Introduction

Using op amps on a split power supply is straightforward 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, VCC/2. When the signal sources are referenced to ground or any potential other than VCC/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.

\[ V_{O+} \] 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 μF capacitor. The equation derivation uses the ideal op amp equations1, 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.

\[ V_{O-} = \left( V_{IN-} \left( \frac{R_2}{R_1 + R_2} \right) + V_{CC-} \left( \frac{R_1}{R_1 + R_2} \right) \right) \left( \frac{R_4}{R_3} \right) \]  

(EQ. 2)

\[ V_{O+} = \left( V_{IN+} \left( \frac{R_6}{R_5 + R_6} \right) + V_{CC+} \left( \frac{R_5}{R_5 + R_6} \right) \right) \left( \frac{R_4 + R_3}{R_3} \right) \]  

(EQ. 3)

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

\[ V_{O} = \left( V_{IN+} \left( \frac{R_6}{R_5 + R_6} \right) + V_{CC+} \left( \frac{R_5}{R_5 + R_6} \right) \right) \left( \frac{R_4 + R_3}{R_3} \right) \]  

\[ \left( V_{IN-} \left( \frac{R_2}{R_1 + R_2} \right) + V_{CC-} \left( \frac{R_1}{R_1 + R_2} \right) \right) \left( \frac{R_4}{R_3} \right) \]  

(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.

\[ y = \pm mx \pm b \]  

(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:
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 VCCX connection is not needed. The resistor connecting the unused VCCX to the circuit should be removed. Furthermore, if R2 is the correct resistor to remove, R1 should be replaced with a short. Also, if R6 is removed, R5 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: VIN = 0.05V to 1.0V, VO must span the range of 0.5 to 4.3V, and VCC = VCC+ = VCC- = 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:

\[ m = 4 = \frac{R_6}{R_6 + R_6} \left( \frac{R_3 + R_4}{R_3} \right) \]  
(EQ. 14)

\[ b = 0.3 = 5 \left( \frac{R_5}{R_5 + R_6} \right) \left( \frac{R_3 + R_4}{R_3} \right) \]  
(EQ. 15)
**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:

$$|b| = 0.5 = 5 \left( \frac{R_1}{R_1 + R_2} \right) \left( \frac{R_4}{R_3} \right)$$  \hspace{1cm} (EQ. 17)

$$m = 6 = \left( \frac{R_6}{R_5 + R_6} \right) \left( \frac{R_3 + R_4}{R_3} \right)$$  \hspace{1cm} (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:

$$m = 6 = \left( \frac{R_3 + R_4}{R_3} \right)$$  \hspace{1cm} (EQ. 18)

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 is: the input voltage range is -1.0 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 $1.0 = m(-1.0) + b$ 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.

$$|m| = 7.777 = \left( \frac{R_2}{R_1 + R_2} \right) \left( \frac{R_4}{R_3} \right)$$  \hspace{1cm} (EQ. 19)

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.

$$|m| = 7.777 = \left( \frac{R_4}{R_3} \right)$$  \hspace{1cm} (EQ. 20)

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 is: $V_{IN} = -1.0V$ 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:

$$|m| = 2 = \left( \frac{R_2}{R_1 + R_2} \right) \left( \frac{R_4}{R_3} \right)$$  \hspace{1cm} (EQ. 22)

$$|b| = 0.5 = 5 \left( \frac{R_1}{R_1 + R_2} \right) \left( \frac{R_4}{R_3} \right)$$  \hspace{1cm} (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.
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/

Notice

1. Descriptions of circuits, software and other related information in this document are provided only to illustrate the operation of semiconductor products and application examples. You are fully responsible for the incorporation or any other use of the circuits, software, and information in the design of your product or system. Renesas Electronics disclaims any and all liability for any losses and damages incurred by you or third parties arising from the use of these circuits, software, or information.

2. Renesas Electronics hereby expressly disclaims any warranties against and liability for infringement or any other claims involving patents, copyrights, or other intellectual property rights of third parties, or by arising from the use of Renesas Electronics products or technical information described in this document, including but not limited to, the product data, drawings, charts, programs, algorithms, and application examples.

3. No license, express, implied or otherwise, is granted hereby under any patents, copyrights or other intellectual property rights of Renesas Electronics or others.

4. You shall not alter, modify, copy, or reverse engineer any Renesas Electronics product, whether in whole or in part. Renesas Electronics disclaims any and all liability for any losses or damages incurred by you or third parties arising from such alteration, modification, copying or reverse engineering.

5. Renesas Electronics products are classified according to the following two quality grades: "Standard" and "High Quality". The intended applications for each Renesas Electronics product depends on the product's quality grade, as indicated below.

   "Standard": Computers, office equipment, communications equipment, test and measurement equipment, audio and visual equipment, home electronic appliances, machine tools, personal electronic equipment, industrial robots, etc.

   "High Quality": Transportation equipment (automobiles, trains, ships, etc.), traffic control (traffic lights), large-scale communication equipment, key financial terminal systems, safety control equipment, etc.

Unless expressly designated as a high reliability product or a product for harsh environments in a Renesas Electronics data sheet or other Renesas Electronics document, Renesas Electronics products are not intended or authorized for use in products or systems that may pose a direct threat to human life or bodily injury (artificial life support devices or systems; surgical implantations, etc.), or may cause serious property damage (space systems; underwater navies; nuclear power control systems; aircraft control systems; key plant systems; military equipment, etc.). Renesas Electronics disclaims any and all liability for any damages or losses incurred by you or any third parties arising from the use of any Renesas Electronics product that is inconsistent with any Renesas Electronics data sheet, user's manual or other Renesas Electronics document.

6. When using Renesas Electronics products, refer to the latest product information (data sheets, user's manuals, application notes, “General Notes for Handling and Using Semiconductor Devices” in the reliability handbook, etc.) and ensure that usage conditions are within the ranges specified by Renesas Electronics with respect to maximum ratings, operating power supply voltage range, heat dissipation characteristics, installation, etc. Renesas Electronics disclaims any and all liability for any malfunctions, failure or accident arising out of the use of Renesas Electronics products outside of such specified ranges.

7. Although Renesas Electronics endeavors to improve the quality and reliability of Renesas Electronics products, semiconductor products have specific characteristics, such as the occurrence of failure at a certain rate and malfunctions under certain use conditions. Unless designated as a high reliability product or a product for harsh environments in a Renesas Electronics data sheet or other Renesas Electronics document, Renesas Electronics products are not subject to radiation resistance design. You are responsible for implementing safety measures to guard against the possibility of bodily injury, injury or damage caused by fire, and/or danger to the public in the event of a failure or malfunction of Renesas Electronics products, such as safety design for hardware and software, including but not limited to, redundancy, fire control and malfunction prevention, appropriate treatment for aging degradation or any other appropriate measures. Because the evaluation of microcomputer software alone is very difficult and impractical, you are responsible for evaluating the safety of the final products or systems manufactured by you.

8. Please contact a Renesas Electronics sales office for details as to environmental matters such as the environmental compatibility of each Renesas Electronics product. You are responsible for carefully and sufficiently investigating applicable laws and regulations that regulate the inclusion or use of controlled substances, including without limitation, the EU RoHS Directive, and using Renesas Electronics products in compliance with all these applicable laws and regulations. Renesas Electronics disclaims any and all liability for damages or losses occurring as a result of your noncompliance with applicable laws and regulations.

9. Renesas Electronics products and technologies shall not be used for or incorporated into any products or systems whose manufacture, use, or sale is prohibited under any applicable domestic or foreign laws or regulations. You shall comply with any applicable export control laws and regulations promulgated and administered by the governments of any countries asserting jurisdiction over the parties or transactions.

10. It is the responsibility of the buyer or distributor of Renesas Electronics products, or any other party who distributes, disposes of, or otherwise sells or transfers the product to a third party, to notify such third party in advance of the contents and conditions set forth in this document.

11. This document shall not be reprinted, reproduced or duplicated in any form, in whole or in part, without prior written consent of Renesas Electronics.

12. Please contact a Renesas Electronics sales office if you have any questions regarding the information contained in this document or Renesas Electronics products.

(Note 1) “Renesas Electronics” as used in this document means Renesas Electronics Corporation and also includes its directly or indirectly controlled subsidiaries.

(Note 2) “Renesas Electronics products” means any product developed or manufactured by or for Renesas Electronics.

(Rev:A-01 November 2017)