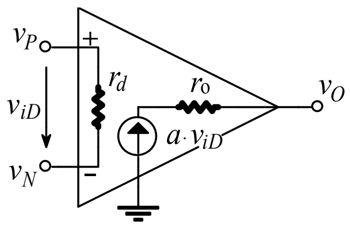
OpAmp dc Effects and Limitations

Low Frequency Model of OpAmp

The model contains an input differential resistance r_d, an output resistance r_o and a finite open-loop differential gain a.



r_d – differential input resistance
r_o – output resistance
a – open-loop differential gain

Figure – *OpAmp low frequency model*

Feedback in OpAmp Circuits

Typical topologies for input mixing and output sampling are presented in the next figure.

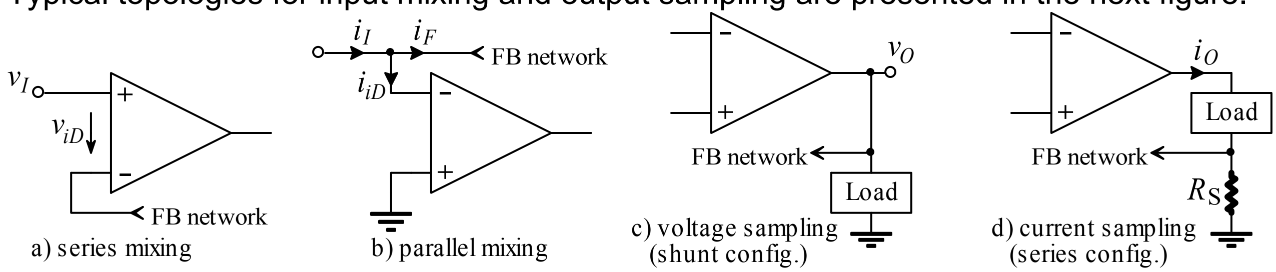


Figure – *Four possible feedback topologies*

Based on the OpAmp model and feedback theory the basic configuration (inverting and non-inverting amplifiers) will be analyzed

The Non-inverting Configuration

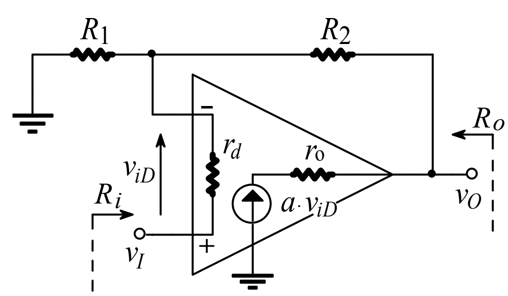


Figure – *Non-inverting amplifier with the low-frequency OpAmp model*

Approximate calculations of gain consider a model with ideal input and output impedances (infinite r_d and zero r_o).

$$v_D = \frac{v_O}{a}, \qquad v_N = v_I - v_D = v_I - \frac{v_O}{a} = R_1 \cdot i_1, \qquad i_1 = \frac{v_I - v_O/a}{R_1}$$

$$v_O = (R_2 + R_1) \cdot i_1 = (R_2 + R_1)\frac{v_I - v_O/a}{R_1}$$

$$R_1 \cdot v_O + (R_2 + R_1) \cdot \frac{v_O}{a} = (R_2 + R_1) \cdot v_I \qquad v_O\left(R_1 + \frac{R_2 + R_1}{a}\right) = (R_2 + R_1) \cdot v_I$$

$$A = \frac{v_O}{v_I} = 1 + \frac{R_2}{R_1} \cdot \frac{1}{1 + \frac{1}{a} + \frac{R_2}{a \cdot R_1}}$$

The feedback factor is:

$$b = \frac{v_F}{v_O} = \frac{v_N}{v_o} = \frac{R_1}{R_1 + R_2}.$$

Based on the feedback theory of the series mixing, voltage sampling configuration, the input and output impedances of the circuit are:

$$R_i \cong r_d(1 + a \cdot b) = r_d\left(1 + a \cdot \frac{R_1}{R_1 + R_2}\right), \quad R_o \cong \frac{r_o}{1 + a \cdot b} = \frac{r_o}{1 + a \cdot \frac{R_1}{R_1 + R_2}},$$

where r_d is the input differential resistance and r_o is the output resistance of the OpAmp.

The Inverting Configuration

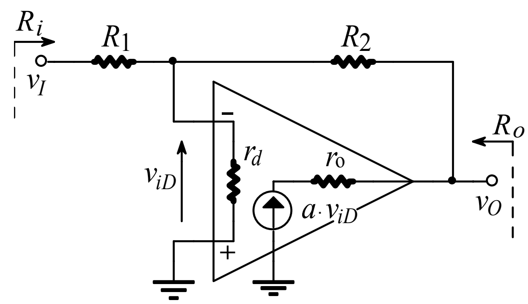


Figure – *Inverting amplifier with the low-frequency OpAmp model*

Same approximations of ideal input and output impedances (infinite r_d and zero r_o) are used to simplify calculations of gain:

$$i_1 = \frac{v_I - v_D}{R_1} = \frac{v_I - v_O/a}{R_1} = i_2 = -\frac{v_O + v_O/a}{R_2}, \quad \frac{v_I}{R_1} = -\frac{1}{R_2}\left(v_O + \frac{v_O}{a} + \frac{v_O}{a}\frac{R_2}{R_1}\right),$$

$$A = \frac{v_O}{v_I} = -\frac{R_2}{R_1} \cdot \frac{1}{1 + \frac{1}{a} + \frac{R_2}{a \cdot R_1}}$$

The input impedance in the inverting terminal of the OpAmp R_n is affected by a shunt mixing feedback:

$$R_n = \frac{R_2 + r_o}{1 + a \cdot b} = \frac{R_2 + r_o}{1 + a \cdot \frac{R_1}{R_1 + R_2}}.$$

The circuit input and output impedances are:

$$R_i = R_1 + \frac{R_2 + r_o}{1 + a \cdot \frac{R_1}{R_1 + R_2}} \quad \text{and} \quad R_o \cong \frac{r_o}{1 + a \cdot b} = \frac{r_o}{1 + a \cdot \frac{R_1}{R_1 + R_2}}.$$

The amplifier parameters (A, R_i and R_o) are very closed to the ideal case for both inverting and non-inverting configuration.

Offset Voltage and Currents

In practice a dc offset voltage can be measured at the output terminal even when the dc input voltage is zero.

The total output offset voltage can be considered to be a function of two separate effects:

- input offset voltage and
- input bias currents.

Both of the two effects are referred to the input (and measured at the output).

Both input terminals must have a dc path to the ground; such are dc connection to the output or dc path through a grounded source.

Offset Circuit Model

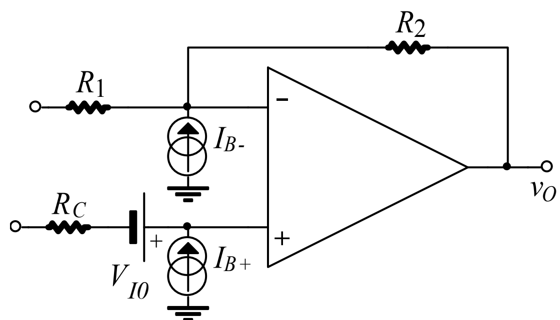


Figure – *Offset circuit model – ideal sources connected to an ideal OpAmp*

V_{I0} – input offset voltage

I_{B+} – input bias current at the non-inverting input

I_{B-} – input bias current at the inverting input

The directions at the current sources are arbitrary as long as both have the same directions.

The effect of the input offset voltage at the output can be either positive or negative at a given time, so that direction of V_{I0} is arbitrary.

The basis for the offset analysis is the principle of superposition.

Input Offset Voltage

The effect of V_{I0} at the output will be V_{O1}. This output voltage is computed (based on superposition) with all other independent sources set to zero:

- bias current sources I_{B+} and I_{B-} will be omitted (current sources set to zero),
- circuit inputs will be grounded (voltage signal sources set to zero).

The circuit that remains is the basic non-inverting amplifier and its output is:

$$|V_{O1}| = \left(1 + \frac{R_2}{R_1}\right) \cdot V_{I0}$$

The actual output can be this value or its negative.

Input Bias Currents

The effect of I_{B+} at the output will be V_{O2+}. The non-inverting input voltage produced by the bias current at this input over the resistance R_C is: $R_C I_{B+}$ and the corresponding output is:

$$|V_{O2+}| = R_C I_{B+}\left(1+\frac{R_2}{R_1}\right)$$

The direction of the offset produced by I_{B+} will always be opposite to that of the I_{B-}:

$$|V_{O2-}| = -R_2 I_{B-}$$

The current through R_1 is zero because the voltage over this resistor (v_N) is zero (the inverting terminal is a virtual ground).

Both input bias currents effect at the output is:

$$|V_{O2}| = \left|R_C\left(1+\frac{R_2}{R_1}\right)I_{B+} - R_2 I_{B-}\right|$$

With an initial assumption that the two bias currents are approximate equal:

$$I_{B+} = I_{B-} = I_B \,,$$

the cancellation of the terms inside the magnitude bars (absolute value bars) can be achieved for:

$$|V_{O2}| = \left|R_C\left(1+\frac{R_2}{R_1}\right)I_B - R_2 I_B\right| = 0 \,.$$

This will give the compensation resistor value that reduces to zero the offset component produced at the output by identical bias currents:

$$R_C = \frac{R_1 R_2}{R_1 + R_2} \,.$$

If the bias currents are not equal and with an optimum R_C, the output offset is:

$$|V_{O2}| = R_2 |I_{B+} - I_{B-}| \quad \text{for} \quad R_C = R_1 \parallel R_2 \,.$$

Input Offset Current

The bias current difference term from the previous relationship appears so frequently that it is assigned a unique definition; that is the input offset current I_{I0}:

$$I_{I0} = |I_{B+} - I_{B-}| \,.$$

The input offset current is the magnitude of the difference between the bias currents at the two inputs. The magnitude of the output voltage offset produced by bias currents with an optimum value of compensating resistance is:

$$|V_{O2}| = R_2 I_{I0} \quad \text{for} \quad R_C = R_1 \parallel R_2 \,.$$

Typical Offset Values

The data sheet for the general purpose OpAmp with the code 741 (e.g. LM741, μA741) indicates offset values:

- V_{I0} – typical value is 1 mV and maximum value is 5 mV;
- I_B – typical value is 80 nA and maximum value is 500 nA;
- I_{I0} – typical value is 20 nA and maximum value is 200 nA.

Null Circuit

Most OpAmps have provisions for nulling or eliminating offset effect at a particular operation point. A variable resistance is adjusted so that the dc output level is zero.