Introduction to Op Amps

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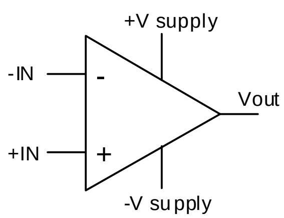
Introduction

Analog design can be intimidating. If your engineering talents have been focused in digital, software or even scientific fields, you may be intimidated with what would seem to be a simple analog circuit. As you trespass into the analog domain you are confronted with terminology and decisions that leave you unsure.

The operational amplifier is a useful foundation for many analog circuits. The term was originally applied to amplifiers that were part of analog computers used during the 1950s and 60s. Those circuit configurations could perform most of the algebraic and calculus operations and could solve differential and integral equations. An op amp in the 50s was in a package measuring 12 cm high by 5 cm wide by 15 cm deep and consumed about 5 watts. They cost about $100. Today we can get two op amps in a package that is 0.3 cm by 0.15 cm by 0.11 cm (SOT-23) and the cost is less than $1. Along with the reduction in cost and size has come a significant increase in the types and variety to choose from.

Assumptions

Let us review some characteristics of op amps. There are some assumptions that can be made about most op amp circuits that will greatly simplify an analysis. As with all simplifications, this will not model all characteristics of the operation amplifiers. But these simplifications do not seriously hamper our intent to get a real understanding of the circuits. We will examine at a later time the limitations of this approach and what we need to consider in actual circuit designs.



The circuit symbol for the basic op amp has two input terminals, one output and two power supply terminals. The inputs are labeled (-) and (+) for the inverting and non-inverting inputs. What that means is when the (+) input has a higher voltage than the (-) input it will cause the output to increase and if the negative input is higher the output will decrease. The gain of the op amp is very high which means that for a very small voltage difference the output will approach the power supply rail.

The ideal op-amp has the following characteristics.

1. Infinite input impedance, which means no loading on source, zero bias current.
2. Zero output impedance, it can drive any load without distortion.
3. Zero offset voltage
4. Infinite gain, which implies zero voltage between the inputs
5. Infinite bandwidth, no delay of the signal through the amplifier and infinite slew rate.

Although currently available op-amps do not meet this ideal, they are close enough to make a reasonable analysis.

Feedback

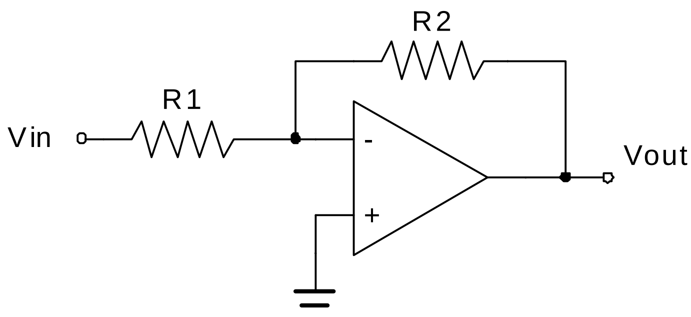
For useful circuits the output is fed back to the input(s) through an impedance network that sets a closely loop gain that is much smaller than the open-loop gain. With a negative feedback circuit we can make some simplifying assumptions.

Rule 1. The output will do whatever is necessary to keep the inputs at the same voltage.

Rule 2. The input draws no current.

Analysis

With these assumptions we can analyze a few circuits. We will start with a basic inverting amplifier.



From rule 1 we know that both inputs are at zero volts. And from rule 2 we know that any current which flows in R1 must also flow in R2 since rule 2 specifies that no current flows into the (-) input. Now we can write an algebraic equation and solve for the response of this circuit.

First of all the current in R1 will be $\frac{(Vin - 0V)}{R1}$ or just $\frac{Vin}{R1}$ and the current in R2 will be the same. But we can also write an equation for the current in R2 as $\frac{(Vout - 0V)}{R2}$ or just $\frac{Vout}{R2}$. But we now have to take into account the direction of the current flow. The two equations Vin/R1 and Vout/R2 both have the direction of the current flowing into node A. Since the currents flowing into and out of a node have to be equal, we have to reverse the direction of the feedback current to match the input current. We could reverse either one, it wouldn't make a difference. We will define the output current as $\frac{(0V - Vout)}{R2}$ or $\frac{-Vout}{R2}$.

Therefore:

$$\frac{-Vout}{R2} = \frac{Vin}{R1}$$

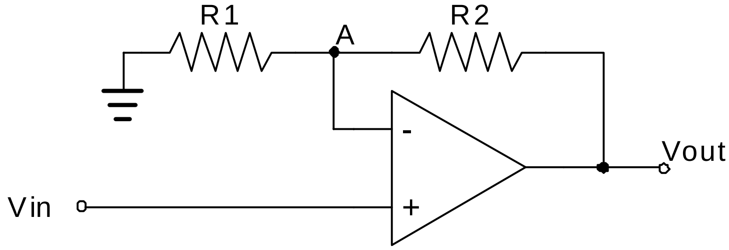
Which yields:

$$Vout = -\frac{R2}{R1}Vin$$

But you will notice that one of the problems with this circuit is that we lost the benefit of the high input impedance. Now the input impedance is equal to R1. Which may not be a problem if you are driving this circuit from a low impedance source such as another op amp.

Since the op amp keeps the inverting input of the op amp at ground potential, this has been named a virtual ground. Which just means that it isn't actually connected to ground, but the circuit can be analyzed as if it was ground. It is important to realize that our first two rules will only work if the op amp is operating in the linear range. If there is some reason why the output is not able to attain the voltage necessary to provide the correct current through R2, then the inverting input would no longer be a virtual ground.

If we want gain while still maintaining the high input impedance, then we can use the following circuit.



This circuit still has negative feedback so we can apply our two rules. Node A will be equal to the input voltage. The current in R1 is equal to $\frac{Vin}{R1}$ and the current in R2 will be $\frac{(Vout - Vin)}{R2}$. Now since those two currents are equal and in the correct direction we have the following:

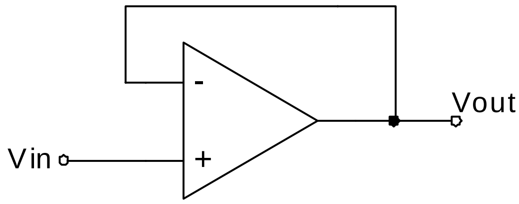
$$\frac{(Vout - Vin)}{R2} = \frac{Vin}{R1}$$

$$\frac{Vout}{R2} - \frac{Vin}{R2} = \frac{Vin}{R1}$$

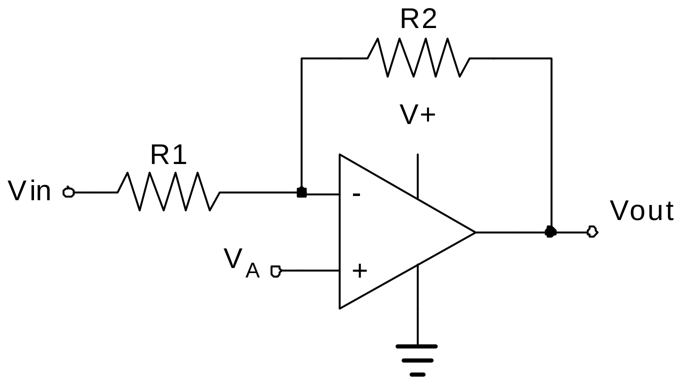
$$\frac{Vout}{R2} = \frac{Vin}{R1} + \frac{Vin}{R2} = Vin\left(\frac{1}{R1} + \frac{1}{R2}\right)$$

$$Vout = Vin\left(\frac{R2}{R1} + 1\right)$$

If you reduce R2 to zero and increase R1, then you just have $Vout = Vin(0 + 1)$ or Vout = Vin. This is a convenient follower circuit. It has a large input resistance and a low output impedance.



The inverting circuit implies the need for bipolar supply voltages. The signal must be able to swing both positive and negative. As supply voltages have decreased, the trend is for the analog circuitry to only use one supply voltage. For this type of inverting configuration to work, the positive input must be referenced with a voltage between the supply and ground. Realize that now the negative input is not referenced to ground but instead to the voltage on the positive input V_A. And so now our "virtual ground" isn't at ground potential, but at V_A. Therefore the current in R1 is now the difference in Vin and V_A.



$$I_{R1} = \frac{Vin - V_A}{R1} = \frac{V_A - Vout}{R2}$$

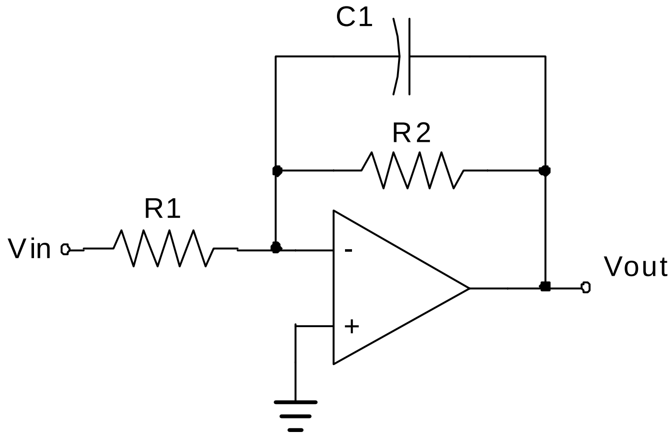
$$\frac{Vout}{R2} - \frac{V_A}{R2} = -\frac{Vin}{R1} + \frac{V_A}{R1}$$

$$Vout = R2\left(\frac{-Vin}{R1} + \frac{V_A}{R1} + \frac{V_A}{R2}\right)$$

$$Vout = -\frac{R2}{R1}Vin + V_A\left(1 + \frac{R2}{R1}\right)$$

Therefore we have same transfer function as the basic inverting op amp configuration, except that it is offset by the fixed voltage of $V_A\left(1 + \frac{R2}{R1}\right)$. You can see the effects of superposition that we will discuss later. The total solution is the result of adding the inverting and non-inverting solutions together.

But we are not limited to using resistors. We can use other impedances in place of the resistors indicated. For example if we use a parallel resistor, capacitor combination in the feedback we can roll off the frequency response. This might be necessary if we want to reduce the bandwidth to filter noise or otherwise filter the signal.



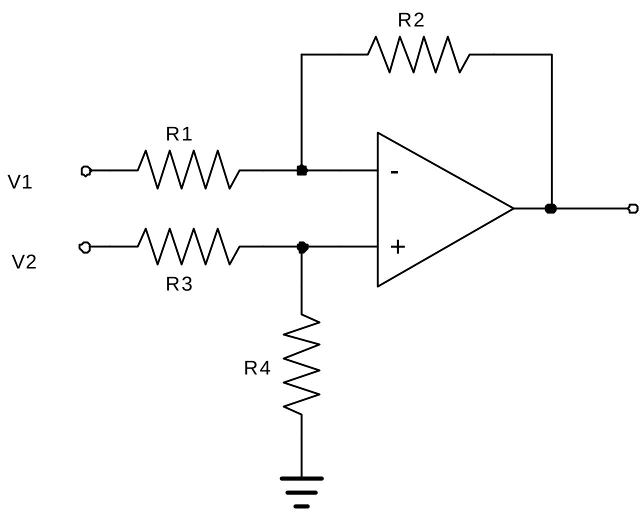
The transfer equation is the same as we derived earlier for the inverting amplifier, except that now we have the parallel combination of C1 and R2 in place of R2. The impedance of the feedback network is:

$$Z_f = R_2 \parallel \frac{1}{j\omega C_1} = \frac{\frac{R_2}{j\omega C_1}}{R_2 + \frac{1}{j\omega C_1}} = \frac{R_2}{1 + j\omega R_2 C_1} = \frac{R_2}{1 + j2\pi f R_2 C_1}$$ and the transfer function is:

$$Vout = -\frac{R_2}{R_1(1 + j2\pi f R_2 C_1)} Vin$$ When the frequency is zero then it is just our original equation for an inverting amplifier: $Vout = -\frac{R_2}{R_1} Vin$. For frequencies beyond $\frac{1}{2\pi R_2 C_1}$ the amplitude is reduced by 6 dB (1/2) for each octave. And the response is down by 3 dB at the corner frequency $f_0 = \frac{1}{2\pi R_2 C_1}$.

Realize that for real op-amps, they have a frequency roll-off of their own. For this circuit to achieve the expected results the frequency $\left(f_0 = \frac{1}{2\pi R_2 C_1} \right)$, needs to be at a much lower frequency than the op-amp frequency response. We will examine that in detail in a future article.

Another convenient tool to analyze op-amp circuits is the property of superposition. In a linear system the resulting output will be the combination of each of the individual inputs. What this means is that if you have several inputs, you can limit the analysis to one input at a time with the other inputs grounded. Then the overall result will be the sum of all the results from each individual analysis. One simple analysis is to add extra input resistors to the inverting op amp. We will see that the output is just the sum of the inputs.



Let's apply the principal of superposition to the Differential Amplifier. The Differential Amplifier uses matched resistors to give us a single-ended output that is the result of the difference in voltage between V1 and V2. If we ground V2, then we have the basic inverting amplifier and $Vout = -\frac{R_2}{R_1}V_1$. If we ground V1, then we have the basic non-inverting amplifier except that the +IN voltage is a divided version of V2. $+IN = \frac{R_4}{R_3 + R_4}V_2$. Remember the non-inverting circuit had the following output. $Vout = Vin\left(\frac{R2}{R1} + 1\right)$. Now if we replace Vin with our expression of V2, we will have: $Vout = \frac{R_4}{R_3 + R_4}V2\left(\frac{R_2}{R_1} + 1\right)$. We now have the expression for the output voltage with V1 and V2 individually. As long as V1 and V2 don't exceed the power supplies, but stay in the linear region, we can add the two solutions together for a total solution. $Vout = -\frac{R_2}{R_1}V1 + \frac{R_4}{R_3 + R_4}V2\left(\frac{R_2}{R_1} + 1\right)$. This might not be very intuitive, but if we set R1=R2=R3=R4, then the output expression becomes: $Vout = -V1 + \frac{1}{2}V2(1+1) = V2 - V1$ which means that the output is equal to the difference of the inputs. Realizing that we will deviate from this if the resistors are not an exact match. Which is hard to do with discrete resistors. Commercially available difference amps have the resistor values laser trimmed and all built on the same process for optimum matching performance.

In the future we will take the opportunity to examine the expected performance of real op-amps and what we must do to achieve our expected results. If you have questions or have topics you would like me to cover, please write me at: russellanderson@engineer.com.