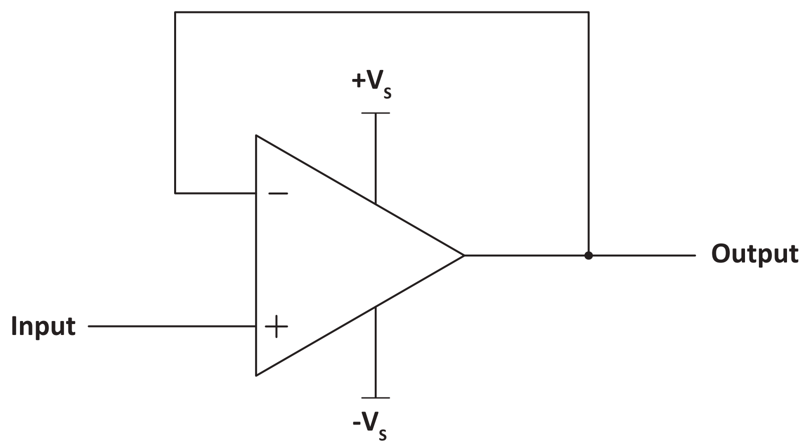
AN71

Op-amp Unity Gain Frequency Response

UNITY GAIN OPERATION

The term ‘unity gain’ in operational amplifiers (op-amps) refers to a configuration where the amplifier has a gain of 1 Volt per Volt. This means that the output voltage is equal to the input voltage (assuming an ideal op-amp with infinite input impedance and zero output impedance). This configuration is commonly achieved by, but not limited to, using a voltage follower or buffer setup, where the output is connected directly to the inverting input, and the signal is fed into the non-inverting input.

Figure 1: Non-Inverting Unity Gain Topology

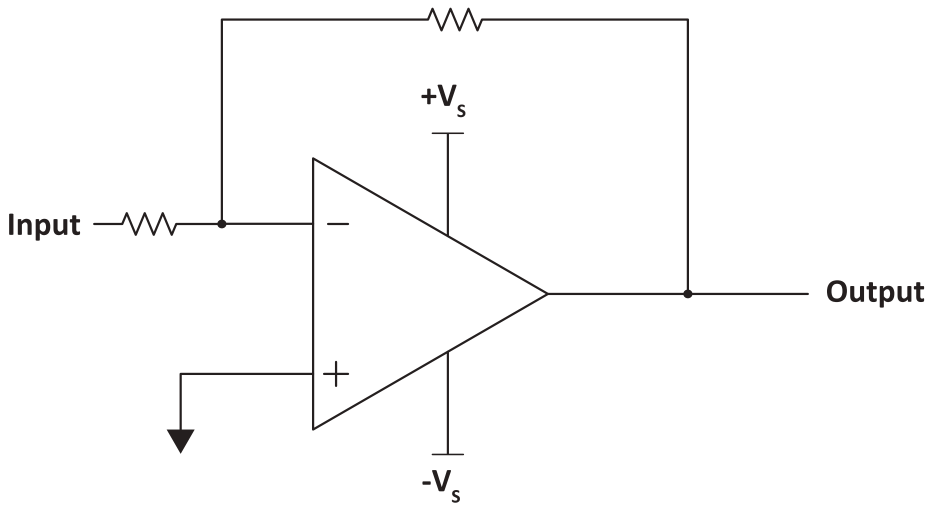


This application note will focus on the practical application of op-amps used at unity gain, and more specifically, the differences in bandwidth that come along with implementing either non-inverting or inverting unity gain configurations.

Before demonstrating the differences in bandwidth between non-inverting and inverting configurations, it would be helpful to review the basic op-amp theory and associated transfer functions for both ideal inverting and non-inverting amplifiers. Additionally, it will be useful to discuss the open loop gain and frequency response characteristics involved with unity gain applications.

AMPLIFIER TRANSFER FUNCTION AND OPEN LOOP GAIN

Figure 2: Inverting Unity Gain Topology



In Figure 3 below, resistors are used for the input and feedback elements. R_{IN} is commonly referred to as the input resistor or summing resistor and R_{FB} is referred to as the feedback resistor. If the operational amplifier is assumed to have ideal properties, no current flows into the input of the operational amplifier, and therefore $I_{IN} = I_{FB}$:

$$I_{IN} = \frac{V_{IN} - V_D}{R_{IN}} = I_{FB} = \frac{V_D - V_{OUT}}{R_{FB}}$$

Rearranging this yields the output:

(1-1)

$$V_{OUT} = -\frac{R_{FB}}{R_{IN}}V_{IN} + \left(\frac{R_{FB}}{R_{IN}} + 1\right)V_D$$

But by definition:

$$V_{OUT} = -AV_D \qquad \text{or} \qquad V_D = -\frac{V_{OUT}}{A}$$

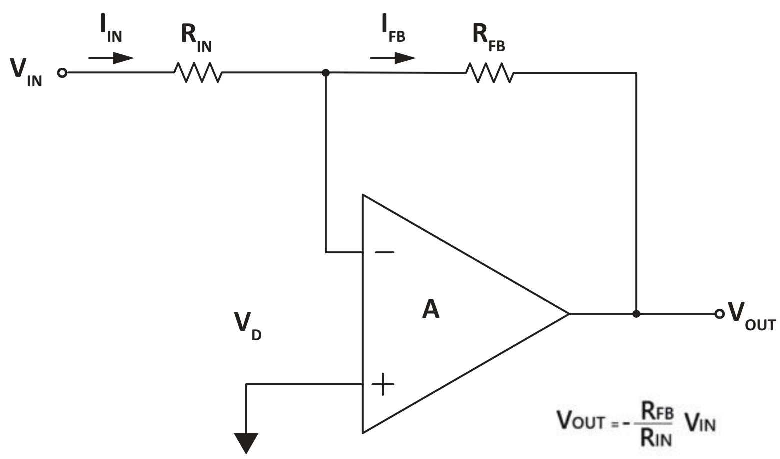
and for arbitrarily large gain(A), as A → ∞, V_D → zero. The equation is then reduced to:

(1-2)

$$\frac{V_{OUT}}{V_{IN}} = -\frac{R_{FB}}{R_{IN}}$$

Notice in Equation 1-2 that the inverting configuration transfer function is dependent on the feedback network, R_{FB}/R_{IN}. Also, because the amplifier has arbitrarily large gain, the summing point voltage, V_D, approaches zero and is a virtual ground.

Figure 3: Inverting Configuration



Two characteristics to remember about summing point constraints that result from ideal op-amp properties:

1. No current flows into either input of the ideal operational amplifier.

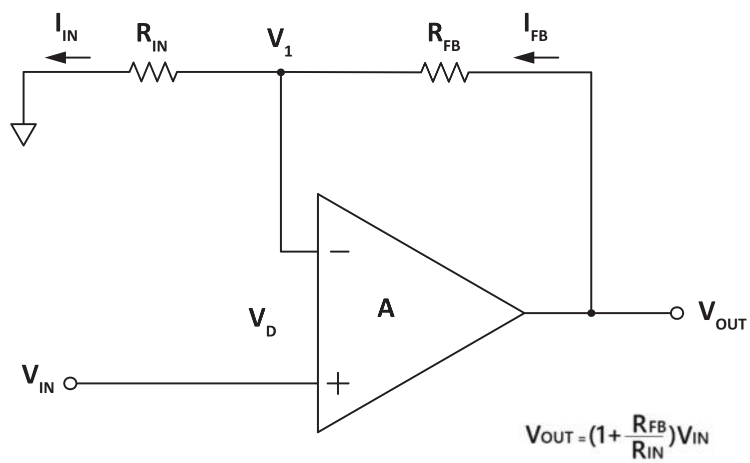
2. When negative feedback is applied around the ideal operational amplifier, the differential input voltage, V_D, approaches zero as A approaches infinity.

Ideal operational amplifier properties are listed below:

Gain = ∞	A → ∞
Offset Voltage = 0	V_{OS} → 0
Input Bias Current = 0	$I_{B1} = I_{B2}$ → 0
Input Impedance = ∞	Z_{IN} → ∞
Output Impedance = 0	Z_{OUT} → 0

With the inverting amplifier, from the previous section, the input signal was fed into the inverting input terminal. The non-inverting amplifier requires the input signal to be fed to the non-inverting input terminal.

Figure 4: Non-Inverting Configuration



The non-inverting amplifier circuit is shown in Figure 4 above. The input signal is applied to the non-inverting (+) input, and a portion of the output is fed back to the inverting (-) input.

If it is assumed that the operational amplifier is ideal, $I_{IN} = I_{FB}$, and the input bias current (I_B) is essentially zero, then the following equations apply:

$$V_1 = \frac{R_{IN}}{R_{IN} + R_{FB}} V_{OUT}$$

V_D approaches zero as A approaches infinity:

$$V_1 = V_{IN} + V_D = V_{IN} - \frac{V_{OUT}}{A} = V_{IN}$$

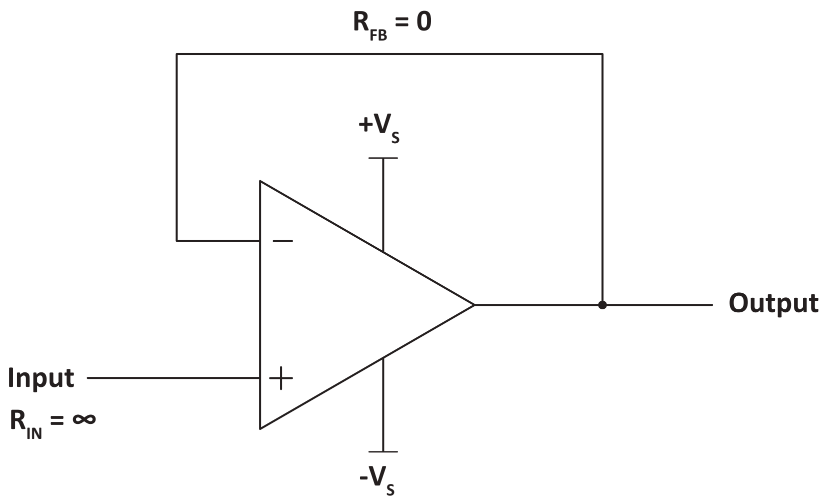
Combining these two equations above and solving for V_{OUT} yields the transfer function equation:

(1-3)

$$\frac{V_{OUT}}{V_{IN}} = \left(1 + \frac{R_{FB}}{R_{IN}}\right)$$

Note, that with an ideal operational amplifier, the non-inverting circuit's transfer function is dependent on the feedback network as it was in the inverting mode. In practice, this voltage follower is implemented by making R_{IN} = ∞ (accomplished by placing no resistor in the inverting input path, = ∞ per ideality) and shorting the output to the inverting input (R_{FB} = 0). This configuration provides a gain of 1V/V.

Figure 5: Ideal Op-amp Non-Inverting Configuration



$R_{IN}(Z_{IN})$ = ∞, per ideal op-amp configurations

Open-loop gain refers to the magnitude of the amplification factor of an operational amplifier with no feedback loop. It is generally abbreviated as simply A or A_{OL}. Closed loop gain refers to the amplification factor that is dictated by the configuration of the external feedback circuit built around an operational amplifier and is commonly abbreviated as A_{CL}. While the amplifier's open loop gain at low frequencies is very large, typically from 90 dB or 1 x $10^{4.5}$ V/V to 140 dB or 10^7 V/V, the open loop gain is a finite quantity and will produce an error in the closed loop gain response that increases with operating frequency. To analyze the effect of finite open-loop gain on the closed-loop gain response, it is convenient to define the feedback factor (β). The feed-back factor in an op-amp circuit, β, refers to the portion of the output voltage that is fed back to the inverting input through the feedback network. It plays a central role in determining the gain, stability, and bandwidth of the amplifier. The feedback factor differs significantly between inverting unity gain and non-inverting unity gain configurations, which will be discussed in further detail in a later section. The dependence on β and its effect on inverting and non-inverting transfer functions is shown here.

β may be defined as:

$$\beta = \frac{R_{IN}}{R_{IN} + R_{FB}}$$

The above equation is shown in a more convenient and/or useful form:

(1-4)

$$\beta = \frac{1}{1 + \frac{R_{FB}}{R_{IN}}}$$

In this case, the output of the inverting amplifier, equation 1-1, can be written as:

(1-5)

$$V_{OUT} = -\frac{R_{FB}}{R_{IN}}V_{IN} + \frac{V_D}{\beta}$$

Since $V_D = \frac{-V_{OUT}}{A}$, by substituting this into Equation (1-5) and rearranging, we obtain the closed loop transfer function for the inverting circuit:

(1-6)

$$A_{CL} = \frac{V_{OUT}}{V_{IN}} = -\frac{R_{FB}}{R_{IN}}\left(\frac{1}{1 + \frac{1}{A\beta}}\right)$$

A similar analysis of the non-inverting circuit yields:

(1-7)

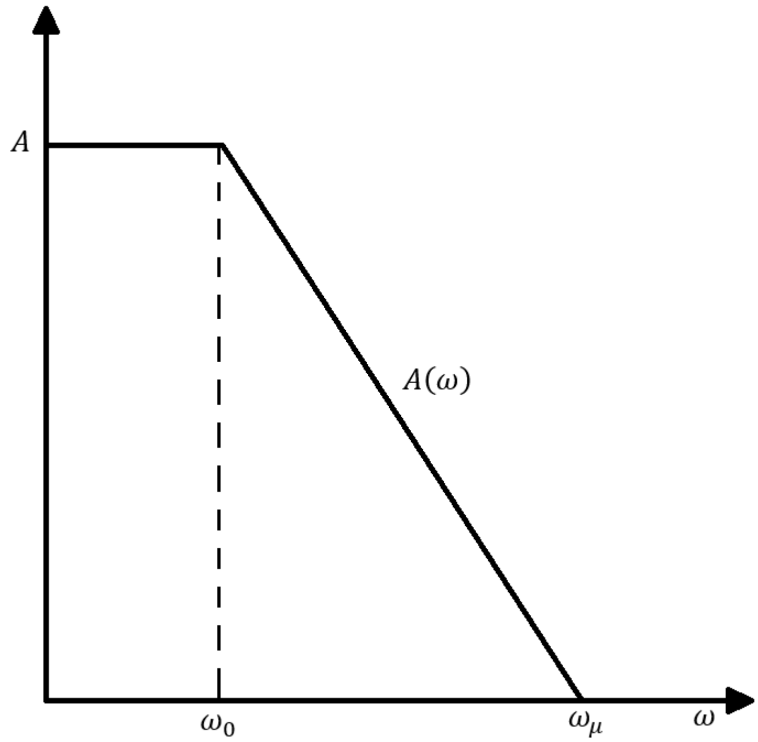
$$A_{CL} = \frac{V_{OUT}}{V_{IN}} = \left(1 + \frac{R_{FB}}{R_{IN}}\right)\left(\frac{1}{1 + \frac{1}{A\beta}}\right)$$

The term Aβ that is shown above, is commonly referred to as loop gain, since it may be thought of as the gain around the feedback loop formed by the amplifier and the feedback network. Since loop gain decreases as a function of frequency, then β influences gain error. The gain error in these equations is then simply represented as 1/Aβ. As would be expected from this error term, finite open-loop gain is a significant error source for large magnitude closed loop gain applications.

Now the frequency response characteristics can be determined. The Bode plot of Figure 6 represents the typical op-amp frequency response. This aids in understanding the difference in bandwidth between both configurations.

FREQUENCY RESPONSE FOR UNITY GAIN CONFIGURATIONS

Figure 6: Frequency Response Bode Plot



In the frequency response plot above:

A = open loop gain

ω = frequency

A(ω) = open loop gain as a function of frequency

ω_0 = frequency at -3dB point

ω_μ = gain bandwidth product

The following equation is given for open loop gain, A, as a function of frequency, ω:

(1-8)

$$A(\omega) = \frac{A}{1 + \frac{\omega}{\omega_0}}$$

Since for an inverting unity gain configuration $R_{IN} = R_{FB}$, then:

$$\beta = \frac{R_{IN}}{R_{IN} + R_{FB}} = \frac{1}{2}$$

Substituting equation 1-8 and β into equation 1-6 yields the following equation:

$$\frac{V_{OUT}}{V_{IN}} = \frac{-1}{1 + \frac{1}{\left[\frac{A}{2\left(1 + \frac{\omega}{\omega_0}\right)}\right]}} = \frac{-1}{1 + \frac{2}{A} + \frac{2\omega}{A \cdot \omega_0}}$$

Since 2/A is very small, the equation can be simplified to:

$$\frac{V_{OUT}}{V_{IN}} = \frac{-1}{1 + \frac{2\omega}{A \cdot \omega_0}}$$

The -3dB point occurs when:

$$\frac{2\omega}{A \cdot \omega_0} = 1$$

However, $\omega_\mu = A\omega_0$ (Gain Bandwidth Product), therefore:

$$A = \frac{\omega_\mu}{\omega_0}$$

Thus the -3dB point occurs when:

$$\frac{2\omega}{\omega_\mu} = 1$$

Rearranging in terms of ω:

$$\omega = \frac{\omega_\mu}{2}$$

These results show that the frequency response capability for inverting configuration is exactly half of the gain bandwidth product. For non-inverting configurations, the frequency response, ω, would equal the entire gain bandwidth product, ω_μ.

This time substituting Equation 1-8 and β into equation 1-7:

$$\frac{V_{OUT}}{V_{IN}} = \frac{1}{1 + \frac{1}{\left[\frac{A}{\left(1 + \frac{\omega}{\omega_0}\right)}\right]}} = \frac{1}{1 + \frac{1}{A} + \frac{\omega}{A \cdot \omega_0}}$$

Since 1/A is very small, the equation can be simplified to:

$$\frac{V_{OUT}}{V_{IN}} = \frac{1}{1 + \frac{\omega}{A \cdot \omega_0}}$$

The -3dB point occurs when:

$$\frac{\omega}{A \cdot \omega_0} = 1$$

Then substituting for A yields:

$$\frac{\omega}{\omega_{\mu}} = 1$$

Rearranging in terms of ω:

$$\omega = \omega_{\mu}$$

This verifies that the frequency response for non-inverting unity gain configuration is twice that of the inverting configuration.

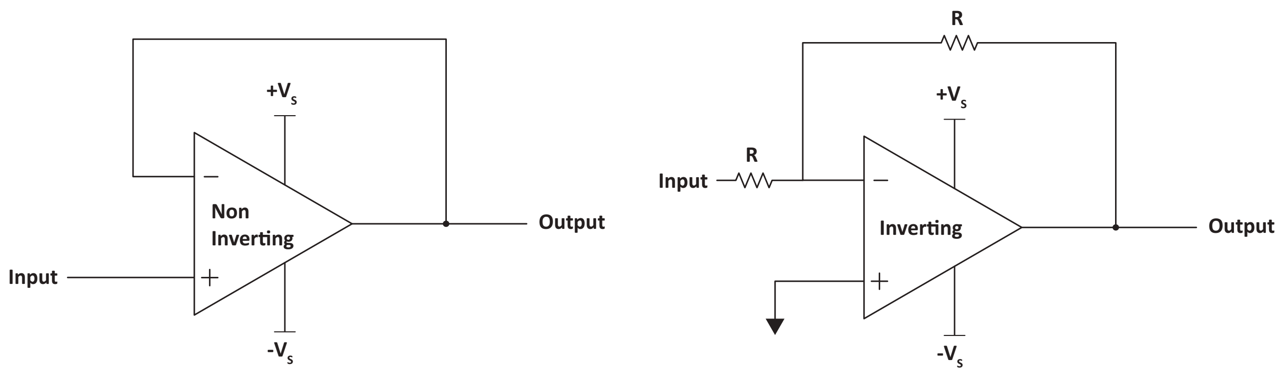
DIFFERENCES BETWEEN INVERTING AND NON-INVERTING UNITY GAIN CONFIGURATIONS

The key difference between inverting unity gain and non-inverting unity gain op-amp configurations results from how the input signal is connected and how the op-amp reproduces the input signal, particularly in terms of bandwidth, phase and input impedance.

In a non-inverting unity gain configuration, also known as a voltage follower, the input signal is applied to the non-inverting (+) input, and the output is connected directly to the inverting (–) input. This creates a feedback loop that forces the op-amp to make the output equal to the input. This configuration provides no phase inversion, meaning the output signal is in phase with the input. It also offers high input impedance and low output impedance, making it ideal for buffering high-impedance sources without loading them. Non-inverting configuration preserves both voltage level and signal integrity and has more usable bandwidth than the inverting configuration.

In comparison, inverting unity gain configuration requires placing a resistor between the input signal and the inverting (–) input, and a feedback resistor of equal value between the output and the inverting input. The non-inverting input is typically grounded. With equal resistor values in the input and feedback path, the closed-loop gain becomes -1 V/V, resulting in a gain magnitude of 1V/V with 180° phase inversion with respect to the input, meaning the output is an inverted version of the input. It is critical that the input and feedback resistances be matched closely in order to achieve an accurate gain of -1V/V in magnitude. Using resistors with mis-matched tolerances or tolerances that are too great can result in increased gain error. The inverting configuration has lower input impedance than non-inverting, equal to the input resistor, and is often used when signal inversion is required or acceptable. This configuration will have significantly less bandwidth than the non-inverting configuration due to the inclusion of extra resistive components. This concept was illustrated mathematically in the frequency response section and a simulation is shown in a later section.

Figure 7: Non-Inverting vs. Inverting Unity Gain



The non-inverting unity gain op-amp maintains the input signal's phase and is ideal for buffering and impedance isolation, while the inverting unity gain op-amp inverts the signal and has more limited input impedance characteristics. Each serves different purposes in circuit design, depending on whether phase integrity or signal inversion is desired.

FEEDBACK FACTOR AS IT RELATES TO BANDWIDTH

In a non-inverting unity gain configuration (voltage follower), the output is connected directly to the inverting input, so 100% of the output is fed back, meaning the feedback factor β = 1. This feedback level makes the circuit output as close to linear as possible. Because of this full feedback factor, the op-amp quickly corrects any deviation between the input and output, resulting in accurate signal tracking and wide bandwidth. The loop gain (Aβ, or A * 1) becomes simply the open-loop gain (A) of the op-amp, and this large loop gain ensures desirable performance in terms of linearity and distortion.

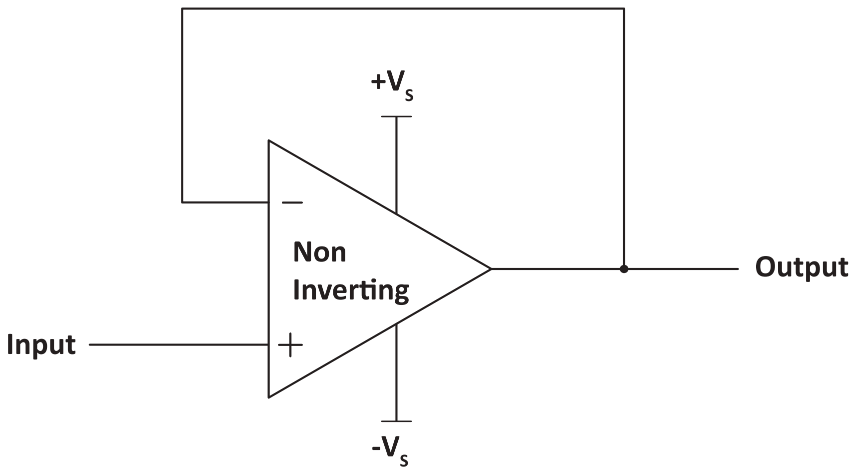
Alternatively, in an inverting unity gain configuration, the feedback network consists of two resistors: one from the input signal to the inverting input, and one from the output to the inverting input, as shown in FIG. 7. When both resistors are equal, the closed-loop gain is –1V/V. However, the feedback factor β in this case is 1/2, because only half of the output voltage (through the resistive voltage driver) is fed back to the inverting input. This lower feedback factor means less of the output voltage is used for error correction, so the loop gain (Aβ) is A⁄2 rather than A. As a result, the inverting unity gain configuration typically has better stability but lower bandwidth and more gain error compared to the non-inverting case, especially when operating at higher frequencies.

The non-inverting unity gain op-amp operates with a feedback factor of β = 1, providing minimum error and maximum frequency response, while the inverting unity gain configuration has a reduced feedback factor of β = 1/2, which leads to less effective error correction and lower usable bandwidth.

The contrast between configurations can be represented mathematically by breaking down the feedback factor (β) and loop gain (Aβ) for both inverting and non-inverting unity gain as shown below:

NON-INVERTING UNITY GAIN (VOLTAGE FOLLOWER) CONFIGURATION:

Figure 8: Non-Inverting Unity Gain Detail



- Input signal is applied to the non-inverting input (+).
- Output is directly connected to the inverting input (-), meaning:

$$V_{-IN} = V_{OUT}$$

Feedback factor (β):

Since the entire output is fed back directly to the inverting input and no resistors are present, a simplified form of the β equation can be used:

$$\beta = \frac{V_{FEEDBACK}}{V_{OUT}} = \frac{V_{-IN}}{V_{OUT}} = 1$$

Which also agrees with Equation 1-4:

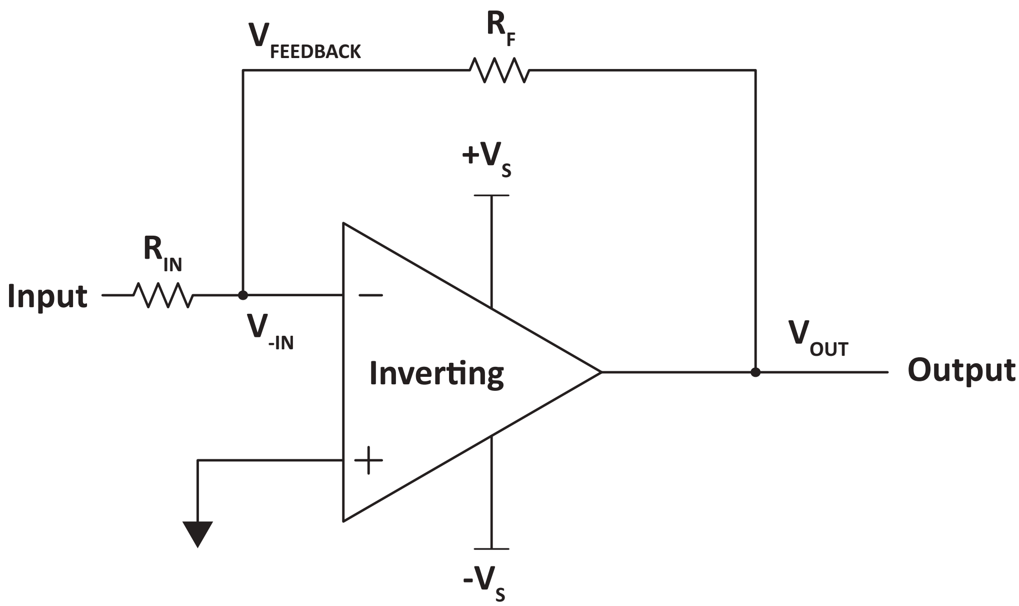
$$\beta = \frac{1}{1 + \frac{R_{FB}}{R_{IN}}} = \frac{1}{1+0} = 1$$

Loop Gain ($A\beta$):

$$A\beta = A_{OL} \cdot \beta = A_{OL} \cdot 1 = A_{OL}$$

The results indicate that, for this configuration, the feedback factor is 1 and the loop gain is the full magnitude of A_{OL}.

Figure 9: Inverting Unity Gain Detail



- The input signal is connected to the inverting input (-) through resistor R_{IN}.
- A feedback resistor R_F connects the output to the inverting input.
- The non-inverting input is grounded
- For unity gain (-1V/V), $R_F = R_{IN}$.

Voltage divider at inverting input:

The voltage at the inverting input is a fraction of the output voltage.:

$$V_{-IN} = \beta V_{OUT} = \frac{R_{IN}}{R_{IN} + R_F} \cdot V_{OUT}$$

Since $R_{IN} = R_F$, this simplifies to:

$$V_{-IN} = \frac{1}{2} \cdot V_{OUT} = \frac{V_{OUT}}{2}$$

Feedback Factor (β):

$$\beta = \frac{V_{FEEDBACK}}{V_{OUT}} = \frac{V_{-IN}}{V_{OUT}} = \frac{\frac{V_{OUT}}{2}}{V_{OUT}} = \frac{1}{2}$$

Which again agrees with equation 1-4:

$$\beta = \frac{1}{1 + \frac{R_{FB}}{R_{IN}}} = \frac{1}{1+1} = \frac{1}{2}$$

Loop Gain (Aβ):

$$A\beta = A_{OL} \cdot \beta = A_{OL} \cdot \frac{1}{2} = \frac{A_{OL}}{2}$$

COMPARISON SUMMARY

Configuration	Feedback Factor (β)	Loop gain ($A_{OL}\beta$)	Gain Error $\left(\frac{1}{1+\frac{1}{A\beta}}\right)$
Non-inverting Unity Gain	1	A_{OL}	1580ppm
Inverting Unity Gain	0.5	$A_{OL}/2$	3125ppm

This comparison table clearly shows that the non-inverting unity gain op-amp has twice the feedback factor and thus a wider bandwidth than the inverting configuration at unity gain. Loop Gain and Gain error are calculated for DC or low frequencies. For Gain Error, the PA85 minimum open loop gain specification of 96dB, from the PA85 datasheet, is used as an example.

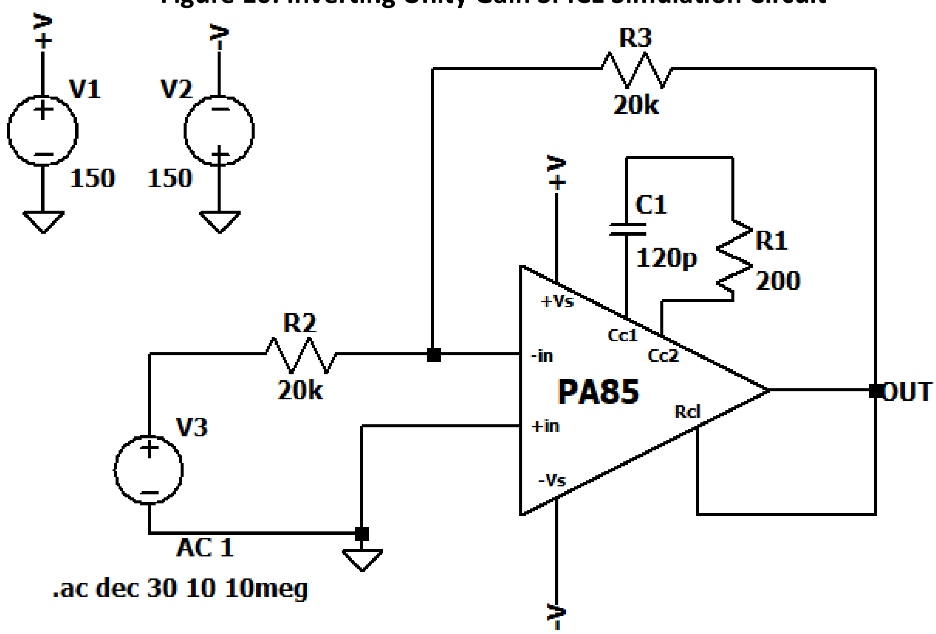
SMALL SIGNAL ANALYSIS TO ILLUSTRATE DIFFERENCE IN BANDWIDTH

Now it would be helpful to review some simulation examples of the bandwidth variation between inverting and non-inverting unity gain configurations that have been described up to this point. These examples can be generated by using an Apex device in either inverting or non-inverting configuration to see how the small signal response and bandwidth may differ.

INVERTING CONFIGURATION SMALL SIGNAL SPICE SIMULATION

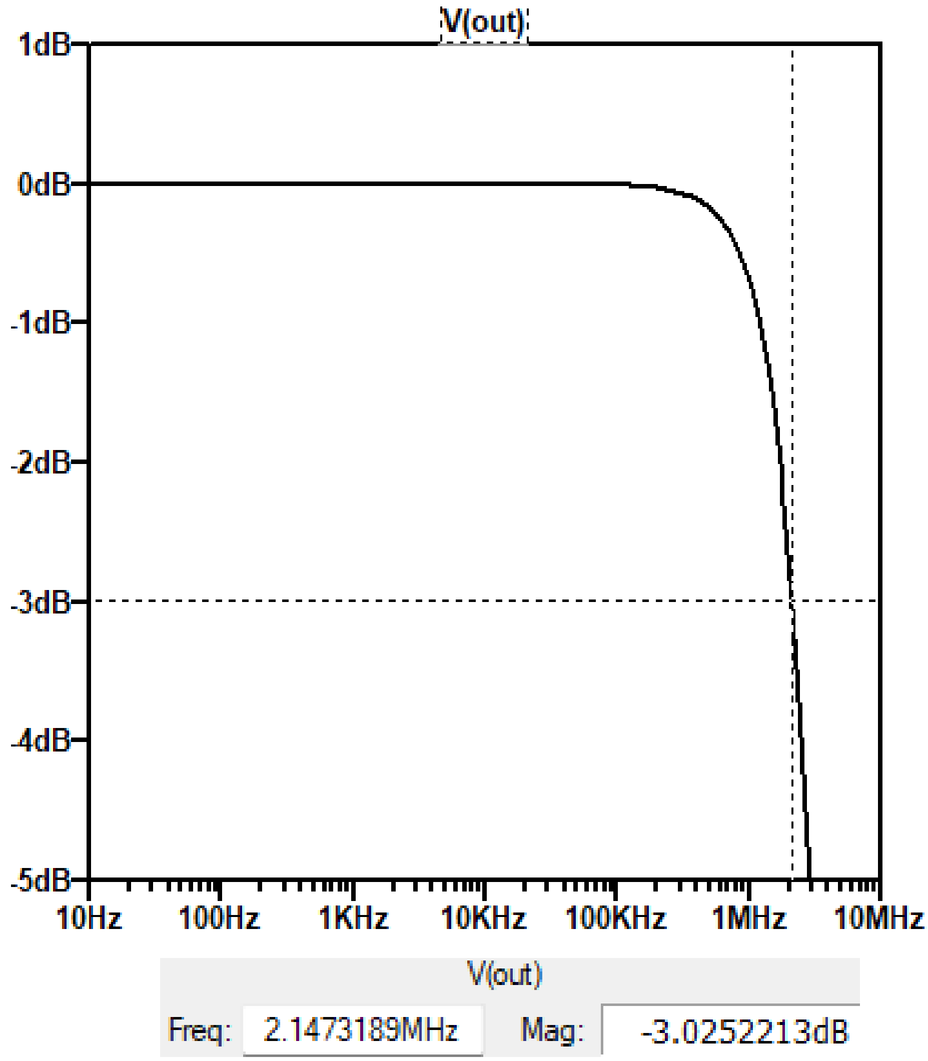
Below is an Apex PA85 in inverting unity gain configuration configured for AC simulation. The 20kΩ feedback and input resistors are seen as a parallel combination by the -input pin with a value of 10kΩ.

Figure 10: Inverting Unity Gain SPICE Simulation Circuit



When bode plot for this configuration is analyzed and the -3dB point is measured, the following results are given:

Figure 11: Inverting Unity Gain SPICE Simulation Bode Plot Results

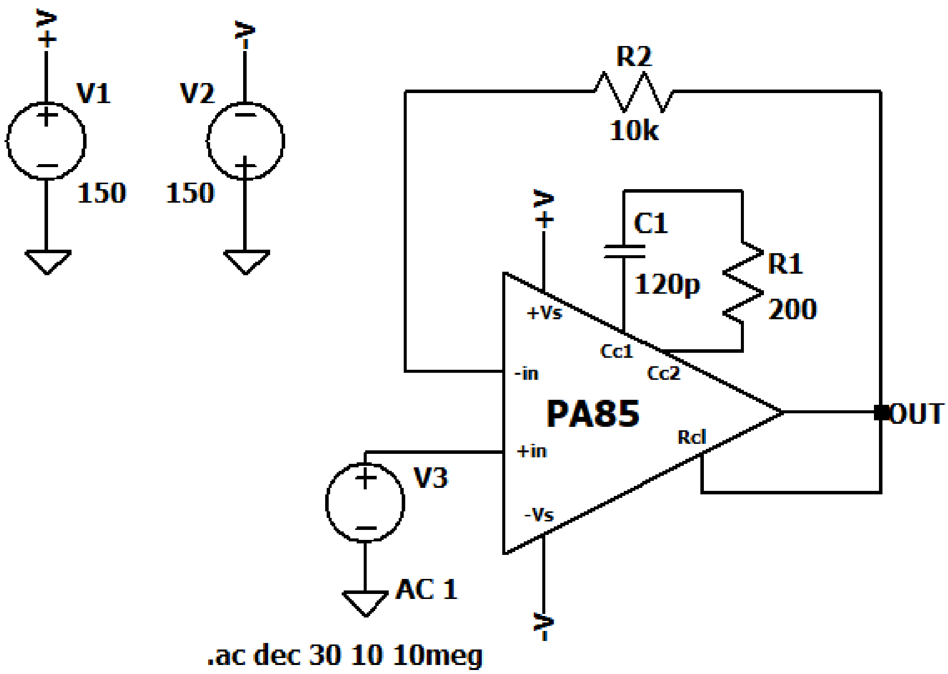


The cursor information provided shows that the -3dB bandwidth for the inverting configuration of unity gain, 0dB, is ~2.14MHz.

NON-INVERTING CIRCUIT SMALL SIGNAL SPICE SIMULATION

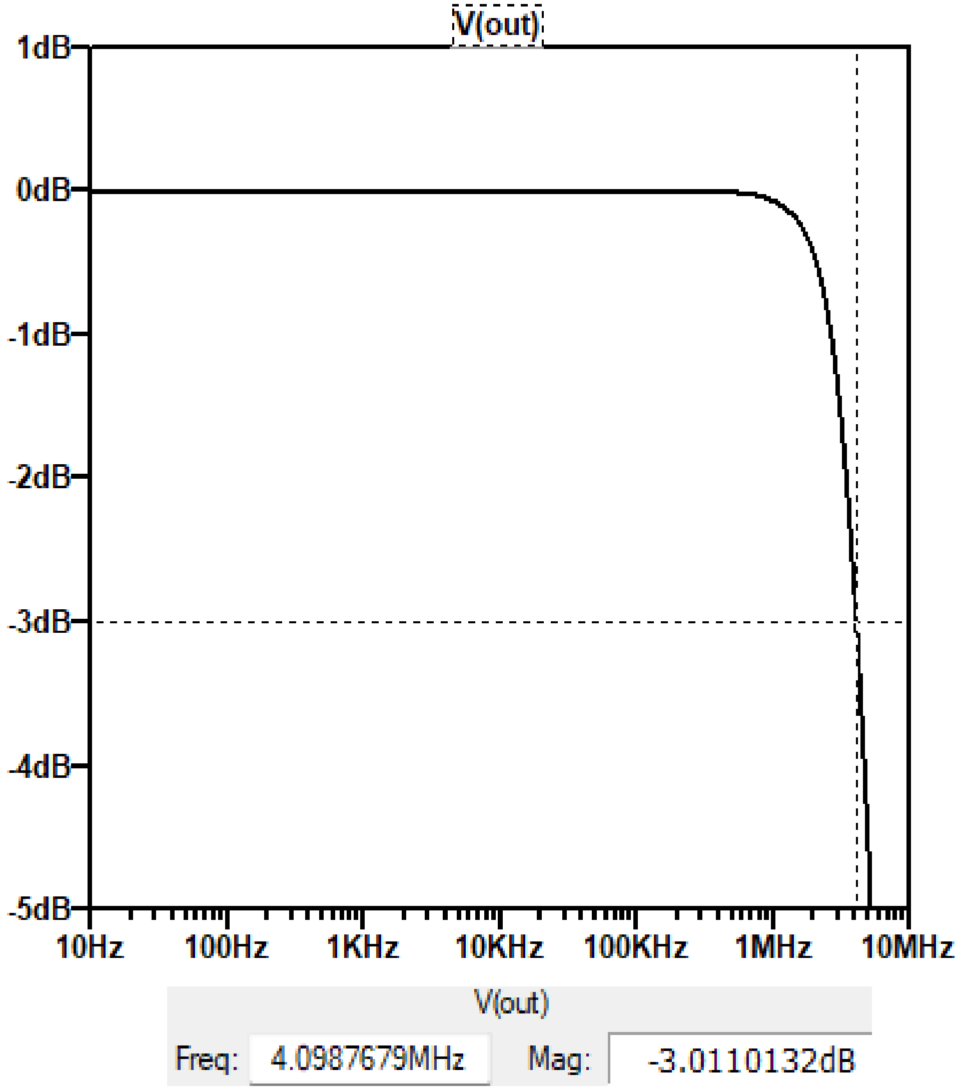
Below is an Apex PA85 in non-inverting unity gain configuration configured for AC simulation. A 10kΩ resistor is provided in the feedback network to match the impedance that is seen by the -input pin in the inverting configuration.

Figure 12: Non-Inverting Unity Gain SPICE Simulation Circuit



When the Bode plot for this configuration is analyzed and the -3dB point is measured, the following results are given:

Figure 13: Non-Inverting Unity Gain SPICE Simulation Bode Plot Results



The cursor information provided shows that the -3dB bandwidth for the inverting configuration of unity gain, 0dB, is ~4.08MHz. This bandwidth is effectively 2x that of the inverting unity gain configuration. This result confirms the previous mathematical analyses.

COMPARISON SUMMARY:

Configuration	Feedback Factor (β)	Loop gain (A_{OL}*β)	-3dB Frequency
Non-inverting Unity Gain	1	A_{OL}	4.09MHz
Inverting Unity Gain	0.5	$A_{OL}/2$	2.14MHz

Those who are interested in using op-amps in unity gain configuration should consider the difference in usable bandwidth between the two possible configurations and plan or revise their design accordingly.

CHOOSING THE APPROPRIATE CONFIGURATION

The choice between inverting unity gain and non-inverting unity gain configurations in op-amps is significant because each offers a set of distinct electrical characteristics suited to different applications. Similarly, each configuration has different bandwidth capabilities that must also be considered based on application requirements.

A non-inverting unity gain configuration (voltage follower) provides no phase inversion, very high input impedance, and very low output impedance. These features make it ideal for buffering or isolating a high-impedance signal source from a low-impedance load without loading the source or distorting the signal. Additionally, because the entire output is fed back (feedback factor β = 1), this configuration has maximum loop gain, offering best possible accuracy.

An inverting unity gain configuration provides an output that is equal in magnitude but 180° out of phase with the input. It requires a feedback network resulting in a gain of –1. This configuration has lower input impedance and a lower feedback factor (β = 0.5), which means reduced loop gain compared to the non-inverting configuration. It is utilized when signal inversion is necessary, such as in differential amplifiers or when matching phase with other inverting stages. It can also be employed when additional stability is desired.

Commonly, the non-inverting unity gain configuration is preferred for buffering and preserving signal integrity, while the inverting unity gain configuration is chosen for its ability to invert signals and integrate cleanly into circuits where inversion is functionally required. The decision of which to utilize always depends on the specific application needs for obvious parameters like phase, impedance, and signal routing in the circuit design. However, it is important to remember that bandwidth is also one of these concerns when differentiating between the use of inverting and non-inverting unity gain.

REFERENCES

1. Wong, Y. J., & Ott, W. E. (1976). *Function circuits: design and applications*, pp.2-5, 12-13. In *McGraw-Hill eBooks*. http://cds.cern.ch/record/104048
2. Apex Microtechnology PA85 Datasheet (n.d.). *Precision. Power. Analog. | Apex Microtechnology*. https://www.apexanalog.com/resources/products/pa85u.pdf

NEED TECHNICAL HELP? CONTACT APEX SUPPORT!

For all Apex Microtechnology product questions and inquiries, call toll free 800-546-2739 in North America. For inquiries via email, please contact apex.support@apexanalog.com. International customers can also request support by contacting their local Apex Microtechnology Sales Representative. To find the one nearest to you, go to www.apexanalog.com