Op-Amp DC Error Analysis

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Introduction

Operational amplifiers are often treated as perfect or ideal. But all op-amps have imperfections that at some level limit what can be done. The purpose of this article is to illustrate how to analyze an op-amp circuit for the three most commonly considered errors – offset voltage, bias current, and offset bias current. We will use ideal op-amp analysis methods and superposition to analyze each effect independently and then combine the results.

Input offset voltage

All op-amps will have an input offset voltage that is defined as the voltage difference between the non-inverting input and the inverting input with the amplifier in a static (i.e. not dynamic) condition with the output not in saturation. The input offset voltage is often single digit millivolts or less but the effect on the output voltage can be considerably more as it is amplified by the non-inverting DC gain of the amplifier. The basic circuit for analysis is shown in Figure 1. Note that this could be the circuit for either a non-inverting amplifier or an inverting amplifier. The actual amplifier type makes no difference on the effect the input offset voltage will have on the output voltage. Whatever input voltage sources there are have been set to zero for superposition analysis of offset voltage.

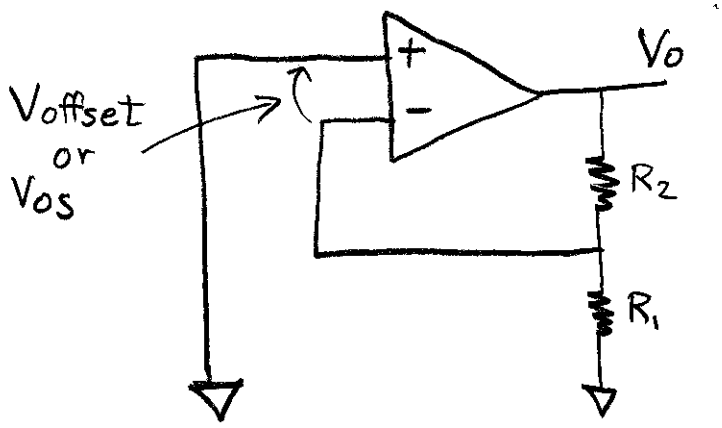

Figure 1: Circuit for offset voltage analysis

$Vin^+ = 0.0$ Eq. 1

$Vin^- = Vo * R1 / (R1 + R2)$ Eq. 2

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$Vin^+ - Vin^- = Vos$ (by definition) Eq. 3

$0.0 – Vo * R1 / (R1 + R2) = Vos$ Eq. 4

Solving for Vo gives

$Vo = -Vos * (1 + R2/R1)$ Eq. 5

Equation 5 assumes we know the polarity of Vos. Except for specific cases where we measure Vos in the laboratory all we know is the maximum magnitude from the data sheet. In application, polarity is not important as it is random. It is the magnitude of the error that we are interested in. A real circuit might not be this simple. All that matters is the non-inverting DC gain. Thus we write

$Vo|_{Vos} = |Vos| *$ non-inverting DC gain Eq. 6

We use Equation 6 even if the amplifier is inverting. The effect of Vos on the output is independent of our use of the amplifier. Equation 6 shows that a small input offset voltage can turn into a large output offset voltage if the closed loop DC gain is high.

Bias current and offset bias current

There is a bias current, IB, associated with each input of the op-amp. Although this current is typically in the nanoampere region and less it causes voltages to appear across the resistances connected to the inputs. These voltages are amplified by the non-inverting DC gain of the amplifier and the result is a voltage offset on the output. Our purpose here is to analyze for the magnitude of this output voltage offset. Bias current by definition is current into the op-amp terminals. It is not unusual for the actual current to be out of the terminal – this would be a negative bias current. We will not worry about the sign of the bias current since in the final result we will only be interested in the magnitude.

Associated with the bias current is what is known as offset bias current, IBos. What this means is that the bias current into each input terminal of the amplifier is not necessarily the same – in fact they never are. Before we proceed we need formal definitions of bias and offset bias currents.

$IB = (IB^+ + IB^-) / 2$ Eq. 7

$IBos = IB^+ - IB^-$ Eq. 8

The data sheet for an op-amp will show the maximum magnitudes of IB and IBos but will never show IB^+ and IB^- as there is no way to know specifically what they are. All we can know is that they are within the specified range. However, this does not prevent us from formulating some useful equations based on the unknown IB^+ and IB^-.

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For our analysis we will use the circuit in Figure 2. This circuit includes a resistor, R3, that could be zero or could be some specific value.

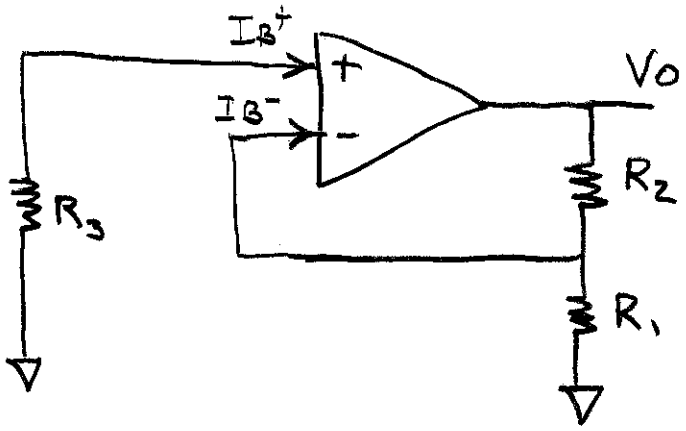

Figure 2: Circuit for bias current analysis

$Vin^+ = -IB^+ * R3$ Eq. 9

$Vin^- = -IB^- * (R1 \parallel R2) + Vo * R1 / (R1 + R2)$ Eq. 10

We now set $Vin^+ = Vin^-$

$-IB^+ * R3 = -IB^- * (R1 \parallel R2) + Vo * R1 / (R1 + R2)$ Eq. 11

We now solve for Vo

$$Vo = \frac{-IB^+ * R3 + IB^- * (R1 \parallel R2)}{R1 / (R1 + R2)} = [-IB^+ * R3 + IB^- * (R1 \parallel R2)] * (1 + R2/R1)$$

Eq. 12

This is the solution except that we do not know what IB+ and IB- are. However, using the definitions in reverse we can arrive at the maximum values we will use for calculations.

$IB^+ = IB + IBos/2$ Eq. 13

$IB^- = IB - IBos/2$ Eq. 14

Substituting Equations 13 and 14 into Equation 12 gives

$Vo = \{[(IB - IBos/2) * (R1 \parallel R2)] - [(IB + IBos/2) * R3]\} * (1 + R2/R1)$ Eq. 15

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Separating the IB and IBos terms gives

$$Vo = \{[IB * ((R1 \parallel R2) - R3)] - [(IBos/2) * ((R1 \parallel R2 + R3)]\} * (1 + R2/R1) \quad \text{Eq. 16}$$

Except for the special case where we have the actual measured values for IB and IBos we can never use Equation 16. Instead, we solve for the magnitude of each effect individually as follows using only the maximum magnitudes of IB and IBos from the data sheet.

$$Vo|_{IB} = IB * ((R1 \parallel R2) - R3) * (1 + R2/R1) \quad \text{Eq. 17}$$

$$Vo|_{IBos} = (IBos/2) * ((R1 \parallel R2) + R3) * (1 + R2/R1) \quad \text{Eq. 18}$$

Equation 17 reveals an interesting result. If R3 is equal to R1 || R2 then the output offset voltage resulting from IB goes to zero. The process of setting these two resistances equal is known as bias current compensation. Whether one should go to the trouble of doing this depends on how the uncompensated error term compares with acceptable error. If the uncompensated error is small in comparison then there is little point in doing this. The engineer must understand when it is appropriate to skip the bias current compensation step. It never hurts to perform the step other than possibly an unneeded resistor that takes up space and cost.

Equation 18 reveals that it is not possible to compensate for IBos. However, by making (R1 || R2 + R3) small then the effect of IBos is minimized. There are practical limits to how small this term can be since the resistance has to be large enough so as not to exceed the output current capability of the op-amp. It should be noted that IBos is typically in the range of 10 to 30 percent of IB so that even with perfect bias current compensation there will still be an output offset voltage related to bias current.

Accumulative effects

Using superposition we have solved for the individual magnitudes of the three most significant DC error terms. The question now is how to combine these into a single result. A simple minded approach is to just add up the extreme numbers to establish the maximum possible offset. The real answer is to use statistical summation since there is very little correlation between the three terms and the probability of all terms being at the maximums and having the same polarity is small. Thus we take the square root of the sum of the squares.

$$Voffset\_total \sim= sqrt((Vo|_{Vos})^2 + (Vo|_{IB})^2 + (Vo|_{IBos})^2) \quad \text{Eq. 19}$$

Equation 19 represents the theoretical 1 sigma error magnitude. Since only three terms are used this is kind of crude but it is the accepted method and is typical of what to expect. The absolute worst case summation is too pessimistic it very rarely occurs.