NON-IDEAL EFFECTS OF OPAMPS

Input Bias Current

Ideally, the inputs of OPAMPs have infinitely high impedance, and there is no input current. In real OPAMPs, there may be a small input current, I_{IB}, called input bias current. The input bias current can vary between tens of femtoamperes to a few microamperes. FET input OPAMPs have very small input bias currents, while BJT OPAMPs have higher values. These currents may depend on temperature. In a FET input OPAMP, as temperature increases by 10°C, the bias current doubles.

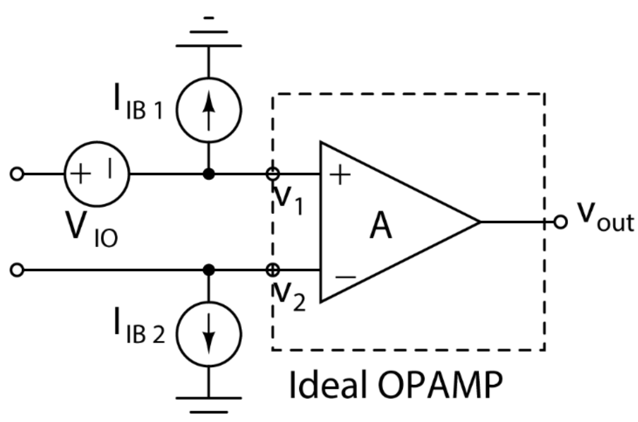
Input Offset Current

Due to asymmetry, there may be a difference between the two input bias currents. Input offset current is the difference between the input bias currents of two OPAMP inputs: $I_{IO}=I_{IB1}-I_{IB2}$.

Input Offset Voltage

An ideal OPAMP's output voltage is written as $A(v_1-v_2)$ where A is the large gain value. With an input offset voltage, the output voltage is written as $A(v_1-v_2-v_{offset})$ where v_{offset} is the input offset voltage. Some OPAMPs have additional pins to help zero the input offset voltage. The input offset voltage is also a function of temperature, usually specified by a temperature coefficient of the input offset voltage.

The model of the OPAMP, including these effects, is shown below:



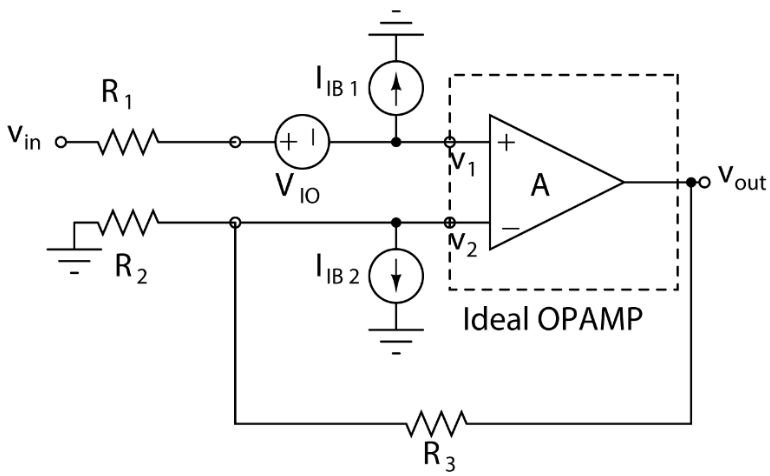
Worst case parameters

The table below shows the worst-case values of these parameters for some common OPAMPs at 25°C. Actual values are smaller in magnitude than the given values.

	LM358/LM324	TL062	TL084
Max input bias current (nA)	−250	0.4	0.4
Max input offset current (nA)	± 50	± 0.2	± 0.2
Max input offset voltage (mV)	± 7	± 15	± 15
$\partial V_{IO}/\partial T$ (µV/°C)	7	10	18

The effect of non-ideal parameters on the performance

The circuit below is the model of a non-inverting amplifier with non-ideal effects included:



We can write

$$v_1 = v_{in} - I_{IB1}R_1 - V_{IO} \text{ and } v_2 = v_{out}\, R_2/(R_2+R_3) - I_{IB2}(R_2 \| R_3)$$

Since $v_1 = v_2$, we find

$$v_{out} = (1+R_3/R_2)\,(v_{in} - V_{IO}) + I_{IB2}\,R_3 - I_{IB1}\,R_1\,(R_2+R_3)/R_2$$

The effect of the input bias currents can be minimized $R_1 = R_2 \| R_3$. With such a choice, we have

$$v_{out} = (1+R_3/R_2)\,(v_{in} - V_{IO}) + (I_{IB2} - I_{IB1})\,R_3 = (1+R_3/R_2)\,(v_{in} - V_{IO}) - I_{IO}\,R_3$$

Example

Consider the case of a non-inverting amplifier with a gain of 1001 using LM324. We choose R_2=1KΩ and R_3=1MΩ. To minimize the effect of the input bias currents, we choose R_1=1K ‖ 1M ≈ 1K. For the worst-case condition, we have

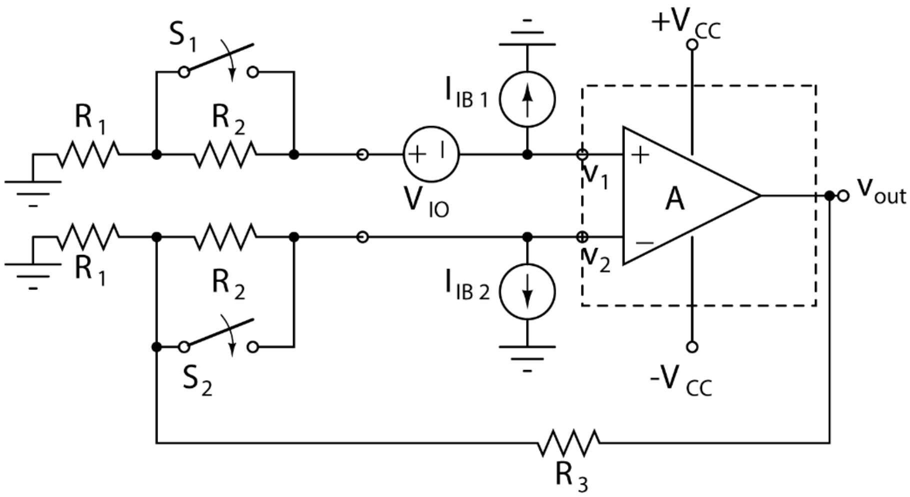
$$v_{out} = 1001\,(v_{in} \pm 0.007) \pm 50\times10^{-9}\ 1\text{M}\Omega = 1001 v_{in} \pm 7 \pm 0.05$$

As the numbers indicate, the input offset voltage is a more serious problem than the input offset current for the resistor values chosen.

In any case, it is a good practice in any OPAMP circuit to choose the Thévenin equivalent resistors seen from the input terminals of the OPAMP to be equal to minimize the effect of input bias currents.

Measurement of Input offset current and voltage

The following circuit can be used to measure the parameters.



Analysis of the circuit gives

$$v_{out} = (1+R_3/R_1)\ [\ -V_{IO} + I_{IB2}\ (R_2 + R_1 \| R_3) - I_{IB1}\ (R_1 + R_2)]$$

If $R_2 \gg R_1$, $R_3 \gg R_1$, and $I_{IB}R_1 \ll V_{IO}$, we make four v_{out} measurements for different combinations of switches and find approximately

$$V_{IO} = -v_{out1}\ R_1/R_3 \text{ with both } S_1 \text{ and } S_2 \text{ closed}$$

$$I_{IB2} = V_{IO}/R_2 + v_{out2}\ R_1/(R_3R_2) \text{ with } S_1 \text{ closed and } S_2 \text{ open}$$

$$I_{IB1} = -\ V_{IO}\ /R_2 - v_{out3}\ R_1/(R_3R_2) \text{ with } S_1 \text{ open and } S_2 \text{ closed}$$

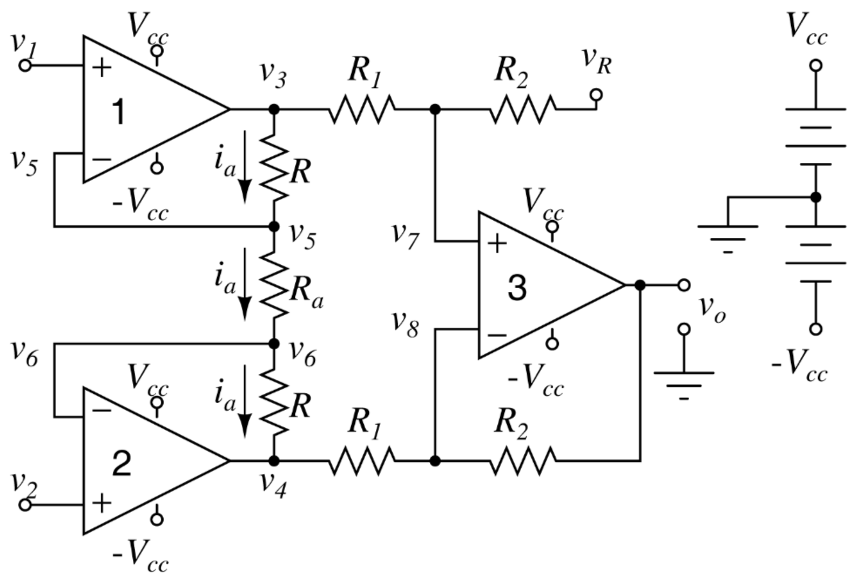
$$I_{IO} = -V_{IO}/R_2\ - v_{out4}\ R_1/(R_3R_2) \text{ with both } S_1 \text{ and } S_2 \text{ open}$$

Typical values for resistors: R_1=100Ω, R_2=100KΩ to 1MΩ, R_3=100KΩ. Larger values of R_2 must be chosen for FET input OPAMPs.

Example: LM324 measurements (with V_{CC}=+12V), R_1=100Ω, R_2=100KΩ, R_3=100KΩ: v_{out1}=−0.593V, v_{out2}=−2.14V, v_{out3}=0.25V, v_{out4}=−1.24V. From the formulas, we find V_{IO}=0.59mV, I_{IB2}=−15nA, I_{IB1}=−8.4nA, and I_{IO}=6.5nA. As a check of results: $I_{IB1}-I_{IB2}$=6.6nA ≈ I_{IO}=6.5nA.

INSTRUMENTATION AMPLIFIER

Instrumentation amplifiers amplify small low-frequency signals obtained from transducers (between v_1 and v_2). They offer small offset voltage and high gain. As shown below, it can be built from three OPAMPs, preferably on the same chip. A single resistor, R_a, can adjust the gain of the instrumentation amplifier. It provides a high input impedance (between v_1 and v_2) and a low output impedance (at v_o). The output voltage can be provided with the required DC shift as determined by the input voltage v_R. Since the input OPAMPs have the same offset voltage, the offset voltages of the input OPAMPs are canceled due to the symmetry of the circuit.



Assuming that the OPAMPs are not saturated, we have $v_1=v_5+v_{offset}$ and $v_2=v_6+v_{offset}$ since the OPAMPs #1 and #2 are identical and have the same temperature. Hence $v_5-v_6=v_1-v_2$. The input offset voltages of OPAMPs #1 and #2 cancel. The current i_a is given by

$$i_a=(v_5-v_6)/R_a=(v_1-v_2)/R_a.$$

Since the same current flows in the neighboring resistors, we have

$$v_3-v_4=i_a(2R+R_a)=(v_1-v_2)(2R+R_a)/R_a.$$

OPAMP #3 is a difference amplifier with an output offset voltage determined by v_R. Using the superposition theorem, we write

$$v_7=R_2/(R_1+R_2)v_3+R_1/(R_1+R_2)v_R \quad \text{and} \quad v_8=R_2/(R_1+R_2)v_4+R_1/(R_1+R_2)v_o$$

since $v_7=v_8+v_{offset}$ (v_{offset} is the input offset voltage of OPAMP #3), the output voltage v_o is given by

$$v_o=v_R+(R_2/R_1)(v_3-v_4)-(R_1+R_2)/R_1\, v_{offset}=v_R+(v_1-v_2)(R_2/R_1)(2R+R_a)/R_a-(R_1+R_2)/R_1\, v_{offset}$$

If the gain of the difference amplifier is kept low (e.g., $R_2=R_1$), the input offset voltage of OPAMP #3 has a negligible effect on the output voltage. So, we have

$$v_o\approx v_R+(v_1-v_2)(R_2/R_1)(2R+R_a)/R_a$$

Single supply voltage operation

One should avoid the saturation of all OPAMPs. The input and output voltages should be in the range specified by the OPAMP datasheet. For example, with single supply (V_{cc}) operation LM324 requires that input voltages be in the range (common mode input voltage range) 0 to V_{CC}−2. The output voltage should be in the range 0.02 to V_{cc}−1.5.

With v_1=v_2, we have

$$i_a=0 \text{ and } v_5=v_6=v_3=v_4=v_1=v_2=v_{sh}$$

We must keep v_3 and v_4 in the middle of the linear range for maximum symmetrical output voltage swing. So, we must shift v_1 and v_2 to the middle of the output linear range. For LM324, this value is v_{sh}=(V_{cc}−1.5)/2.

Similarly, the DC shift of the output voltage (v_o) should be provided by the input voltage v_R to satisfy the linearity requirement. If the input voltage of the instrumentation amplifier is expected to be always positive (v_1>v_2), the change in the output voltage is always in the positive direction. In this case, the output DC shift voltage, V_R, can be chosen to be very small (e.g., 0.02V) to provide the maximum linear operation range.