Basic Analog for Digital Designers

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What Is This Application Note Trying To Accomplish?

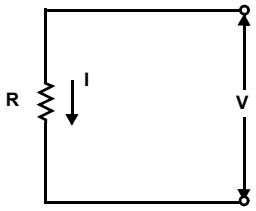
There is a long gap between engineering college and mid career in a non-engineering position, but technology marches on so a simple method of keeping abreast with the latest developments is required. This application note starts with an overview of the basic laws of physics, progresses through circuits 1 and 2, and explains op amp operation through the use of feedback principles. Math is the foundation of circuit design, but it is kept to the simplest level possible in this application note. For more advanced op amp topics please refer to the technical papers listed in references 1 and 2.

Basic Physics Laws, Circuit Theorems and Analysis

Good news and bad news. The bad news is that it takes a certain amount of dog work, like relearning physics and circuit theorems, before proficiency becomes second nature. The good news is that if you just hang in for a few pages you will experience the joy of analyzing circuits like an expert. You will gain ten years experience in a few hours. You will be able to write op amp equations like a design engineer. You might think this is a worthless effort, but imagine the look on the analog engineer's face, the one who thinks non-analog engineers are as dumb as a box of rocks, when you write your own op amp circuit equations.

Ohm's and Kirchoff's Laws

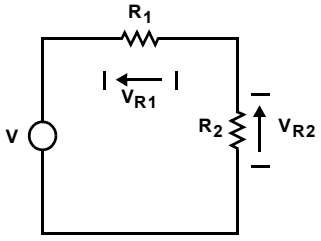
Ohm's law states that there is a relationship between the current in a circuit and the voltage potential across a circuit. This relationship is a function of a constant called the resistance.



$$V = IR \quad \text{(EQ.1)}$$

FIGURE 1. ILLUSTRATION OF OHM'S LAW

Kirchoff's voltage law states that the algebraic sum of the voltages around any closed loop equals zero. The sum includes independent voltage sources, dependent voltage sources and voltage drops across resistors (called IR drops).

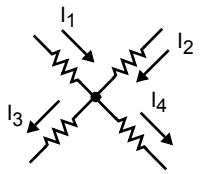


$$V - V_{R1} - V_{R2} = 0 \quad \text{or} \quad V = V_{R1} + V_{R2} \quad \text{(EQ. 2)}$$

$$\Sigma \text{ voltage sources} = \Sigma \text{ voltage drops} \quad \text{(EQ. 3)}$$

FIGURE 2. ILLUSTRATION OF KIRCHOFF'S VOLTAGE LAW

Kirchoff's current law states that the algebraic sum of all the currents leaving a node equals zero. The sum includes independent current sources, dependent current sources, and component currents.



$$I_1 + I_2 = I_3 + I_4 \quad \text{(EQ. 4)}$$

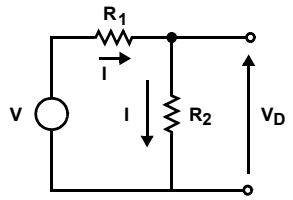
$$I_1 + I_2 - I_3 - I_4 = 0 \quad \text{(EQ. 5)}$$

$$\Sigma \text{ currents into a junction} = 0 \quad \text{(EQ. 6)}$$

FIGURE 3. ILLUSTRATION OF KIRCHOFF'S CURRENT LAW

Voltage and Current Dividers

Voltage dividers are seen often in circuit design because they are useful for generating a reference voltage, for biasing active devices, and acting as feedback elements. Current dividers are seen less often, but they are still important so we will develop the equations for them. The voltage divider equations, which assume that the load does not draw any current, are developed in Figure 4.



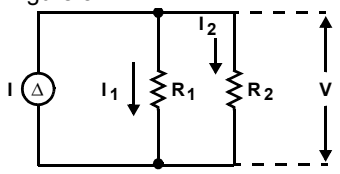
$$V = IR_1 + IR_2 = I(R_1 + R_2) \quad \text{(EQ. 7)}$$

$$I = \frac{V}{(R_1 + R_2)} \quad \text{(EQ. 8)}$$

$$V_D = IR_2 = \frac{V}{(R_1 + R_2)}(R_2) = V\frac{R_2}{R_1 + R_2} \quad \text{(EQ. 9)}$$

FIGURE 4. DERIVATION OF THE VOLTAGE DIVIDER RULE

The current divider equations, assuming that the only load is R_2, is given in Figure 5.



$$I = I_1 + I_2 \quad \text{(EQ. 10)}$$

$$V = I_1 R_1 = I_2 R_2 \quad \text{(EQ. 11)}$$

$$I_1 = I_2 \frac{R_2}{R_1} \quad \text{(EQ. 12)}$$

$$I = I_1 + I_2 = I_2 \frac{R_2}{R_1} + I_2 = I_2\left(1 + \frac{R_2}{R_1}\right) = I_2\left(\frac{R_1 + R_2}{R_1}\right) \quad \text{(EQ. 13)}$$

$$\text{Then: } I_2 = I \frac{R_1}{R_1 + R_2} \quad \text{(EQ. 14)}$$

FIGURE 5. DERIVATION OF THE CURRENT DIVIDER RULE

Thevenin's and Norton's Theorems

There are situations where it is simpler to concentrate on one component rather than write equations for the complete circuit. When the input source is a voltage source, Thevenin's theorem is used to isolate the component of interest, but if the input source is a current source, Norton's theorem is used to isolate the component of interest.

To apply Thevenin's theorem one must look back into the terminals of the component being replaced. Now calculate the open circuit voltage seen at these terminals, and during this calculation consider that there is no load current so the voltage divider rule can be used. Next short independent voltage sources and open independent current sources; now calculate the impedance seen looking into the terminals. The final step is to replace the original circuit with the Thevenin equivalent voltage, V_{th}, and Thevenin equivalent impedance, Z_{th}.

Thevenin's theorem is illustrated in Figure 6.

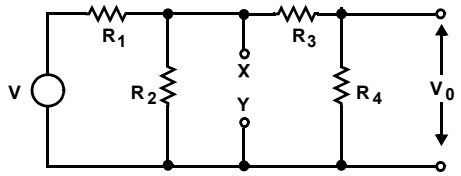


FIGURE 6. THE ORIGINAL CIRCUIT

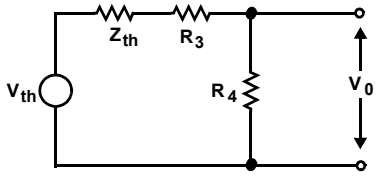
The open circuit voltage is calculated by looking into the terminals X - Y, and then calculating the open circuit voltage with the voltage divider rule.

$$V_{th} = V \frac{R_2}{R_1 + R_2} \quad \text{(EQ. 15)}$$

The impedance looking back into the terminals X - Y with the independent source, V, shorted is given below.

$$Z_{th} = Z_{x-y} = \frac{R_1 R_2}{R_1 + R_2} \equiv R_1 \parallel R_2 \quad \text{(EQ. 16)}$$

The circuit to the left of X - Y is now replaced by the Thevenin equivalents.

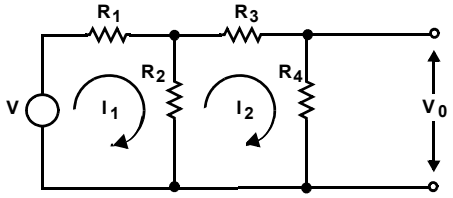


$$V_0 = V_{th} \frac{R_4}{Z_{th} + R_3 + R_4} \quad \text{(EQ. 17)}$$

$$= V \frac{R_2}{R_1 + R_2} \frac{R_4}{\frac{R_1 R_2}{R_1 + R_2} + R_3 + R_4}$$

FIGURE 7. THE THEVENIN EQUIVALENT CIRCUIT

The loop equations are worked out below. Notice that not only is the derivation of the equations more laborious, but the labor will get out of hand with the addition of another loop. This is why Thevenin's theorem is preferred over loop equations.



$$V = I_1(R_1 + R_2) - I_2 R_2 \quad \text{(EQ. 18)}$$

$$I_2(R_2 + R_3 + R_4) = I_1 R_2 \quad \text{(EQ. 19)}$$

$$I_1 = \frac{R_2 + R_3 + R_4}{R_2} I_2 \quad \text{(EQ. 20)}$$

$$I_2 \frac{(R_2 + R_3 + R_4)}{R_2}(R_1 + R_2) - I_2 R_2 \quad \text{(EQ. 21)}$$

$$I_2 = \frac{V}{\frac{R_2 + R_3 + R_4}{R_2}(R_1 + R_2) - R_2} \quad \text{(EQ. 22)}$$

$$V_0 = I_2 R_4 \quad \text{(EQ. 23)}$$

$$V_0 = V \frac{R_4}{\frac{(R_2 + R_3 + R_4)(R_1 + R_2)}{R_2} - R_2} \quad \text{(EQ. 24)}$$

FIGURE 8. LOOP EQUATION ANALYSIS OF THE SAME CIRCUIT

The Norton equivalent circuit is seldom used in circuit design, so it's derivation [3] and illustration will be left to the serious student.

Superposition

The principle of superposition states that the equation for each independent source can be calculated separately, and then the equations (or results) can be added to give the total result. When implementing superposition the equation for

each source is calculated with the other independent voltage sources short circuited and the independent current sources open circuited. The equations for all the sources are added together to obtain the final answer.

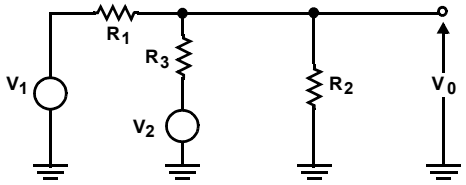


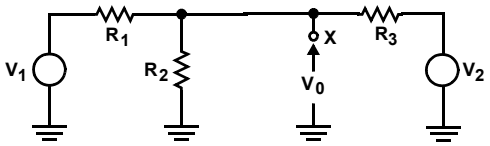
FIGURE 9. SUPERPOSITION EXAMPLE

$$V_{01}|_{V_2=0} = \frac{R_2 \parallel R_3}{R_1 + R_2 \parallel R_3} V_1 \quad V_{02}|_{V_1=0} = \frac{R_1 \parallel R_2}{R_3 + R_1 \parallel R_2} V_2 \quad \text{(EQ. 25)}$$

$$V_0 = V_{01} + V_{02} = V_1 \frac{R_2 \parallel R_3}{R_1 + R_2 \parallel R_3} + V_2 \frac{R_1 \parallel R_2}{R_3 + R_1 \parallel R_2} \quad \text{(EQ. 26)}$$

Analysis Tools - Why Do We Need More Than One?

Each one of the analysis tools shown has a place where it is optimal. Later during the op amp analysis the tools will be employed to relieve the burden of detailed calculation. Figures 10 and 11 illustrate an example of the extra calculations caused by using the less optimal tool to perform the analysis.



$$V_{th} = \frac{R_2}{R_1 + R_2} V_1 \quad R_{th} = R_1 \parallel R_2 \quad \text{(EQ. 27)}$$

FIGURE 10. SUPERPOSITION EXAMPLE REDRAW

$$I = \frac{V_2 - V_{th}}{R_{th} + R_3} \qquad V_0 = V_2 - IR_3 \quad \text{(EQ. 28)}$$

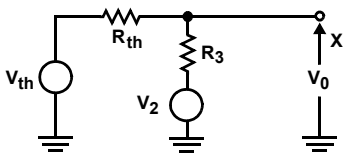


FIGURE 11. THEVENIN EQUIVALENT CIRCUIT MODEL

$$V_0 = V_2 - \frac{V_2 - V_{th}}{R_{th} + R_3} R_3 = V_2 - \frac{V_2 - \frac{R_2 V_1}{R_1 + R_2}}{R_1 \parallel R_2 + R_3} R_3 \quad \text{(EQ. 29)}$$

Notice that the Thevenin method used twice as many equations to describe the circuit as were required to arrive at the same result with superposition. Also, the form of the final equation arrived at by superposition is much easier to analyze.

Feedback Principles

This discussion of feedback principles is simple because they are easy to understand. The application of the principles can be very complicated for the design engineer, but we can grasp the principles without understanding all of the nuances. If this material creates a thirst it may be slaked by reading references 2 and 3.

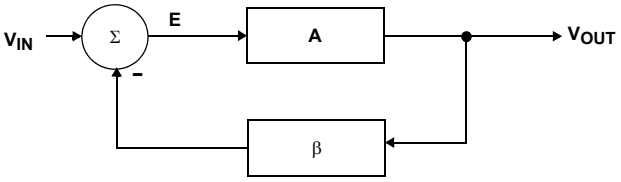


FIGURE 12. FEEDBACK BLOCK DIAGRAM

$$V_{OUT} = EA \quad \text{(EQ. 30)}$$

$$E = V_{IN} - \beta V_{OUT} \quad \text{(EQ. 31)}$$

$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{1 + A\beta} \quad \text{(EQ. 32)}$$

Equations 30 and 31 are written on the block diagram, and Equation 32 is obtained by combining them to eliminate the error, E. If $\beta = 1$ in Equation 32 $V_{OUT} = V_{IN}$, or the feedback circuit has turned into a unity gain buffer. If $\beta = 0$ in Equation 32 $V_{OUT} = AV_{IN}$, or there is no feedback. Notice that the direct gain, A, does not control the feedback circuit closed loop gain; rather, the feedback factor, β, controls the closed loop gain in a feedback circuit. This is the essence of a feedback circuit; now the closed loop gain is a function of the feedback factor which is comprised of passive components. The closed loop gain error, stability and drift are now dependent on stable, accurate, and inexpensive passive components. The closed loop gain assumption is valid as long as $A\beta >> 1$, also $E \Rightarrow 0$ if this assumption is valid.

If $A\beta = -1$ then Equation 32 becomes $V_{OUT}/V_{IN} = 1/0$, or it is indeterminate. If the energy in the circuit was unlimited the circuit would consume the world, but luckily it is limited, so the circuit oscillates from positive to negative saturation. This is an oscillator, thus the definition of an oscillator is that the gain be ≥ 1 while the phase shift equals -180 degrees. Now we conclude that the feedback factor controls the closed loop gain, and the direct gain/feedback factor combination determines if the circuit will be stable or will be an oscillator.

The Op Amp Symbol

It is important to understand the op amp symbol shown in Figure 13. The -input, V-, is the inverting input, and the +input, V+, is the non-inverting input. The point of the triangle is the op amp output, and the op amp multiplies the differential voltage, (V+ - V-), by a large gain, a.

The Inverting Op Amp

Three assumptions are made in the calculation of the inverting op amp circuit equations. First, the current into the op amp inputs, I_B in Figure 13, is assumed to be zero; this is a valid assumption because the bias currents are usually much lower than signal currents. The second assumption is that the op amp gain, a, is extremely high, and this is a valid assumption in most situations where the op amp's bandwidth is much greater than the signal bandwidth. The third assumption, which is that the error voltage, V_E, equals zero, is a result of assuming an extremely high op amp gain. When a is very large V_{OUT}, can assume any value required to drive the inverting input voltage to the non-inverting input voltage, so V_E will always be forced to zero.

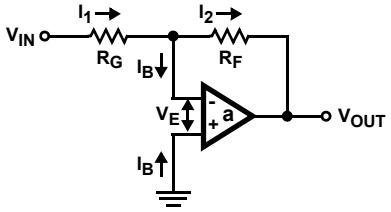


FIGURE 13. INVERTING OP AMP CIRCUIT

Assume $I_B = 0$, $V_E = 0$, $a = \infty$
Then:

$$I_1 = \frac{V_{IN}}{R_G} = I_2 = -\frac{V_{OUT}}{R_F} \quad \text{(EQ. 33)}$$

$$V_{IN}\,R_F = -V_{OUT}\,R_G \quad \text{(EQ. 34)}$$

$$\frac{V_{OUT}}{V_{IN}} = -\frac{R_F}{R_G} \quad \text{(EQ. 35)}$$

Equation 33 is written by applying Kirchoff's current law to the inverting node. Equation 35 is obtained through algebraic manipulation of Equations 33 and 34. Note that the ideal closed loop gain, Equation 33, does not contain the op amp gain, so it is independent of the op amp gain so long as the assumptions are valid.

The inverting op amp can be configured as an inverting adder as shown in Figure 14. The analysis is similar to that shown for the inverting amplifier, but it is easier to understand if the concept of a virtual ground is understood. Virtual is defined as "existing or resulting in effect though not in actual fact". The inverting node acts as a real ground because no voltage is developed across it, but the current path is restricted to the PC traces attached to the node. The non-inverting input of the op amp is connected to ground, thus if the error voltage is to be zero as was assumed, the inverting input functions as though it were tied to ground. Considering the virtual ground, the three currents flowing through R_{G1}, R_{G2}, and R_{G3} can be calculated separately. Now superposition can be applied to the circuit; Equation 36 calculates the gain for each independent source, and Equation 37 recombines the separate gains.

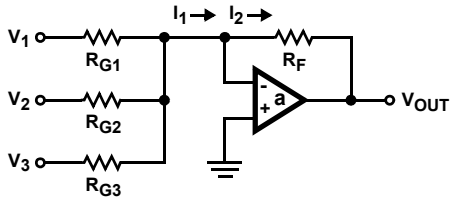


FIGURE 14. THE INVERTING ADDER

$$V_{01} = -V_1\frac{R_F}{R_{G1}},\ V_{02} = -V_2\frac{R_F}{R_{G2}},\ V_{03} = -V_3\frac{R_F}{R_{G3}} \quad \text{(EQ. 36)}$$

$$V_{OUT} = V_{01} + V_{02} + V_{03} = -V_1\frac{R_F}{R_{G1}} - V_2\frac{R_F}{R_{G2}} - V_3\frac{R_F}{R_{G3}} \quad \text{(EQ. 37)}$$

If $R_F / R_{GX} = 1$ Then;

$$V_{OUT} = -(V_1 + V_2 + V_3) \quad \text{(EQ. 38)}$$

The Non-Inverting Op Amp

Referring to Figure 15, because V_E is equal to zero the voltage at point X is equal to V_{IN}. There is voltage divider formed by the feedback resistor, R_F, and the gain setting resistor, R_G, and the voltage divider input voltage is the output voltage of the op amp. Equation 39 is written using the voltage divider rule, and Equation 40 is obtained through algebraic manipulation. Notice that the ideal closed loop gain is again independent of the op amp gain.

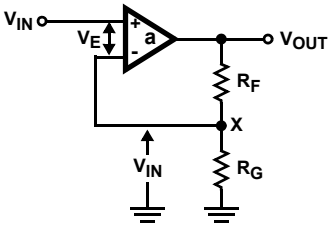


FIGURE 15. NON-INVERTING OP AMP

$$V_{IN} = \frac{V_{OUT}R_G}{R_F + R_G} \quad \text{(EQ. 39)}$$

$$\frac{V_{OUT}}{V_{IN}} = \frac{R_F + R_G}{R_G} \quad \text{(EQ. 40)}$$

The Differential Amplifier

The differential amplifier schematic is given in Figure 16, and the analysis will be done in two parts because we will use superposition. Two output voltages, one corresponding to each input voltage source, will be calculated separately and added together. The output from V_1 is calculated in Equation 42; V+ is first calculated with the voltage divider rule, and then it is substituted into the non-inverting gain equation yielding Equation 43. The output from V_2 is calculated from the inverting gain equation in Equation 44. The

results of Equations 43 and 44 are added in Equation 45 to obtain the complete circuit equation. Notice that the output is a function of the difference between the two input voltages, this accounts for the name differential amplifier.

If a small signal is riding on a large signal, say 10mV, 0.001Hz riding on $5V_{DC}$, the DC can be stripped off by putting the combined signal into the non-inverting input, and putting $5V_{DC}$ into the inverting input. The $5V_{DC}$ becomes a common mode signal (a signal which is common to both inputs), so it is rejected by the differential amplifier if $R_1 = R_3$, and $R_2 = R_4$.

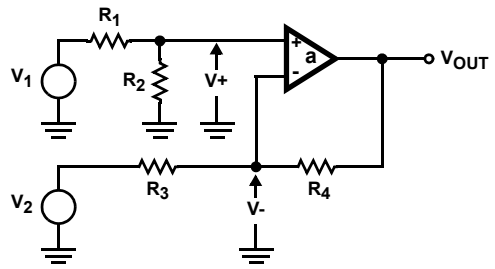


FIGURE 16. THE DIFFERENTIAL AMPLIFIER

$$V_{OUT} = V_{OUT_1} + V_{OUT_2} \quad \text{(EQ. 41)}$$

$$V_{OUT_1} = V+\left(1+\frac{R_4}{R_3}\right) \quad V+ = V_1\frac{R_2}{R_1+R_2} \quad \text{(EQ. 42)}$$

$$V_{OUT_1} = V_1\frac{R_2}{R_1+R_2}\left(\frac{R_3+R_4}{R_3}\right) \quad \text{(EQ. 43)}$$

$$V_{OUT_2} = V_2\left(-\frac{R_4}{R_3}\right) \quad \text{(EQ. 44)}$$

$$V_{OUT} = V_1\frac{R_2}{R_2+R_1}\left(\frac{R_3+R_4}{R_3}\right) - V_2\frac{R_4}{R_3} \quad \text{(EQ. 45)}$$

If $R_1 = R_3$ and $R_2 = R_4$

$$V_{OUT} = (V_1 - V_2)\frac{R_4}{R_3} \quad \text{(EQ. 46)}$$

This effect could be accomplished through the use of a coupling capacitor, but because the frequency of the signal is so low the capacitor value and size would be too big. The differential amplifier also rejects AC common mode signals. Data transmission schemes often use twisted pairs for the interconnections so that any noise coupled on the lines will be common mode. Differential amplifiers are used as receivers in this data transmission scheme because they reject the common mode noise while amplifying the signal.

T Networks in the Feedback Path

Putting a T network in the feedback path as shown in Figure 17 complicates the analysis, but offers the advantage of high closed loop gain coupled with low value feedback resistors. This configuration is also useful for some filter configurations. Thevenin's theorem is applied as shown in Figure 18. Look into R_4 from X, Y and calculate the Thevenin equivalent voltage and resistance, then redraw the circuit as shown in Figure 18. Now the inverting gain can be calculated in the normal manner using the algebraic simplification shown in Equation 48.

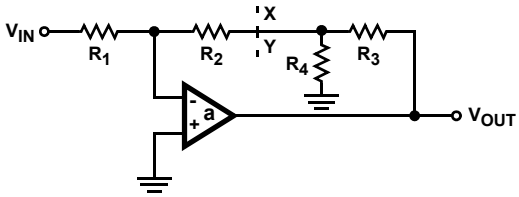


FIGURE 17. T NETWORK IN THE FEEDBACK PATH

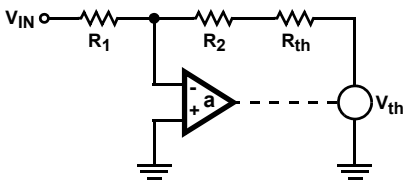


FIGURE 18. THEVENIN ANALYSIS OF T NETWORKS IN THE FEEDBACK PATH

$$V_{th} = \frac{V_0 R_4}{R_3+R_4} \quad R_{th} = R_3 \| R_4 - \frac{V_{th}}{V_{IN}} = \frac{R_2+R_{th}}{R_1} \quad \text{(EQ. 47)}$$

$$-\frac{V_{OUT}}{V_{IN}} = \frac{R_2+R_{th}}{R_1}\frac{R_3+R_4}{R_4} = \frac{R_2+\frac{R_3R_4}{R_3+R_4}}{R_1}\frac{R_3+R_4}{R_4}$$

$$= \frac{R_2+R_3+\frac{R_2R_3}{R_4}}{R_1} \quad \text{(EQ. 48)}$$

Video Amplifiers

Until now we have implicitly assumed that all op amps are the same. This is not true, but because the ideal closed loop equations are identical, it is a workable assumption. The two big classifications of op amps are voltage feedback and current feedback. The type of feedback is not the only difference between these op amps. The internal circuit configurations are dramatically different, so much so that recommended reference #1 dwells on voltage feedback while reference #2 dwells on current feedback. Whenever an op amp is used in a high frequency circuit such as a video amp there is a strong likelihood that it will be a current feedback op amp. Again, because the closed loop ideal gain equations are identical for voltage and current feedback op amps we will not distinguish between them.

In Figure 19, R_{IN} is usually the terminating resistance for the input cable, and it is usually 50Ω or 75Ω. R_M is the matching resistance for the cable being driven, and R_T is the terminating resistance for the driven cable. R_T is often shown here for gain calculations while it is physically placed at the cable end. Using Equation 49, we see that when $R_G = R_F$ and $R_M = R_T$, the overall circuit gain is one.

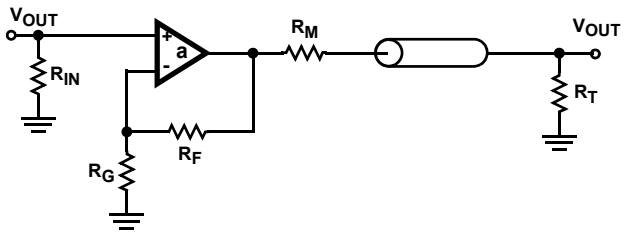


FIGURE 19. A TYPICAL VIDEO AMPLIFIER

$$\frac{V_{OUT}}{V_{IN}} = \frac{R_F + R_G}{R_G} \frac{R_T}{R_M + R_T} \quad \text{(EQ.49)}$$

AC Theory

The emphasis here is on capacitors because they are responsible for the vast majority of AC effects. The capacitor has an impedance and a phase shift both of which are a function of frequency. Although it is paramount in stability calculations, we will neglect the phase shift because you can obtain a reasonable understanding of circuit performance by just considering the impedance. Referring to Equation 50 it is apparent that when the frequency is very high, s = jω is very high, so the capacitor impedance, X_C, is very low. The converse happens when the frequency is very low.

The key to this section of AC theory is that high frequency means low capacitive impedance, and low frequency means high capacitive impedance. At F = ∞, X_C = 0, and at F = 0, X_C = ∞. At intermediate values of frequency the capacitive impedance must be calculated with the assistance of Equation 50.

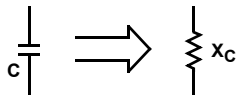


FIGURE 20. CAPACITOR IMPEDANCE

$$X_C = \frac{1}{SC} = \frac{1}{j\omega C} \quad \text{where S = jw and } j = \sqrt{-1} \quad \text{(EQ.50)}$$

Op Amp Circuits Containing Capacitors

Referring to Figure 21, when F = 0, X_C = ∞ so the gain, G = $-R_F/R_G$. When F = ∞, X_C = 0 then G = 0. The gain starts off high and decreases to zero at very high frequencies. Very often C_F is an unwanted stray capacitor which yields an undesirable effect; namely, the circuit loses high frequency performance.

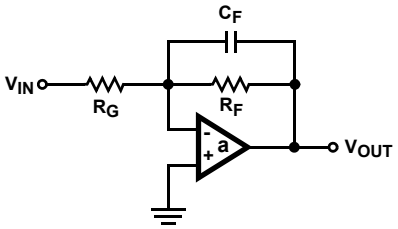


FIGURE 21. LOW PASS FILTER

A high pass filter is shown in Figure 22. At F = 0 the gain is $(R_F + R_G)/R_F$, and at very high frequencies the gain tries to approach the op amp gain, a. Sometimes the stray input capacitance forms this circuit, and the result is unwanted peaking or overshoot because the capacitor phase shift tends to make the circuit unstable.

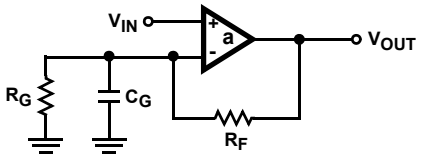


FIGURE 22. HIGH PASS FILTER

This general method is useful for analyzing the performance of op amp circuits which have capacitors. Depending on where they are connected the capacitors can stabilize or destabilize the op amp, but they always shape the transfer function in the frequency domain.

Conclusion

Some algebra, the basic laws of physics, and the basic circuit laws are adequate to gain an understanding of op amp circuits. By applying these tools to various circuit configurations it is possible to predict performance. Further in-depth knowledge is required to do op amp design, and there are many sources where this knowledge can be obtained. Don't hesitate to try some of these tricks on your local circuit design engineer, but be aware that it may result in a long lecture about circuit design.

References

[1] Intersil Corporation, Application Note 9415.

[2] Intersil Corporation, Application Note 9420.

[3] Van Valkenberg, N.E., Network Analysis, Prentice-Hall, 1964.

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