A Cookbook Approach to Single Supply DC-Coupled Op Amp Design

Introduction

Using op amps on a split power supply is straight forward because the op amp inputs are referenced to the center of the supplies which is normally ground. Most signal sources are also referenced to ground, so input referencing is not consciously considered when designing with op amps powered from split supplies. In those rare instances when the signal source is not referenced to ground, split supply op amp design becomes an equivalent challenge to single supply design. When an op amp is powered from a single supply all the op amp inputs appear to be referenced from half the power supply voltage, $V_{CC}/2$. When the signal sources are referenced to ground or any potential other than $V_{CC}/2$, some type of bias must be introduced into the circuit if it is desirable to have the output referenced to ground. Designing the bias circuit is a time consuming detail job which is not always approached correctly, thus, this paper takes a general purpose circuit which includes bias circuitry, and reduces it to a cookbook procedure. The general purpose circuit looks formidable at first glance, but don't be intimidated by the complex looking circuit because the analysis will show that some components can be eliminated during the design process.

Developing an Equation for the General Case

The schematic for the general case op amp circuit is given in Figure 1. An op amp circuit normally can assume any one of the four possible equations for a straight line, thus, the equation derived for this circuit configuration must adequately describe all of these cases.
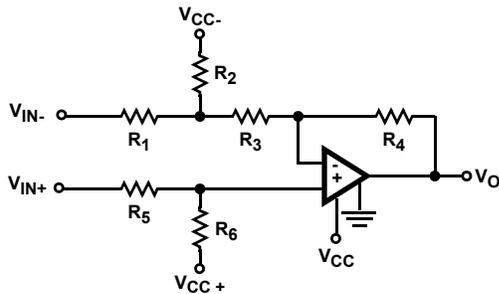

FIGURE 1. SCHEMATIC OF THE GENERAL CASE CIRCUIT

The equation derivation will be done in two parts through the use of superposition. The final output voltage, V_O, equals the sum of the constituent output voltages resulting from the independent application of each input voltage as shown in Equation 1.

$$V_O = V_{O+} + V_{O-} \qquad \text{(EQ. 1)}$$

V_{O+} is the output voltage that results from the input voltage V_{IN+}, and V_{O-} is the output voltage which results from the input voltage V_{IN-}. The assumption that the parallel resistance of R_1 and R_2 is much less than R_3 is made to simplify the calculation complexity; this is a rather easy assumption to satisfy in practice. V_{CC+} and V_{CC-} will usually be the same power supply, and much of the time they will be equal to V_{CC} because only one power supply will be available. Sometimes it is convenient for V_{CC+}, V_{CC-}, or both to be different from V_{CC}, so they are identified as different supplies during the development of Equation 4. Remember, all power supplies in op amp circuits must be decoupled to ground with at least a $0.1\mu F$ capacitor. The equation derivation uses the ideal op amp equations[1], and the design engineer must verify these assumptions. The ideal op amp equation requirement is not a detriment to this analysis because there are a multitude of op amps available which satisfy it.

$$V_{O-} = \left\{ V_{IN-} \left(\frac{R_2}{R_1 + R_2} \right) + V_{CC-} \left(\frac{R_1}{R_1 + R_2} \right) \right\} \left(-\frac{R_4}{R_3} \right) \qquad \text{(EQ. 2)}$$

$$V_{O+} = \left\{ V_{IN+} \left(\frac{R_6}{R_5 + R_6} \right) + V_{CC+} \left(\frac{R_5}{R_5 + R_6} \right) \right\} \left(\frac{R_4 + R_3}{R_3} \right) \qquad \text{(EQ. 3)}$$

Equations 2 and 3 are combined to yield Equation 4 which mathematically describes the operation of the circuit shown in Figure 1.

$$V_O = \left\{ V_{IN+} \left(\frac{R_6}{R_5 + R_6} \right) + V_{CC+} \left(\frac{R_5}{R_5 + R_6} \right) \right\} \left(\frac{R_4 + R_3}{R_3} \right) - {}^{""}$$

$$\left\{ V_{IN-} \left(\frac{R_2}{R_1 + R_2} \right) + V_{CC-} \left(\frac{R_1}{R_1 + R_2} \right) \right\} \left(\frac{R_4}{R_3} \right) \qquad \text{(EQ. 4)}$$

The Equation of a Straight Line

The op amp is being used as a linear device in this application, so its transfer function can be described by the equation of a straight line. There are four possible transfer functions described by the equation of a straight line.

$$y = \pm mx \pm b \qquad \text{(EQ. 5)}$$

The dependent variable y represents the output voltage, V_O, and the independent variable x represents the input voltage, V_{IN}. The slope of the line is m, and it will be represented by the coefficients of V_{IN}. The y intercept, b, is represented by the coefficients of V_{CC}. The four different equations of a straight line can be extracted from Equation 4 by comparing Equations 4 and 5:

$$y = mx + b \tag{EQ. 6}$$

$$V_O = V_{IN+}\left(\frac{R_6}{R_5 + R_6}\right)\left(\frac{R_3 + R_4}{R_3}\right) + V_{CC+}\left(\frac{R_5}{R_5 + R_6}\right)\left(\frac{R_3 + R_4}{R_3}\right) \tag{EQ. 7}$$

$$y = -mx - b \tag{EQ. 8}$$

$$V_O = V_{IN+}\left(\frac{R_6}{R_1 + R_6}\right)\left(\frac{R_3 + R_4}{R_3}\right) - V_{CC-}\left(\frac{R_1}{R_1 + R_2}\right)\left(\frac{R_4}{R_3}\right) \tag{EQ. 9}$$

$$y = mx + b \tag{EQ. 10}$$

$$V_O = -V_{IN-}\left(\frac{R_2}{R_1 + R_2}\right)\left(\frac{R_4}{R_3}\right) + V_{CC+}\left(\frac{R_5}{R_5 + R_6}\right)\left(\frac{R_3 + R_4}{R_3}\right) \tag{EQ. 11}$$

$$y = -mx - b \tag{EQ. 12}$$

$$V_O = -V_{IN-}\left(\frac{R_2}{R_1 + R_2}\right)\left(\frac{R_4}{R_3}\right) - V_{CC-}\left(\frac{R_1}{R_1 + R_2}\right)\left(\frac{R_4}{R_3}\right) \tag{EQ. 13}$$

Consider the Boundary Conditions

Because of the single supply restrictions, say a supply with the negative end connected to ground and the positive end connected to V_{CC}, the condition $0 \leq V_O \leq V_{CC}$ must be satisfied. As long as the output voltage stays between the supply rails the circuit will function normally, but when the output voltage tries to go outside the supply rails the output will saturate and become nonlinear. For example, if in Equation 13 $V_{IN-} = -1V$, $V_{CC-} = -1V$, $R_1 = R_2$, and $R_3 = R_4$ then the output voltage will be +1V and everything works fine, but if V_{IN-} goes to +2V the output will go to the bottom rail and give a false reading. Beware of working with negative input voltages because a negative voltage on some op amp inputs will turn off the input transistors causing nonlinear operation or possibly damaging the op amp.

Design Procedure

Given the two input voltages and their corresponding desired output voltages, the signs and magnitude of m and b are calculated using simultaneous equations. Don't worry about signs when you set the equations up because the solution will indicate the sign of m and b.

After you have determined the magnitude and sign for m and b, compare the signs of m and b to Equations 6, 8, 10, and 12 to determine which of these equations fit. After determining which one of the four equations to use, select its corresponding equation from Equations 7, 9, 11, or 13, and equate equivalent terms to m and b. The resistor ratios can be calculated at this time, and after values have been selected for key resistors, each resistor value can be calculated.

You will find that certain resistors are not needed, so you should eliminate them by setting them equal to shorts or opens. By observing which equation coincides with the signs of m and b, it becomes obvious which V_{CCX} connection is not needed. The resistor connecting the unused V_{CCX} to the circuit should be removed. Furthermore, if R_2 is the correct resistor to remove, R_1 should be replaced with a short. Also, if R_6 is removed, R_5 should be replaced with a short. Now build and test the circuit, and then you are finished with the design.

There will be times, just like in symmetrical supply op amp design, when the data just cannot be processed correctly with a simple circuit, and then you have to reach into your bag of tricks for a new circuit. Increasing one of the supply voltages may yield another degree of freedom, limiting the output voltage range may ease the problem, or a more involved configuration may be required to solve the problem.

Design Example #1

Given data is: V_{IN} = 0.05V to 1.0V, V_O must span the range of 0.5 to 4.3V, and $V_{CC} = V_{CC+} = V_{CC-}$ = 5V. The simultaneous equations are 0.5 = m(0.05) + b and 4.3 = m (1) + b. Solving these equations yields m = 4 and b = 0.3. Both signs are positive so Equation 6 applies, and the data is compared to Equation 7 to yield:

$$m = 4 = \left(\frac{R_6}{R_5 + R_6}\right)\left(\frac{R_3 + R_4}{R_3}\right) \tag{EQ. 14}$$

$$b = 0.3 = 5\left(\frac{R_5}{R_5 + R_6}\right)\left(\frac{R_3 + R_4}{R_3}\right) \tag{EQ. 15}$$
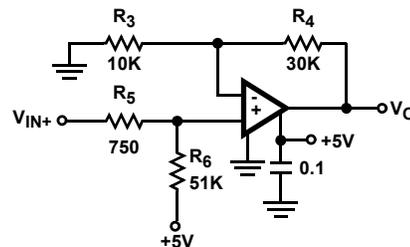
FIGURE 2. SCHEMATIC FOR DESIGN EXAMPLE #1

Because the V_{CC-} connection is not needed, R_2 is an open, and R_1 is a short. The revised circuit is shown in Figure 2. Solving Equations 14 and 15 yields the ratios: R_6/R_5 = 66.66 and R_4/R_3 = 3. Using the closest standard values R_5 is selected as 750Ω and then R_6 = 51K. R_3 is selected as 10K and then R_4 = 30K. The selection of R_5 and R_3 was rather arbitrary in this example; in an actual design impedance levels, leakage currents, or some other parameter will influence the selection of the initial resistor value.

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Design Example #2

Given data is: V_{IN} = 0.25V when V_O = 1.0V, V_{IN} = 0.75V when V_O = 4.0V, and V_{CC+} = V_{CC-} =V_{CC} = 5.0V. The simultaneous equations are 4.0 = m(0.75) + b and 1.0 = m(0.25) + b. Solving these equations yields m = 6 and b = -0.5. The slope, m, is positive and the vertical intercept, b, is negative so Equation 8 applies, and the data is compared to Equation 9 to yield:

$$|b| = 0.5 = 5\left(\frac{R_1}{R_1 + R_2}\right)\left(\frac{R_4}{R_3}\right) \tag{EQ. 17}$$

$$m = 6 = \left(\frac{R_6}{R_5 + R_6}\right)\left(\frac{R_3 + R_4}{R_3}\right) \tag{EQ. 16}$$

Because the V_{CC+} connection is not needed R_6 is opened, R_5 is shorted, and Equation 16 is simplified as shown below.

$$m = 6 = \left(\frac{R_3 + R_4}{R_3}\right) \tag{EQ. 18}$$
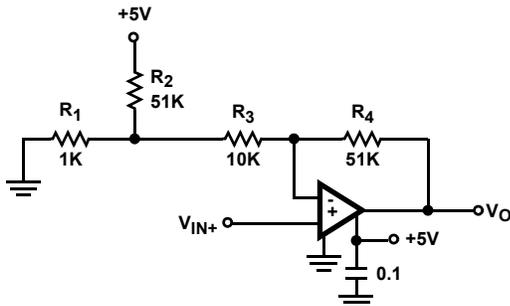
FIGURE 3. SCHEMATIC FOR DESIGN EXAMPLE #2

The revised circuit is shown in Figure 3. Solving Equations 17 and 18 yields the ratios R_4/R_3 = 5 and R_2/R_1 = 50. Using the closest standard values R_3 is selected as 10K and then R_4 = 51K. R_1 is selected as 1K and then R_2 = 51K. Again, the selection of R_1 and R_3 was rather arbitrary, but experience says that these values will not be too far from appropriate for the average circuit built with modern op amps.

Design Example #3

Given data: the input voltage range is -0.1 to -1.0V, the corresponding output voltage is to be 1.0 to 8.0V, and V_{CC+} = V_{CC-} = V_{CC} =10V. The simultaneous equations are 1.0 = m(-0.1) + b and 8.0 = m(-1.0) + b. Solving these equations yields m = -7.777 and b = 2/9. The slope, m, is negative while the vertical intercept is positive, so Equation 10 applies. Equations 19 and 20 result when the data is compared to Equation 11.

$$|m| = 7.777 = \left(\frac{R_2}{R_1 + R_2}\right)\left(\frac{R_4}{R_3}\right) \tag{EQ. 19}$$

$$b = \frac{2}{9} = 10\left(\frac{R_5}{R_5 + R_6}\right)\left(\frac{R_3 + R_4}{R_3}\right) \tag{EQ. 20}$$
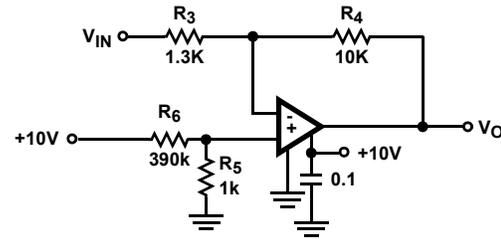

FIGURE 4. SCHEMATIC FOR DESIGN EXAMPLE #3

Because the V_{CC-} connection is not needed R_2 is opened, and R_1 is shorted. Now Equation 19 is simplified as shown below.

$$|m| = 7.777 = \left(\frac{R_4}{R_3}\right) \tag{EQ. 21}$$

Solving Equations 19 and 21 yields the resistor ratios R_4/R_3 = 7.777 and R_6/R_5 = 390. The selection of R_3 = 1.3K results in R_4 = 10K, and the selection of R_6 = 1K results in the selection of R_5 = 390K.

Design Example #4

Given data: V_{IN} = -1.0V when V_O = 1.5V, V_{IN} = -2.5V when V_O = 4.5V, and V_{CC} = 5V. The simultaneous equations are 1.5 = m(-1.0) + b and 4.5 = m(-2.5) + b. Solving these equations yields m = -2 and b = -0.5. Both signs are negative so Equation 12 applies, and the data is compared to Equation 13 to yield:

$$|m| = 2 = \left(\frac{R_2}{R_1 + R_2}\right)\left(\frac{R_4}{R_3}\right) \tag{EQ. 22}$$

$$|b| = 0.5 = 5\left(\frac{R_1}{R_1 + R_2}\right)\left(\frac{R_4}{R_3}\right) \tag{EQ. 23}$$

Because the V_{CC+} connection is not needed R_6 is opened, and R_5 is shorted. Solving Equations 22 and 23 yield the resistor ratios R_4/R_3 = 2.1 and R_2/R_1 = 20. Selecting standard value resistors which satisfy the assumption that $R_1 \| R_2 << R_3$ leads to the final values of R_1 = 1K, R_2 = 20K, R_3 = 130K, and R_4 = 270K. The schematic for design example #4 is shown in Figure 5.
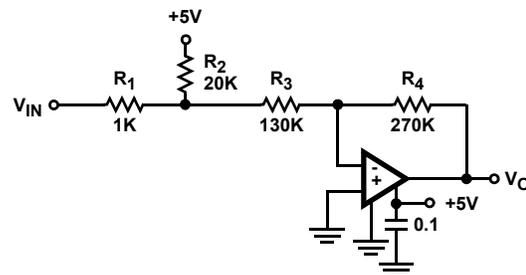

FIGURE 5. SCHEMATIC FOR DESIGN EXAMPLE #4

Conclusions

All four forms of the equation of a straight line can be implemented with an op amp operated from a single supply if the proper bias circuitry is included in the design. It is not harder to design single supply op amp circuits than it is to design split supply op amp circuits, but more attention must be paid to the details to achieve a successful single supply design. Equation 4 contains all of the information required to design single supply circuits.

Two cautions which apply to any op amp circuit design must be included: first the inputs must be protected from input voltages which may fall out of the supply range (even for transient voltages). And second, the output voltage will saturate as it approaches either limit of the supply range. Within these two limits single supply design is the equal of split supply design, and it saves the cost of an additional power supply.

Reference

For Intersil documents available on the internet, see web site http://www.intersil.com/

[1] AN9510 Application Note, Intersil Corporation, "Basic Analog for Digital Engineers".

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