Equivalent Circuits for Operational Amplifier Drift and Noise

by Richard Conant, Application Engineer, Analog Devices, Inc.

We recently received a letter arguing very logically that the equivalent circuit (Figure 1A) which we give in our application notes for drift and noise is incorrect. Instead the circuit of Figure 1B was put forth with good reasons as a more accurate representation. Since in some applications these two circuits give different results, one must be wrong assuming that we apply the same set of published drift specifications. The question then arises as to which circuit is correct and how do we decide which one is correct.

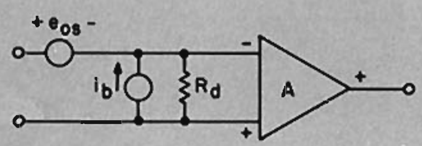


FIGURE 1A

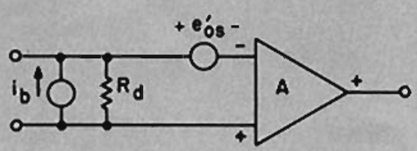


FIGURE 1B

This controversy has come up a number of times in our applications department, since there are a number of equivalent circuits now published in the op amp literature which can in essence be reduced to either the circuit of Figure 1A or Figure 1B. Basically, the only difference is whether the equivalent voltage generator is located on the input or output side of the open loop input impedance R_d.

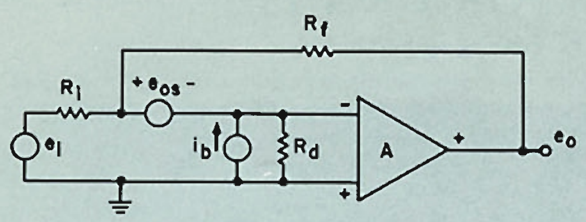
First let us compare the closed loop errors for these two circuits to see what difference we get. To simplify our discussion we shall consider only offset and drift errors but completely analogous results would apply to noise errors. Additionally, we shall look at only the single ended case where the plus input is grounded but the same arguments would apply to differential or noninverting circuits as well. Figures 2A and 2B show the closed loop errors for the two equivalent circuits for the inverting amplifier configuration where e_{os} is the equivalent offset voltage generator, i_b is the equivalent bias current generator, R_d is the open loop input impedance and A is the open loop gain. The primed quantities for e_{os} and i_b indicate that the numerical values for the generators may differ due to the different equivalent circuit configurations.

We can better compare Equations 1 and 2 if we rewrite Equation 2 as follows:

$$e_o = \frac{e_i\left(\frac{R_f}{R_i}\right) + e'_{os}\left(\frac{R_i + R_f}{R_i}\right) - \left(i'_b + \frac{e'_{os}}{R_d}\right) R_f}{1 + 1/A + R_f/AR_d + R_f/AR_i}$$

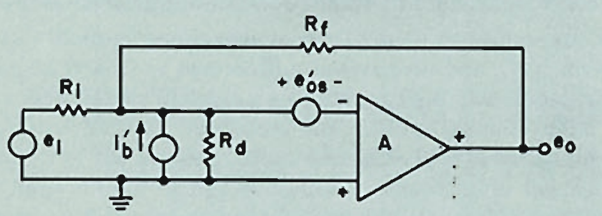
Now we see that the only difference between Equations 1 and 2 is the term e'_{os}/R_d. That is the voltage generator in Figure 2B will generate an effective bias current through the finite impedance R_d which adds to the bias current i'_b. As a practical matter the only time this difference would show up is when the term e'_{os}/R_d is comparable to or larger than i'_b. For most transistor or FET input operational amplifiers, bias current (i'_b) is much larger than voltage offset divided by R_d, that is, e'_{os}/R_d. However for chopper stabilized amplifiers R_d and i'_b are sufficiently small that the effect of e'_{os} cannot be ignored. Additionally, the difference between the two equivalent circuits becomes very striking for high frequency noise errors since shunt capacitance across R_d reduces this impedance at high frequencies.

Another almost philosophical point can be made in comparing the circuits of Figures 2A and 2B. That is offset errors for the equivalent circuit in Figure 2A can be predicted without any knowledge of the value for input impedance R_d (except for the second order gain reduction due to reduced loop gain). The primary effect of finite



$$e_o = \underbrace{\left[e_i\left(\frac{R_f}{R_i}\right)}_{\text{Signal}} + \underbrace{e_{os}\left(\frac{R_i+R_f}{R_i}\right)}_{\text{Voltage Drift Error}} - \underbrace{i_b R_f\right]}_{\text{Current Drift Error}} \underbrace{\left[\frac{1}{1+1/A+R_f/AR_d+R_f/AR_i}\right]}_{\text{Error Due To Finite Gain}} \quad \text{Eq.(1)}$$

FIGURE 2A. Equivalent circuit and error equation.



$$e_o = \underbrace{\left[e_i\left(\frac{R_f}{R_i}\right)}_{\text{Signal}} + \underbrace{e'_{os}\left(\frac{R_i+R_f}{R_i}+\frac{R_f}{R_d}\right)}_{\text{Voltage Drift Error}} - \underbrace{i'_b R_f\right]}_{\text{Current Drift Error}} \underbrace{\left[\frac{1}{1+1/A+R_f/AR_d+R_f/AR_i}\right]}_{\text{Error Due To Finite Gain}} \quad \text{Eq.(2)}$$

FIGURE 2B. Equivalent circuit and error equation.

R_d is to increase gain errors and to reduce loop gain. One could then theoretically eliminate errors due to R_d by adding enough open loop gain at the output of the amplifier. On the other hand offset errors for the circuit of Figure 2B depend on the value for R_d. While offset voltage and bias current are usually specified as maximum values, R_d is given as a typical value since it is difficult to measure this parameter with better than order of magnitude accuracy.

We still have not answered the question of which is the correct equivalent circuit and why. The subtle point here is not which circuit is right or wrong but rather which circuit corresponds to the published specifications on the data sheet. That is either circuit can be correct and one can translate back and forth between the equivalent circuits by solving the equations:

$$e_{os} = e'_{os}$$

$$i_b = i'_b + e'_{os}/R_d$$

The question of which set of parameters to use is resolved by examining the test circuit with which the offset and/or noise parameters are measured. Figure 3 shows the test circuit for measuring offset, drift and noise used by most operational amplifier manufacturers.

To measure offset voltage, switch S_1 is shorted and R_f is selected so that the term $i_b R_f$ is small compared with $e_{os}(R_i + R_f)/R_i$ in Equation 1. The output voltage is measured and the offset voltage is then computed from the equation $e_o = e_{os}(R_i + R_f)/R_i$.

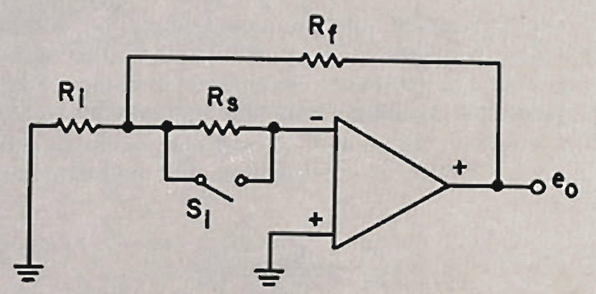


FIGURE 3. Test circuit for offset drift and noise.

One way to measure bias current would be to increase the value of R_f (still assuming S_1 is shorted) until the term $i_b R_f$ in Equation 1 is large compared to $e_{os}(R_i + R_f)/R_i$, to measure e_o and then to compute for i_b from $e_o = i_b R_f$. It turns out to be more practical to use the same values for R_i and R_f as for measuring e_{os} and to switch in a resistor R_s whose value is such that $i_b R_s >> e_{os}$. Then you measure e_o and solve

$$e_o = (i_b R_s)(R_i + R_f)/R_i$$

In either case notice that the value measured for i_b corresponds to the equivalent circuit of Figure 2A. That is, compared to Figure 2B, this measurement includes the contributions of bias current drift i'_b and offset voltage e'_{os}/R_d. Or in other words, $i_b = i'_b + e'_{os}/R_d$.

In conclusion, not only does the equivalent circuit of Figure 2A correspond to test circuits and therefore the published specifications but also this equivalent circuit makes more sense from the point of view of solving applications problems. That is, offset and noise errors are clearly divided into two categories; offset voltage errors (e_{os}) which are independent of the values chosen for the external feedback components, and bias current errors which are directly proportional to the value chosen for the external feedback components. Additionally offset errors can be predicted without any knowledge of the open loop input impedance R_d.