the inverting and non-inverting amplifiers
  - Sweep input voltage from Vcc- to Vcc+
  - Plot the voltage transfer curve
  - Save the data to a text file
    - Results will be analyzed in MATLAB
Use the VCC_BAR device (PWR tool) in each instance and rename. All instances with the same name are assumed to be connected.

Supply Power and Input

Inverting Amplifier Data

<table>
<thead>
<tr>
<th>Input Voltage (V)</th>
<th>Output Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.400E+01</td>
<td>1.461E+01</td>
</tr>
<tr>
<td>-5.000E+00</td>
<td>1.461E+01</td>
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<tr>
<td>-3.000E+00</td>
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<td>0.000E+00</td>
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<tr>
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<tr>
<td>5.000E+00</td>
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</tr>
<tr>
<td>1.400E+01</td>
<td>-1.461E+01</td>
</tr>
</tbody>
</table>
Elements of Code

- % Analysis of input/output data using MATLAB
- % Read data using load command
- load 'ex6_1ps.dat'
- vin = ex6_1ps(:,1);
- vo = ex6_1ps(:,2);
- vo_max = max(vo); % maximum value of output
- vo_min = min(vo); % minimum value of output
- % calculation of gain
- m = length(vin);
- m2 = fix(m/2);
- gain = (vo(m2 + 1) - vo(m2 - 1))/(vin(m2 + 1) - vin(m2 - 1));
- % range of input voltage with linear amp
- vin_min = vo_min/gain; % maximum input voltage
- vin_max = vo_max/gain; % minimum input voltage

Code Output

1. Maximum Output Voltage is 1.4610e+01V
2. Minimum Output Voltage is -1.4610e+01V
3. Gain is -4.86650e+00
4. Minimum input voltage for Linear Amplification is -3.00216e+00
5. Maximum input voltage for Linear Amplification is 3.00216e+00
Measuring Slew Rate

- Texas Instruments slew rate test schematic
- This is a Unity Gain amplifier, also called a Voltage Follower. $V_{out} = V_{in}$.

Apply a step voltage $V_{in}$ to input
- $0 \leq V_{in} \leq 1$ V
- Set scope to trigger on the rising edge of $V_{in}$

Capture data
- Pick a square wave frequency
  - $f = 100$ Hz, 1 kHz, 10 kHz, or 100 kHz
- Transfer data to Excel using the “Get Waveform Data” macro

Switch opamps and repeat
- Be careful to check $V_{cc}$
Scope Data Captured to Excel

Worksheets

Measuring Slew Rate

DC Supply
Ch1 Ch2 Ch3

Waveform Generator
Output

Vcc+ Vcc-
Vin AMP
GND GND

Computer, Macros

Scope
ChA1 ChA2
Scope Setup

uA741, Fin = 100 Hz, 0 V \leq \text{Vin} \leq 1 V, Rout = 2 k\Omega, Cout = 100 pF

A1 = \text{Vin}, A2 = \text{Vout}

This was captured to Word using the “Get Screen Image” macro

Slew Rate Analysis

- The slew rate analysis MATLAB code in Example 6.3 works fine on clean PSpice simulation results
- It is less than satisfactory when dealing with our experimental data
Slew Rate Analysis

Identify Linear Region
Linear Fit

Slew Rate is 0.689 V/\mu s

Deliverables

- Inverting or non-inverting amp schematic
- Analysis of the amp
- Slew rate measurements on both opamp models
- Analysis of the slew rate data
- Comparison of the slew rate results to those on datasheets
The Memo

- Your manager would like to know which opamp is better suited for a high slew rate application
  - Compare the two opamps measured to each other
  - Compare your results to datasheets
  - Be quantitative!

References

- MATLAB internal documentation