Op Amp Circuits

Measurement of Offset Voltage, Bias Currents, and Open-loop Gain

Input offset voltage

In an ideal op amp, we assume that the V_o versus V_i curve goes through $(0, 0)$, i.e., for an input voltage of $V_i = 0\,\text{V}$, the output voltage V_o is also $0\,\text{V}$, as shown in Fig. 1 (a). This condition is valid if the transistors in the op amp (see Fig. 2) such as Q_1 and Q_2 which are supposed to be identical are indeed identical in all respects. In reality, there are always some small differences between them, e.g., their β values could be slightly different. As a result of this mismatch, the V_o versus V_i relationship of a real op amp exhibits a shift along the V_i axis, as shown in Fig. 1 (b).

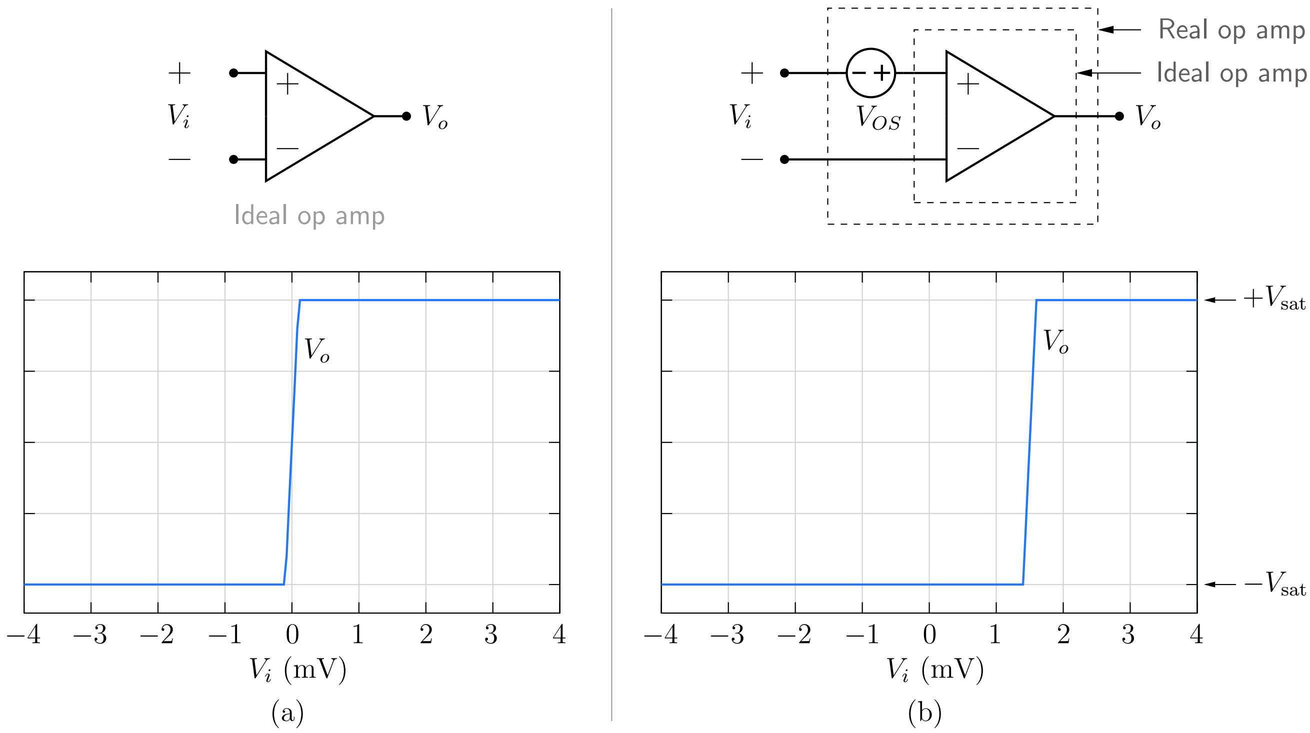

Figure 1: V_o versus V_i relationship for (a) ideal op amp, (b) op amp with an input offset voltage $V_{OS} = -1.5\,\text{mV}$.

The effect of the offset voltage can be incorporated with a voltage source V_{OS} (called the input offset voltage), as shown in Fig. 1 (b). In other words, if we apply $V_i = V_+ - V_- = -V_{OS}$, we get an output voltge $V_o = 0\,\text{V}$. For Op Amp 741, the offset voltage is typically in the range $-5\,\text{mV}$ to $+5\,\text{mV}$.

Input bias currents

The transistors of the input stage (Q_1 and Q_2 in Fig. 2) of Op Amp 741 draw small but non-zero base currents I_B^+ and I_B^-. Since Q_1 and Q_2 may not be perfectly matched, I_B^+ and I_B^-

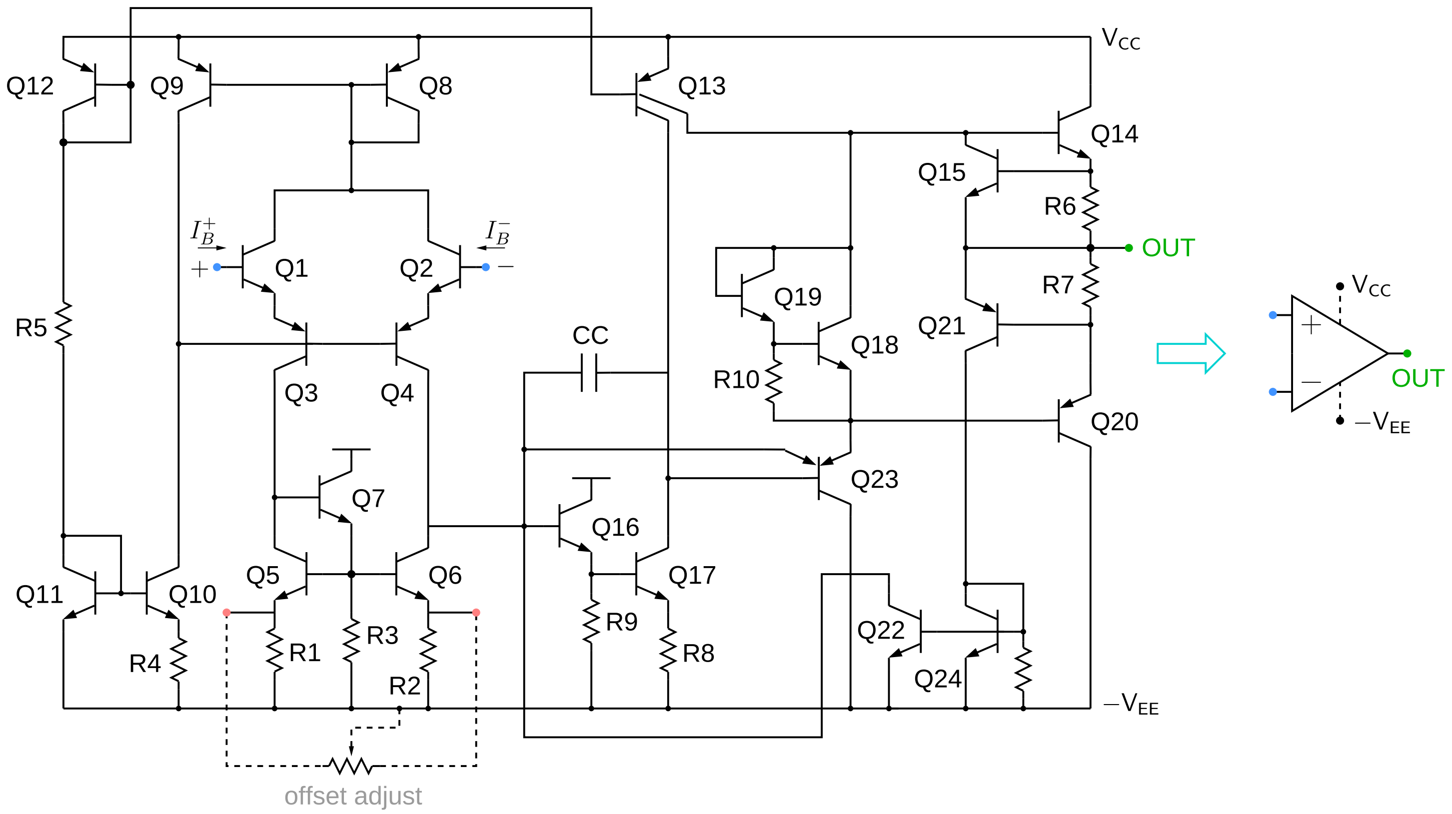

Figure 2: Internal circuit of Op Amp 741.

would be generally different. The average of the two currents is called the input bias current I_B, and the difference between the two is called the input offset current I_{OS}, i.e.,

$$I_B = \frac{I_B^+ + I_B^-}{2}, \quad I_{OS} = |I_B^+ - I_B^-|\,. \tag{1}$$

For Op Amp 741, I_B is typically 100 nA, and I_{OS} is 10 nA at 25 °C.

The effect of the bias currents can be represented by the equivalent circuit shown in Fig. 3 (a), and the overall op amp model showing bias currents as well as offset voltage is shown in Fig. 3 (b).

Measurement of offset voltage and bias currents [1]

When an op amp is used in a circuit, the bias currents I_B^+ and I_B^- as well as the input offset voltage V_{OS} would generally affect the output voltage. In order to measure these quantities, we require circuits which enhance the contributions of one of these parameters while keeping the other two contibutions small.

Fig. 4 (a) shows a circuit which can be used for measurement of V_{OS}. Fig. 4 (b) shows the same circuit re-drawn using the op amp equivalent circuit of Fig. 3 (b) which accounts for the op-amp non-idealities, viz., V_{OS}, I_B^+, and I_B^-. Using superposition, we can show that

$$V_o = V_{OS}\left(1 + \frac{R_2}{R_1}\right) + R_2 I_B^-\,. \tag{2}$$

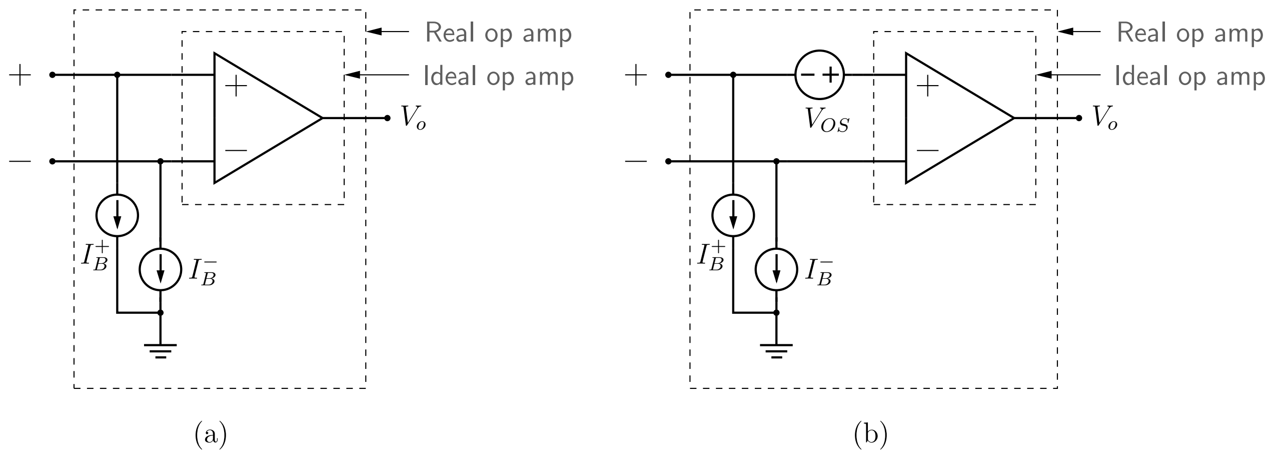

Figure 3: (a) Representation of bias currents of an op amp, (b) representation of bias currents and offset voltage of an op amp.

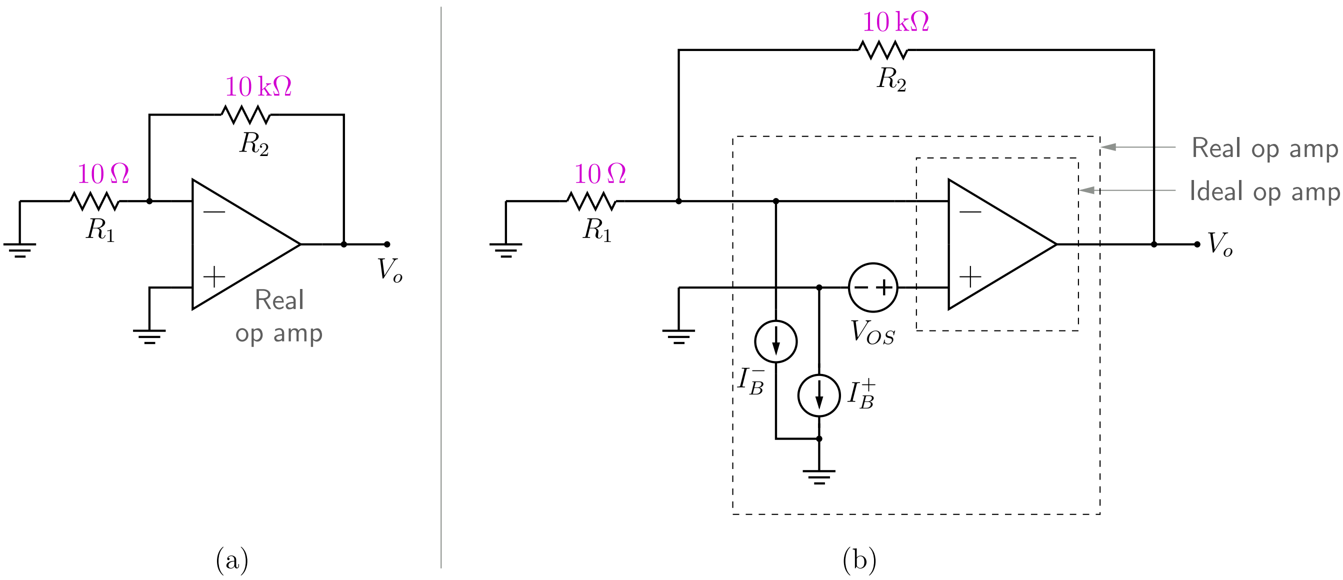

Figure 4: (a) Circuit for measurement of V_{OS}, (b) equivalent circuit.

For $V_{OS} \approx 5\,\text{mV}$ and $I_B^- \approx 100\,\text{nA}$, the contributions from the two terms for $R_1 = 10\,\Omega$ and $R_2 = 10\,\text{k}\Omega$ are about 5 V and 1 mV, respectively. Clearly, I_B^- has a negligible effect on the output voltage, and we can write

$$V_{OS} = \frac{V_o}{1 + R_2/R_1} \approx \frac{V_o}{R_2/R_1}\,. \tag{3}$$

A circuit for measurement of the bias current I_B^- is shown in Fig. 5 (a), and the corresponding equivalent circuit is shown in Fig. 5 (b). Since the op amp in Fig. 5 (b) is ideal, we have $V_- = V_+ = V_{OS}$, and the output voltage is

$$V_o = V_- + I_B^- R = V_{OS} + I_B^- R\,. \tag{4}$$

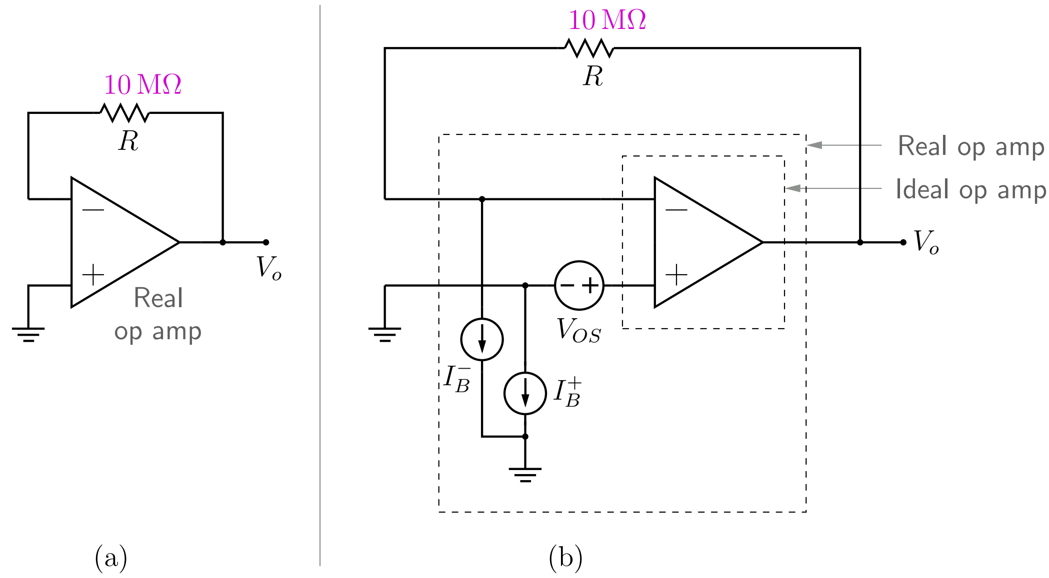

Figure 5: (a) Circuit for measurement of I_B^-, (b) equivalent circuit.

As an example, let $V_{OS} = 5\,\text{mV}$ and $I_B^- = 100\,\text{nA}$. With $R = 10\,\text{M}\Omega$, the second term is 1 V which is much larger than V_{OS}, and therefore we get

$$I_B^- = V_o/R\,. \tag{5}$$

The circuit shown in Fig. 6 (a), with the corresponding equivalent circuit shown in Fig. 6 (b), can be used for measurement of I_B^+. Since the input current for the ideal op amp of Fig. 6 (b)

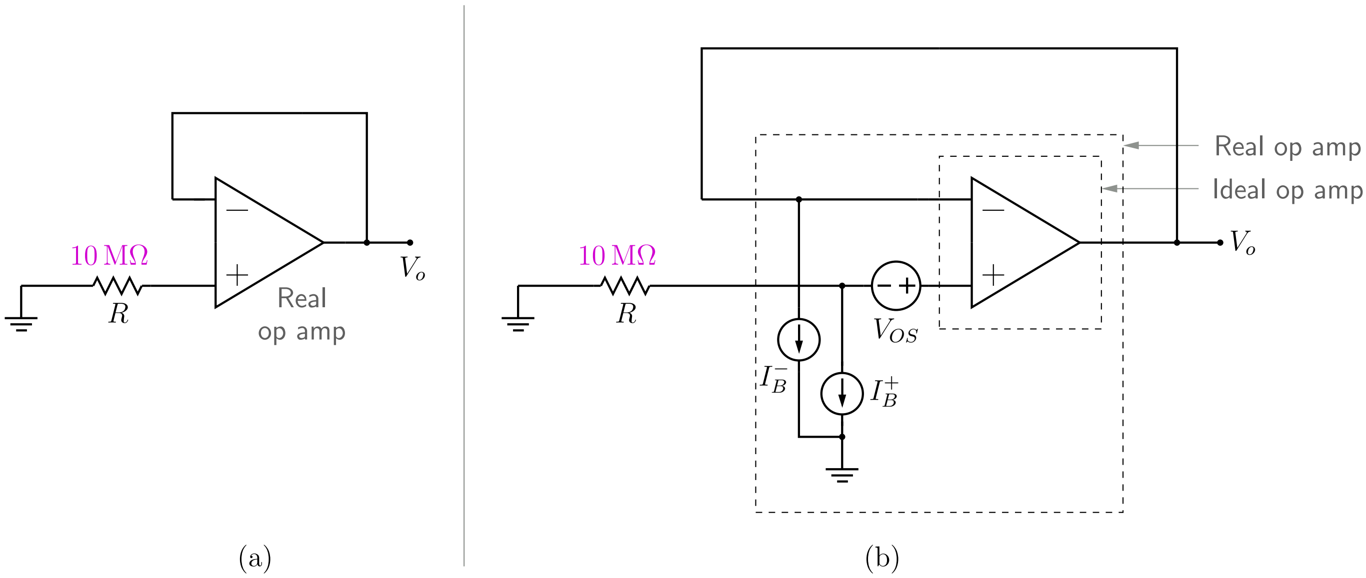

Figure 6: (a) Circuit for measurement of I_B^+, (b) equivalent circuit.

is zero, the current I_B^+ must go through R, causing $V_+ = I_B^+ R + V_{OS}$, and

$$V_o = V_- = V_+ = I_B^+ R + V_{OS}\,. \tag{6}$$

For typical values of I_B^+ and V_{OS}, with $R = 10\,\text{M}\Omega$, the first term dominates, giving

$$I_B^+ = V_o/R\,. \tag{7}$$

Measurement of DC open-loop gain

One of the most important features of an op amp is a high open-loop gain A_{OL} which is typically in the range 10^5 to 10^6. Measurement of A_{OL} with a simple scheme shown in Fig. 7 does not work for the following reasons:

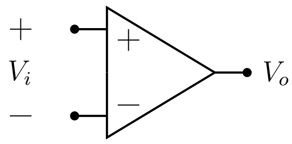

Figure 7: An op am operated in the open-loop configuration.

(a) With a large gain of 10^5 or more, the op amp is likely to be driven to saturation on account of the input offset voltage V_{OS} which is typically in the range $-5\,\text{mV}$ to $+5\,\text{mV}$ for Op Amp 741.

(b) Even if we had a magical op amp with $V_{OS} = 0\,\text{V}$ (or we compensated for the effect of V_{OS} by some means), measurement of A_{OL} is still a challenge. Suppose $A_{OL} = 2 \times 10^5$, and we want an output voltage of 1 V, for example. This would require $V_i = 1\,\text{V}/2 \times 10^5 = 5\,\mu\text{V}$, a very small voltage to apply or measure in the lab.

Given the above difficulties, how to we reliably measure V_{OL}? The trick is to use the op amp in a "servo loop" which ensures that its input voltage remains small enough to keep it in the linear region. Fig. 8 shows the circuit diagram [2]. The op amp for which we want to measure A_{OL}

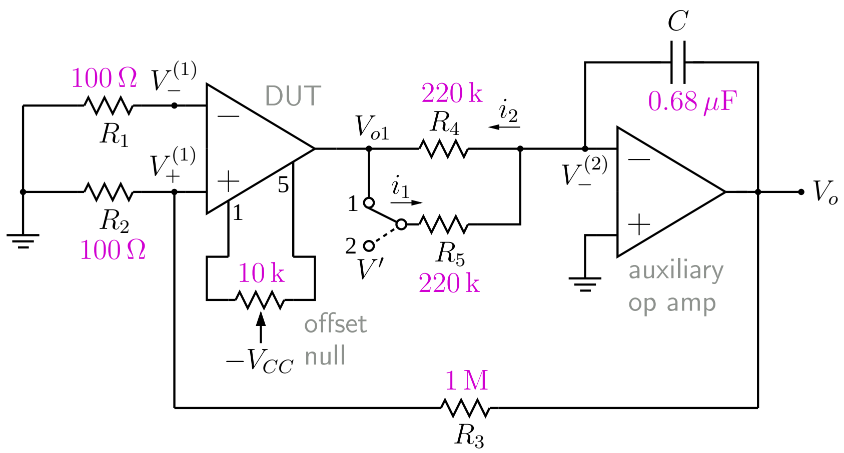

Figure 8: Measurement of DC open-loop gain A_{OL}.

is marked in the figure as the Device Under Test (DUT). The circuit has a high overall gain, but because of the negative feedback provided by R_3, it is stable. The capacitor C prevents the circuit from oscillating. We can measure the open-loop gain A_{OL} of the DUT using the following steps.

(a) Using the 10 k pot, we first nullify the effect of the offset voltage of the DUT to the extent possible, i.e., we adjust the pot, with the switch in position 1 (or simply open), to make V_o as small as possible. Let us use V_o^A and V_{o1}^A to denote the values of V_o and V_{o1}, respectively, in this situation. Because of the large gain of the auxiliary op amp, we can say that $V_{o1}^A = 0\,\text{V}$.

(b) We now change the switch to position 2. With $V_-^{(2)} \approx V_+^{(2)} = 0\,\text{V}$ and with the capacitor behaving like an open circuit in the DC condition, we have $i_1 = i_2$, and

$$V_{o1} = V_-^{(2)} - i_2 R_4 = 0 - \frac{V'}{R_5}\,R_4 = -V'\,. \tag{8}$$

In this situation, let V_o be denoted by V_o^B and V_{o1} by V_{o1}^B. We can attribute the difference $(V_o^B - V_o^A)$ to the change in V_{o1}, i.e., $\Delta V_{o1} = V_{o1}^B - V_{o1}^A = -V' - 0 = -V'$.

For the DUT, its output V_{o1} has undergone a change of $-V'$, and it is a result of a change in $(V_+^{(1)} - V_-^{(1)})$ which is equal to $\dfrac{R_2}{R_2 + R_3} \times (V_o^B - V_o^A)$. In other words,

$$\frac{R_2}{R_2 + R_3}\,(V_o^B - V_o^A) \times A_{OL} = -V'\,, \tag{9}$$

which can be used to obtain A_{OL} for the DUT.

References

1. Texas Instruments, "Understanding Op Amp parameters,"
   `http://www.ti.com/lit/ml/sloa083/sloa083.pdf`

2. James Bryant, "Simple Op Amp measurement,"
   `http://www.analog.com/library/analogDialogue/archives/45-04/op_amp_measurements.html`