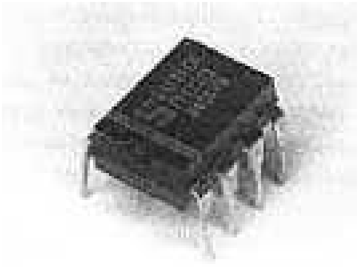


Engineering Sciences 154

Laboratory Assignment 1

OPERATIONAL AMPLIFIERS

Introduction

The primary objective of this experiment is to familiarize you with basic properties and applications of the integrated-circuit operational amplifier, the op amp, one of the most versatile building blocks currently available to electronic-circuit designers. Design of very compact transfer characteristics can be accomplished with an understanding of only a few simple rules about op amps. An ideal op amp draws no input current, has zero output impedance and has infinite gain. Of course no real op amp can actually achieve any of these requirements, but the "errors" can often be neglected when using proper design methods. In this assignment you will be asked to examine some of these errors and apply these design rules to a few basic op amp circuits.

References

- Chapter 2 in *Microelectronic Circuits,* 4th edition, Adel S. Sedra and Kenneth C. Smith
- *Understanding Operational Amplifier Specifications,* Jim Karki, Texas Instruments White Paper: SLOA011
  (available as pdf at: http://www-s.ti.com/sc/psheets/sloa011/sloa011.pdf)
- Chapter 4 in Paul Horowitz and Winfield Hill's *The Art of Electronics*

Prelab Exercises : General Differential Amplifier.

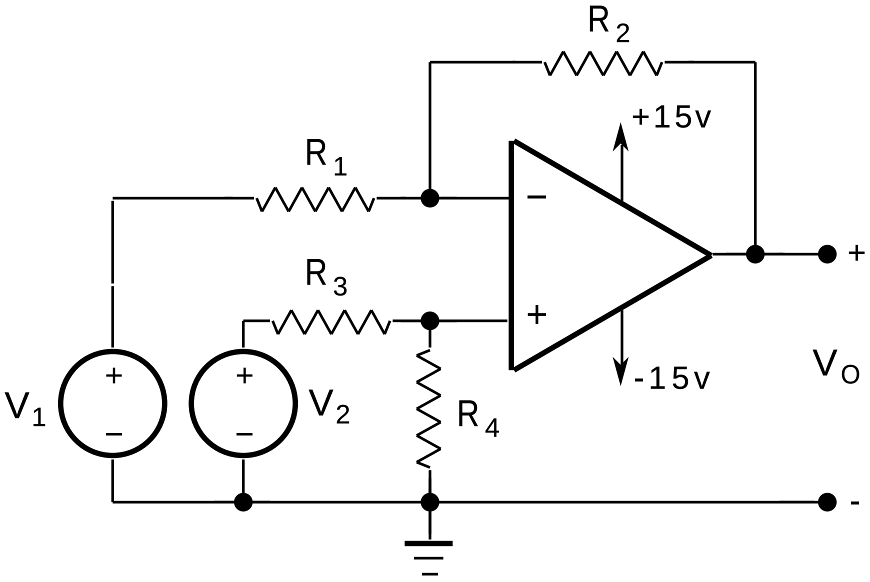


Figure 1: General differential amplifier circuit schematic.

(a) For the circuit show above. use the ideal op amp design technique to compute the output voltage V_O in terms of the inputs V_1 and V_2, and the resistor values R_1 to R_4. The correct answer is

$$V_O = \frac{R_4\left(R_1 + R_2\right)}{R_1\left(R_3 + R_4\right)} V_2 - \frac{R_2}{R_1} V_1 \qquad [1.1]$$

You will use special cases of this circuit to design inverting and non inverting ;amplifiers.

Real operational amplifiers have errors in their characteristics which can be modeled by current and voltage sources connected to the inputs of an ideal op amp as shown below:

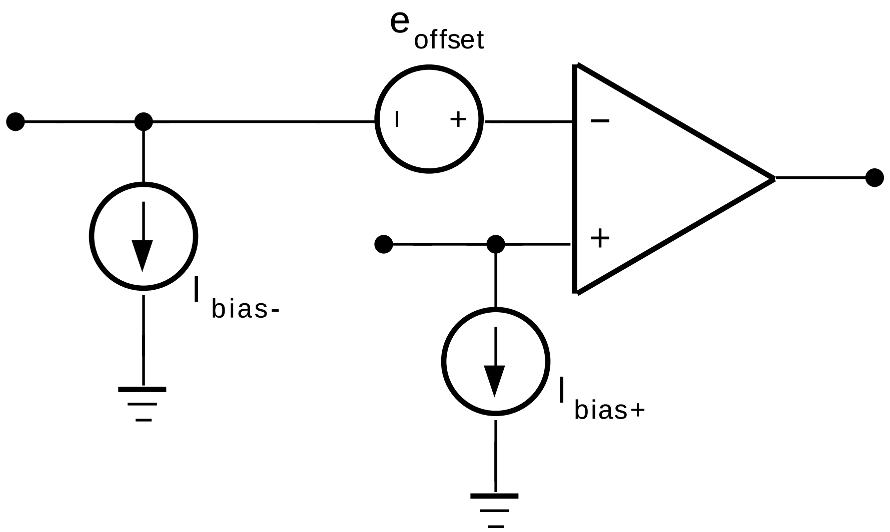


Figure 1.2: Real op amp with error sources modeled.

(b) Using the principle of superposition, calculate the output response to the bias currents I_{bias+} and I_{bias-} and the offset voltage e_{offset} for the special case of an inverting amplifier with $R_3 = R_4 = 0$. Remember to zero the input voltage V_1 and V_2. The correct answer is

$$V_{\text{error}} = -e_{\text{offset}}\left(1+\frac{R_2}{R_1}\right) + I_{\text{bias-}}\,R_2 \qquad [1.2]$$

Note that both e_{offset} and I_{bias-} are amplified, and either can produce a large error signal at the output if the circuit is poorly designed.

(c) Repeat this analysis for the case of a non inverting amplifier with R_3 and R_4 non zero. The correct answer for this case is

$$V_{\text{error}} = -e_{\text{offset}}\left(1+\frac{R_2}{R_1}\right) + I_{\text{bias-}}\,R_2 - I_{\text{bias+}}\left(R_3 \parallel R_4\right)\left(1+\frac{R_2}{R_1}\right) \qquad [1.3]$$

A trick often used to minimize the influence of the bias currents is to choose $R_3 \parallel R_4 = R_1 \parallel R_2$ so that the amplified part of the error is proportional to $I_{offset} = I_{bias-} - I_{bias+}$ which is generally an order of magnitude smaller than either bias current individually.

These formulas apply equally well to time dependent errors called voltage and current noise and are specified in data sheets. A good low-noise amplifier design takes into account the response to both types of sources. Note that the input resistors can affect the noise performance in ways which may not be obvious at first.

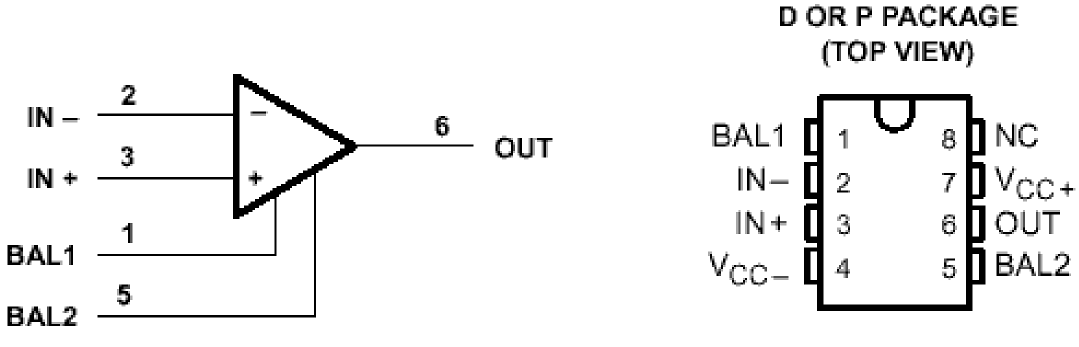
Practical Op Amps

The first few generations of commercial op amps, which made their appearance more than 50 years ago, were large, heavy devices fabricated from vacuum tubes and discrete RLC components. Size, cost, and appetite for power limited their use to the most critical applications, particularly the performance of key mathematical operations in predigital computer fire-control units for air defense batteries (hence the name operational amplifier). In 1962, Fairchild Electronics introduced the μA709, the first monolithic op amp, miniaturized onto an eggshell-thin chip of silicon just a fraction of an inch square. The sharp reductions in size and cost created by this use of integrated-circuit technology opened the door to the extensive use of op amps in a broad range of industrial and consumer electronics. Successive generations of op amps have taken advantage of advances in microelectronics, resulting in steadily improved integration, performance, and reliability, all at prices less than that of a postage stamp. Today's op amp is truly a wonder of invention and refinement and is one of the prime workhorses of modern electronic design.

Op amps are currently available in a variety of convenient packages and ratings. The popular general-purpose FL411 op amp in an 8-pin dual-in-line (DIP) package is shown in illustration below. This device is a low-cost, high-speed, high input impedance (10^{12} Ω) JFET-input operational amplifier with very low input offset voltage (1 mV) and input offset voltage drift (10 mV/°C). It requires low supply current, yet maintains a large gain-bandwidth product and a fast slew rate (13 V/μs). In addition, the matched high-voltage JFET input provides very low input bias (50 pA) and offset currents (25 pA). The LF411 can be used in applications such as high-speed integrators, digital-to-analog converters, sample-and-hold circuits, and many other circuits. As illustrated, pins 4 and 7 are assigned to be connected to the power supply. Without the proper dc bias currents supplied by the power supply at the rated voltage levels, the transistors contained in the op amp circuit will not act to produce a VCVS with high-gain behavior that characterizes all functional op amps.

Besides their packaging as separate chips, op amps are frequently deployed as modules contained in other integrated-circuit chips. Voltage followers are commonly used as buffers at the input and output pins of integrated circuits to prevent loading. Op amps form essential parts of analog-to-digital (AD) and digital-to-analog (DA) converters, instrumentation amplifiers, active filters, and numerous other chip-level electronic modules. It is not uncommon for dozens of op amp modules to be designed into a single very large scale integrated (VLSI) circuit chip.

LF411 Pinout Diagram



NC – No internal connection

Laboratory Tasks

Task 1 The Inverting Amplifier.

(a) Construct an inverting amplifier from a LF411 (or similar) integrated circuit op amp using the general circuit shown in Figure 1.1 with resistor values R_1 = 1kΩ, R_2 = 39 kΩ, and R_3 = R_4 = 0.

(b) Adjust the function generator to produce a sinusoidal wave form V_1 = 0.1v peak-to-peak (V_{pp}) at a frequency of about 1kHz and observe the output voltage on an oscilloscope. Use the scope in the x-y mode to verify that this is an inverting amplifier with V_o on channel 2 and V_1 on channel 1 and measure the voltage gain V_o/V_1. Compare your results with Equation [1.1].

(c) Increase the amplitude of V_1 until the output begins to distort and observe the effect on the shape of the output wave form. At what two voltage levels does this distortion begin to occur?

At room temperature a typical LF4l1 op amp has “errors” values of approximately $I_{bias+} \approx I_{bias-} = 50pA$ and $e_{offset} = 1mV$.

(d) Measure the dc offset voltage for your op amp by increasing the gain for voltage errors in Equation. [1.2] (also called the voltage noise gain) using resistor values $R_1 = 10k\Omega$, $R_2 = 10k\Omega$.

(e) Short the input and measure the dc output voltage to determine e_{offset} using Equation.[1 2]. For this choice of R_2 the contribution from the bias current in Equation.[1 2] is of the order of microvolts and obviously negligible.

(f) Next measure the dc bias current by changing the resistor values to $R_1 = R_2 = 1M\Omega$ using Equation.[1 2].

Task 2 The Noninverting Amplifier.

(a) Construct a simple non inverting amplifier from the general case above by choosing $R_1 = 1k\Omega$, $R_2 = 39k\Omega$, $R_3 = 0$, and $R_4 = \infty$ (open circuit). The output voltage can be derived using the ideal op amp design procedure, or by taking the limit of Equation [1.1]. 1 as R_4 -> ∞:

$$V_O = \left(1 + \frac{R_2}{R_1}\right) V_2 \qquad [1.4]$$

(b) Repeat the procedure used above for the inverting amplifier to measure the gain, and compare it with this expression.

Task 3 The Differential Amplifier

A differential amplifier has the property that its output is proportional to the difference $V_d = (V_2 - V_1)$ between the inputs and independent of the common mode value $V_{CM} = (V_1 + V_2)/2$

(a) Construct a differential amplifier by choosing values for the resistors $R_1 = R_3 = 1k\Omega$, $R_2 = 39k\Omega$, and replacing R_4 by an adjustable resistor (pot) of 0 to 100kΩ.

(b) Connect the two inputs together and apply a sinusoidal wave form to both inputs of amplitude -0.1V, and frequency 1kHz.

(c) Adjust R_4 to minimize the ac output, and thus maximize the rejection of the common mode signal applied.

(d) Measure R_4 using a multimeter with at least one side of the resistor removed from the circuit (Why?) and compare the value with that predicted for best common mode rejection from Equation [1.1]. For this value of R_4 the circuit will now function as a differential amplifier with gain predicted by Equation [1.1] -- *viz.*

$$V_O = \frac{R_2}{R_1}\left(V_2 - V_1\right) \qquad [1.4]$$

(e) Verify the operation of the circuit by first grounding V_1 and measuring the gain as above, then grounding V_2 and repeating the measurement.

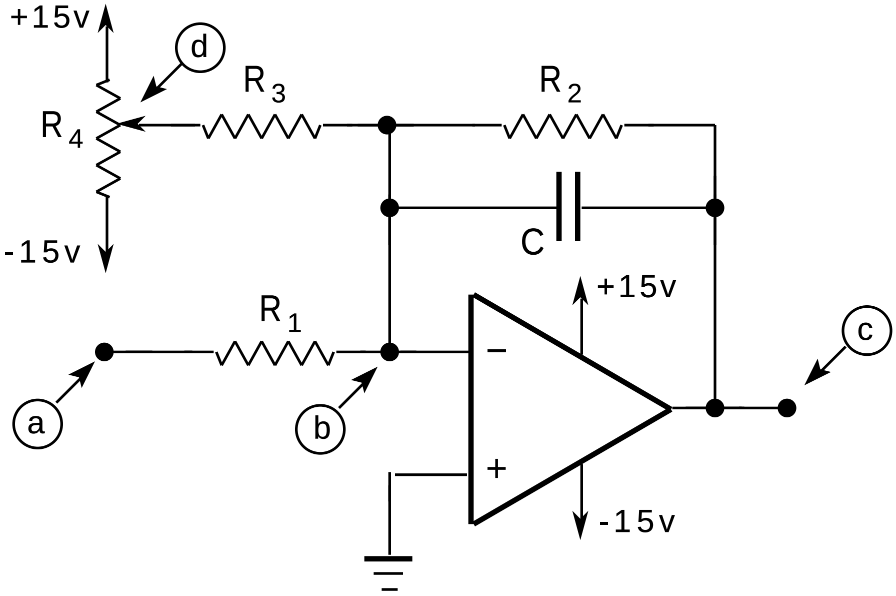
(f) Use the measured values of e_{offset} and $I_{bias+} \approx I_{bias-}$ from above with Equation [1.3] to compute the dc error at the output for the values of resistors used in this section.

(g) Measure the actual error at the output with both inputs shorted to ground, and compare with the calculated value. Comment on the limits these errors place on the choice of the resistors for this circuit.

Task 4 A Compensated Miller Integrator

To quote Sedra and Smith (page 75), "…Comparison of the frequency response of the integrator to that of an STC low-pass network indicates that the integrator behaves as a low-pass filter with a corner frequency at zero. Observe also that at $\omega = 0$ the magnitude of the integrator transfer function is infinite. This indicates that at dc the op amp is operating with an open loop. This should also be obvious from the integrator circuit itself; reference to Fig. 2.11(a) shows that the feedback element is a capacitor, and thus at dc where the capacitor behaves as an open circuit, there is no negative feedback! This is a very significant observation and one that indicates a source of problems with the integrator circuit: Any tiny dc component in the input signal will theoretically produce an infinite output. Of course, no infinite output voltage results in practice; rather, the output of the amplifier saturates at a voltage close to the op-amp positive or negative power supply, depending on the polarity of the input dc signal.

Here we study the following, so-called compensated (or stabilized) integrator which has finite gain at zero frequency:



(a) Construct a compensated Miller integrator as illustrated above using $R_1 = 10k\Omega$, $R_2 = R_3 = 1M\Omega$, $R_4 = 10\ k\Omega$ and $C = 0.1\mu F$.

(b) Adjust for offsets by making the following dc measurements (use a DVM):

  i. With node **a** open and measuring V_O (output voltage at node **c**) adjust R_4 to make V_O zero.

  ii. Ground node **a** then measure the voltages at node **c** and node **d**.

  iii. With node **a** grounded and measuring V_O (output voltage at node **c**) adjust R_4 to make V_O zero.

(c) With compensation adjusted found in (b), connect a function generator to the input (node **a**). Using a dual-channel oscilloscope with external triggering, a the generator to provide a 1 kHz symmetric square wave at the input of 1 V_{pp}. Measure the voltages at nodes **a** and **c**. Sketch the waveforms, noting peak amplitudes and relative timing.

(d) Switch the generator to provide a 1 V_{pp} sine wave at the input. Again sketch the input and output waveforms, noting the peak amplitude and relative timing.

(e) Adjust the generator to find the frequency at which the input and output signals have the same amplitude. Note the relative phase. You may want to adjust the input signal level to make the display more convenient while maintaining a sinewave output.