Application Note

Demystifying the Relationship of Overshoot and Phase Margin

Shota Mago

ABSTRACT

This application note describes how percent overshoot and AC gain peaking correlate to phase margin in second order systems.

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1 Introduction

In second order systems like many op-amps have, damping ratio determines percent overshoot in the time domain and gain peaking in frequency domain. This application note shows how the phase margin of second order systems is a function of the damping ratio, which can be estimated from the step response.

2 General Transfer Function of the Second Order System

The general transfer function of a second order system can be described as below using DC gain K, damping ratio ζ and natural frequency ω_n.

$$G(s) = \frac{K\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{1}$$

From denominator of Equation 1, obtain poles shown in Equation 3 by solving Equation 2

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0 \tag{2}$$

$$-\omega_n\zeta \pm \omega_n\sqrt{\zeta^2 - 1} \tag{3}$$

2.1 Damping Ratio

From Equation 3, the system behavior changes depending on dumping ratio ζ.

A step response in time domain at each ζ is calculated as Inverse Laplace Transform.

$$y(t) = \mathcal{L}^{-1}\left[G(s)\frac{1}{s}\right] = \mathcal{L}^{-1}\left[\frac{K\omega_n^2}{s(s^2 + 2\zeta\omega_n s + \omega_n^2)}\right] \tag{4}$$

2.1.1 Underdamped (0 < ζ < 1)

If 0 < ζ < 1, poles are complex number and step response can be calculated as equation 5. The equation includes sine, meaning the system has overshoot.

$$y(t) = K\left\{1 - \frac{1}{\sqrt{1-\zeta^2}}e^{-\zeta\omega_n t}\sin\left(\omega_n\sqrt{1-\zeta^2}t + \phi\right)\right\}$$
$$\phi = \tan^{-1}\left(\frac{\sqrt{1-\zeta^2}}{\zeta}\right) \tag{5}$$

The percent overshoot of the second order system with 0 < ζ < 1, when a unit step is applied, is given by:

$$PO(\text{PercentOvershoot}) = 100e^{-\frac{\pi\zeta}{\sqrt{1-\zeta^2}}} \tag{6}$$

As Equation 6 implies, ζ determines the percent overshoot. To prove phase margin determines overshoot, users must confirm that ζ totally depends on phase margin.

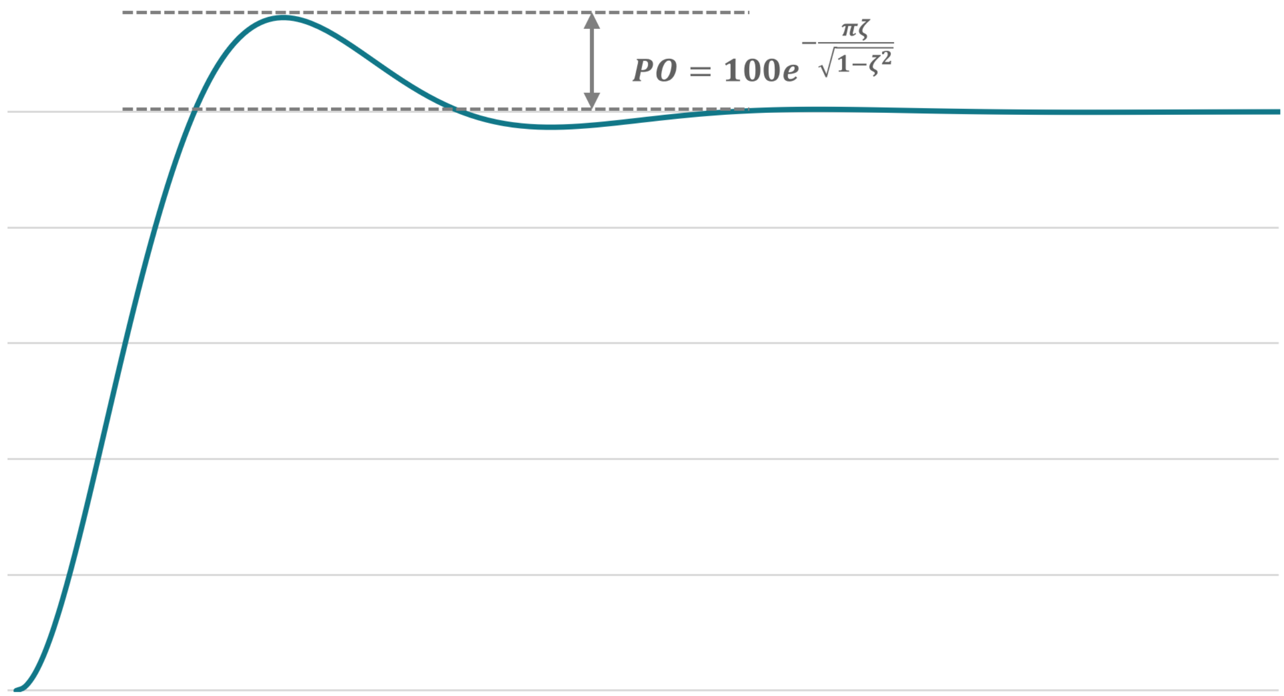

Figure 2-1. Percent Overshoot

In this document, only 0 < ζ < 1 is considered because other conditions (ζ=1 and ζ>1) do not exhibit overshoot.

2.1.2 Critically Damped (ζ = 1)

Critically damped, where ζ=1 is the border between overdamped and underdamped.

$$y(t) = K\left\{1 - (1 + \omega_n t)e^{-\omega_n t}\right\} \tag{7}$$

2.1.3 Overdamped (ζ>1)

Overdamped, where ζ>1 has two real poles and it does not show ringing. As equation 8 implies, the system with overdamped does not include sine or cosine, meaning the system does not exhibit any ringing.

$$y(t) = K\left\{1 - \frac{\zeta + \sqrt{\zeta^2 - 1}}{2\sqrt{\zeta^2 - 1}}e^{-\omega_n\left(\zeta - \sqrt{\zeta^2 - 1}\right)t} + \frac{\zeta - \sqrt{\zeta^2 - 1}}{2\sqrt{\zeta^2 - 1}}e^{-\omega_n\left(\zeta + \sqrt{\zeta^2 - 1}\right)t}\right\} \tag{8}$$

3 Modeling Op-Amp as a Second Order System

In general, an op-amp can be approximately modeled as a second order transfer function, shown in Equation 9.

$$A(s) = \frac{A_{OL}}{\left(1+\frac{s}{\omega_{p1}}\right)\left(1+\frac{s}{\omega_{p2}}\right)} \tag{9}$$

Where:

A_{OL} = DC gain

ω_{p1} = first pole

ω_{p2} = second pole

Figure 3-1 shows gain and phase response of Equation 9.

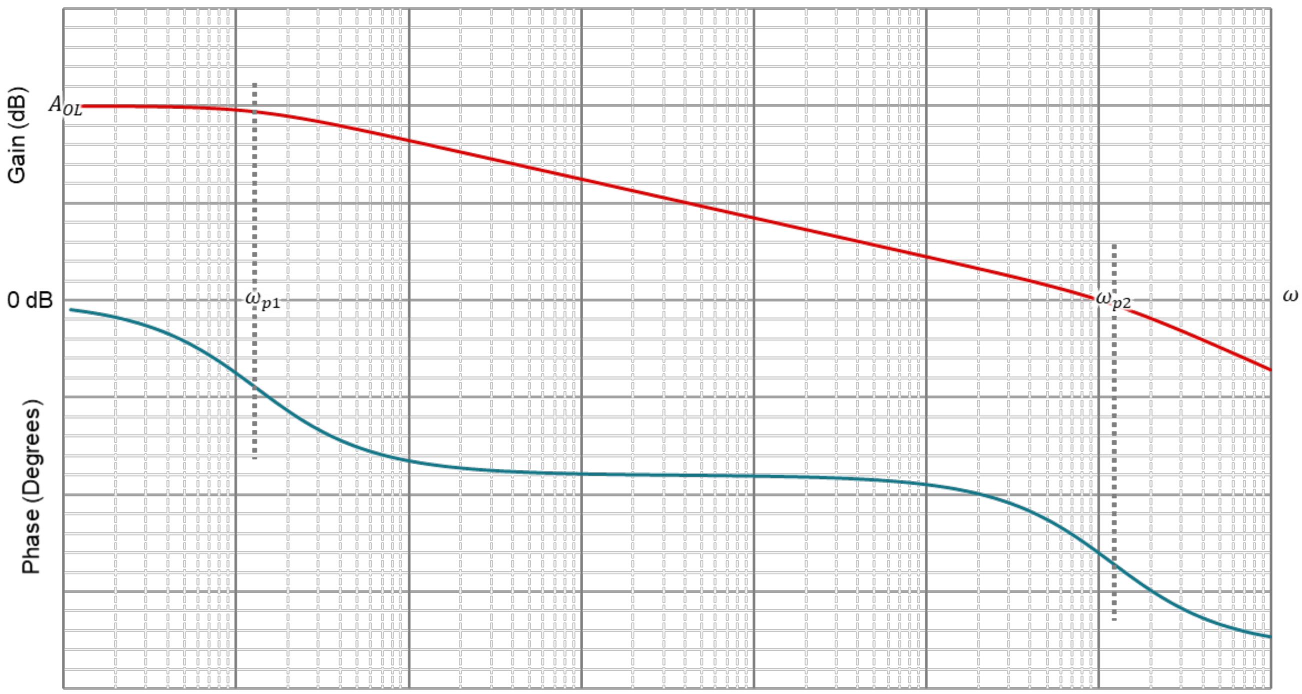

Figure 3-1. Gain and Phase Plot of a Second Order System

Figure 3-2 shows an op-amp with negative feedback, where β is the feedback factor.

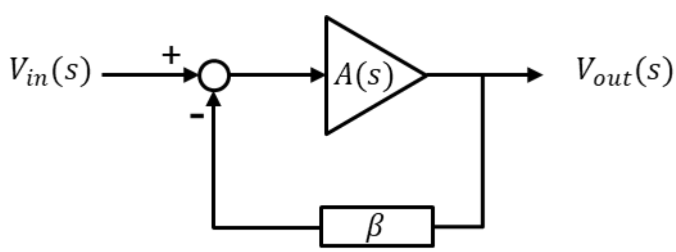

Figure 3-2. Negative Feedback

Closed loop gain, A_{CL} is given by

$$A_{CL}(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{A(s)}{1 + A_{(s)}\beta} \tag{10}$$

$$= \frac{1}{\frac{1}{A(s)} + \beta} \tag{11}$$

Substituting Equation 9 into Equation 11 :

$$= \frac{1}{\frac{\frac{1}{\omega_{p1}\omega_{p2}}s^2 + \left(\frac{1}{\omega_{p1}} + \frac{1}{\omega_{p2}}\right)s + 1}{A_{OL}} + \beta} \tag{12}$$

$$= \frac{A_{OL}\omega_{p1}\omega_{p2}}{s^2 + \left(\omega_{p1} + \omega_{p2}\right)s + \omega_{p1}\omega_{p2}(1 + A_{OL}\beta)} \tag{13}$$

By comparing Equation 1 and Equation 13 ,we can derive each key parameter.

$$\omega_n = \sqrt{\omega_{p1}\omega_{p2}(1 + A_{OL}\beta)} \tag{14}$$

$$K = \frac{A_{OL}}{1 + A_{OL}\beta} \tag{15}$$

$$\zeta = \frac{\omega_{p1} + \omega_{p2}}{2\omega_n} \tag{16}$$

$$= \frac{\sqrt{\frac{\omega_{p2}}{\omega_{p1}}} + \sqrt{\frac{\omega_{p1}}{\omega_{p2}}}}{2\sqrt{1 + A_{OL}\beta}} \tag{17}$$

To simplify Equation 17, damping ratio ζ, the ratio of ω_{P2}/ω_{P1} is represented as h.

$$h = \frac{\omega_{p2}}{\omega_{p1}} \tag{18}$$

$$\zeta = \frac{\sqrt{h} + \frac{1}{\sqrt{h}}}{2\sqrt{1 + A_{OL}\beta}} \tag{19}$$

4 Phase Margin vs Percent Overshoot

To represent ζ in terms of phase margin Φ_{PM}, $A_{OL}\beta$ must be represented by form of Φ_{PM} from equation 19.

4.1 Phase Margin

Phase margin Φ_{PM} is calculated as the difference between the phase shift of the system at the crossover frequency, ω_C and 180 degrees. In a second order system, phase lag is caused by the first pole, ω_{p1} and the second pole, ω_{p2} as shown in Figure 4-1.

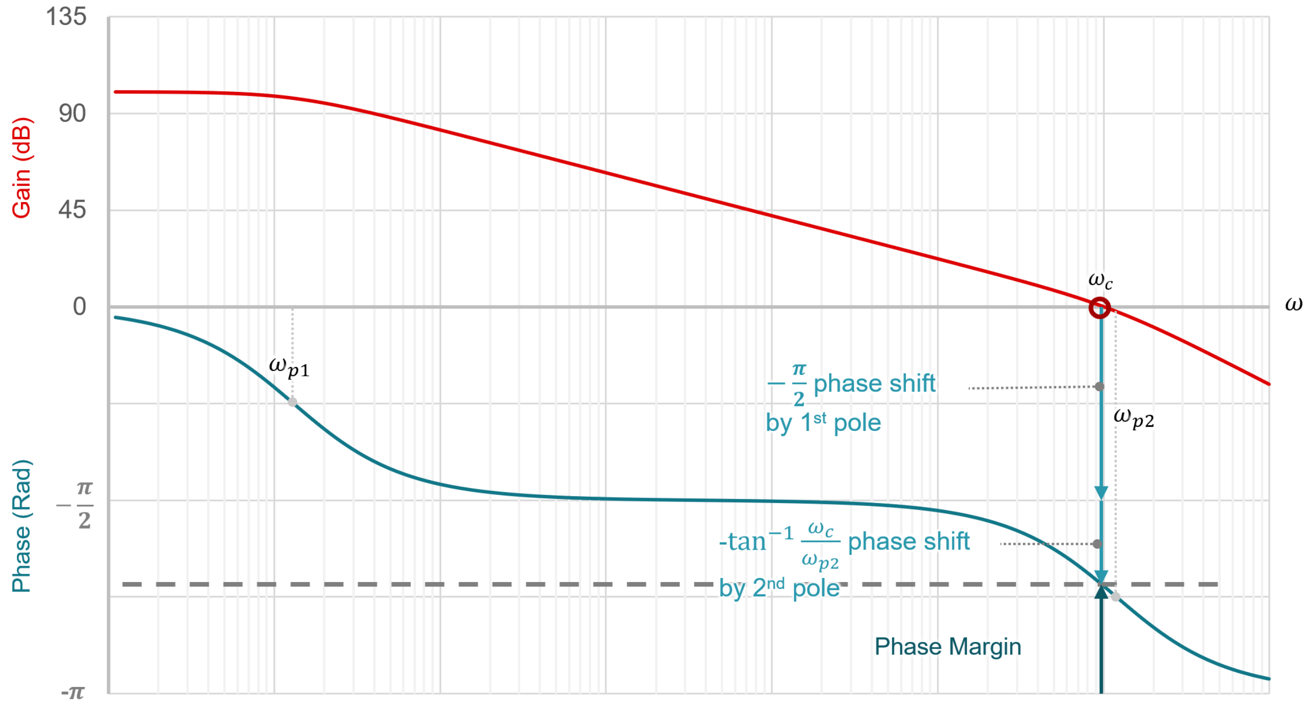

Figure 4-1. Phase Margin of a Second Order System

In general, the first pole is located at much lower than crossover frequency, leading to 90 degrees (=π/2) lag.

An equation of the second pole is given by:

$$\frac{1}{1+\frac{\omega}{\omega_{p2}}j} = \frac{1}{1+\left(\frac{\omega}{\omega_{p2}}\right)^2} - \frac{\frac{\omega}{\omega_{p2}}}{1+\left(\frac{\omega}{\omega_{p2}}\right)^2}j \quad (20)$$

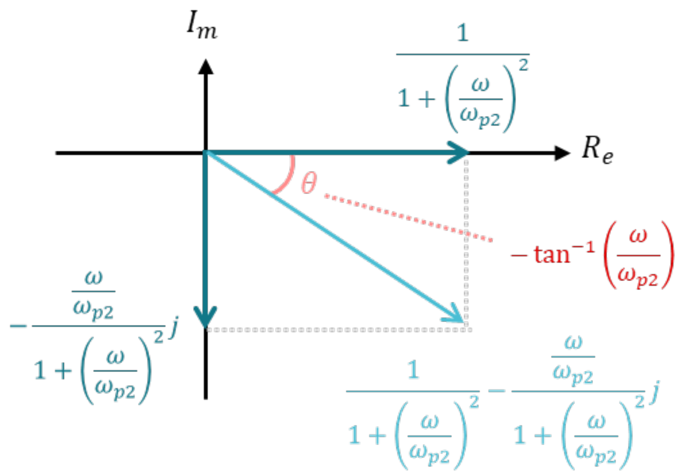

Figure 4-2. Phase Lag of the Second Pole

As shown in Figure 4-2, the phase shift of the second pole can be calculated as follows.

$$\tan\theta = -\frac{\frac{\frac{\omega}{\omega_{p2}}}{1+\left(\frac{\omega}{\omega_{p2}}\right)^2}}{\frac{1}{1+\left(\frac{\omega}{\omega_{p2}}\right)^2}} \tag{21}$$

$$= -\frac{\omega}{\omega_{p2}} \tag{22}$$

$$\theta = \tan^{-1}\left(-\frac{\omega}{\omega_{p2}}\right) \tag{23}$$

$$= -\tan^{-1}\left(\frac{\omega}{\omega_{p2}}\right) \tag{24}$$

At crossover frequency, ω_C where magnitude of loop gain is equal to 1, the phase shift by the second pole becomes below from Equation 24.

$$-\tan^{-1}\left(\frac{\omega_C}{\omega_{p2}}\right) \tag{25}$$

The total phase shift at crossover frequency due to first pole and second pole can be calculated as

$$-\frac{\pi}{2} - \tan^{-1}\left(\frac{\omega_C}{\omega_{p2}}\right) \tag{26}$$

Calculation of difference between π and Equation 26 yields phase margin.

$$\phi_{PM} = \pi - \frac{\pi}{2} - \tan^{-1}\left(\frac{\omega_C}{\omega_{p2}}\right) \tag{27}$$

$$= \frac{\pi}{2} - \tan^{-1}\left(\frac{\omega_C}{\omega_{p2}}\right) \tag{28}$$

4.2 Represent $A_{OL}\beta$ as Φ_{PM}

At crossover frequency ω_C, loop gain $A_{(S)}\beta$ can be written as

$$A_{(j\omega_c)}\beta = \frac{A_{OL}}{\left(1+\frac{\omega_c}{\omega_{p1}}j\right)\left(1+\frac{\omega_c}{\omega_{p2}}j\right)}\beta \tag{29}$$

Substitute Equation 18 into Equation 29 yields Equation 30.

$$A_{(j\omega_c)}\beta = \frac{A_{OL}}{\left(1+\frac{\omega_c}{\omega_{p1}}j\right)\left(1+\frac{\omega_c}{h\omega_{p1}}j\right)}\beta \tag{30}$$

Since the magnitude of the loop gain at the crossover frequency becomes 1, Equation 30 can be written as:

$$\left|A_{(j\omega_c)}\beta\right| = \frac{A_{OL}}{\sqrt{1+\left(\frac{\omega_c}{\omega_{p1}}\right)^2}\sqrt{1+\left(\frac{\omega_c}{h\omega_{p1}}\right)^2}}\beta = 1 \tag{31}$$

$$A_{OL}\beta = \sqrt{1+\left(\frac{\omega_c}{\omega_{p1}}\right)^2}\sqrt{1+\left(\frac{\omega_c}{h\omega_{p1}}\right)^2} \tag{32}$$

From Equation 28, ω_C can be represented as:

$$\omega_c = \omega_{p2}\tan\left(\frac{\pi}{2} - \phi_{PM}\right) \tag{33}$$

$$= \omega_{p2}\cot\phi_{PM} \tag{34}$$

Substitute the above equation into Equation 32 to represent $A_{OL}\beta$ as function of Φ_{PM}.

$$A_{OL}\beta = \sqrt{1+\left(\frac{\omega_{p2}\cot\phi_{PM}}{\omega_{p1}}\right)^2}\sqrt{1+\left(\frac{\omega_{p2}\cot\phi_{PM}}{h\omega_{p1}}\right)^2} \tag{35}$$

$$= \sqrt{\left(1+h^2\cot^2\phi_{PM}\right)\left(1+\cot^2\phi_{PM}\right)} \tag{36}$$

4.3 Represent Φ_{PM} as Damping ratio

Now, $A_{OL}\beta$ is represented by phase margin and h, which is ratio of $\omega_{p2/}\omega_{p1}$. Substitute Equation 36 into damping ratio ζ represented by Equation 19.

$$\zeta = \frac{\sqrt{h} + \frac{1}{\sqrt{h}}}{2\sqrt{1 + \sqrt{\left(1 + h^2\cot^2\phi_{PM}\right)\left(1 + \cot^2\phi_{PM}\right)}}} \quad (37)$$

$$= \frac{1 + \frac{1}{h}}{2\sqrt{\frac{1}{h} + \sqrt{\left(\frac{1}{h^2} + \cot^2\phi_{PM}\right)\left(1 + \cot^2\phi_{PM}\right)}}} \quad (38)$$

In general, the second pole of most op-amps is much higher than the first pole, resulting in h >>1 and the approximation from Equation 38 to Equation 39 .

$$\zeta \fallingdotseq \frac{1}{2\sqrt{\cot\phi_{PM}\sqrt{1 + \cot^2\phi_{PM}}}} \quad (39)$$

Equation 39 shows that damping ratio totally depends on phase margin as long as h>>1, which means overshoot is determined by phase margin.

Solving the above equation for Φ_{PM}.

$$\cot\phi_{PM}\sqrt{1 + \cot^2\phi_{PM}} = \frac{1}{4\zeta^2} \quad (40)$$

$$\cot^2\phi_{PM} + \cot^4\phi_{PM} = \frac{1}{16\zeta^4} \quad (41)$$

Let $\cot^2\Phi_{PM}$ be x. Then, Equation 41 can be written as:

$$x^2 + x - \frac{1}{16\zeta^4} = 0 \quad (42)$$

$$x = \cot^2\phi_{PM} = \frac{-1 + \sqrt{1 + \frac{1}{4\zeta^4}}}{2} \quad (43)$$

$$cot\phi_{PM} = \frac{1}{\tan\phi_{PM}} = \sqrt{\frac{\sqrt{1 + \frac{1}{4\zeta^4}} - 1}{2}} \quad (44)$$

$$\phi_{PM(Radians)} = \tan^{-1}\sqrt{\frac{2}{\sqrt{1 + \frac{1}{4\zeta^4}} - 1}} \quad (45)$$

To obtain degrees from radians, multiply 180/π.

$$\phi_{PM(Degrees)} = \frac{180}{\pi}\tan^{-1}\sqrt{\frac{2}{\sqrt{1 + \frac{1}{4\zeta^4}} - 1}} \quad (46)$$

4.4 Phase Margin Represented by Percent Overshoot

Solving Equation 6 for ζ yields the below equation.

$$\zeta = -\frac{\ln\frac{PO}{100}}{\sqrt{\left(\ln\frac{PO}{100}\right)^2 + \pi^2}} \quad (47)$$

By substituting Equation 47 into Equation 46, it allows the user to estimate phase margin from percent overshoot.

$$\phi_{PM(Degrees)} = \frac{180}{\pi}\tan^{-1}\sqrt{\frac{2}{\sqrt{1+\frac{1}{4\left(-\frac{\ln\frac{PO}{100}}{\sqrt{\left(\ln\frac{PO}{100}\right)^2+\pi^2}}\right)^4}}-1}} \quad (48)$$

Using Equation 48, draw Figure 4-3, representing phase margin vs percentage overshoot, which can be used to estimate the phase margin from overshoot of step response in a second order system.

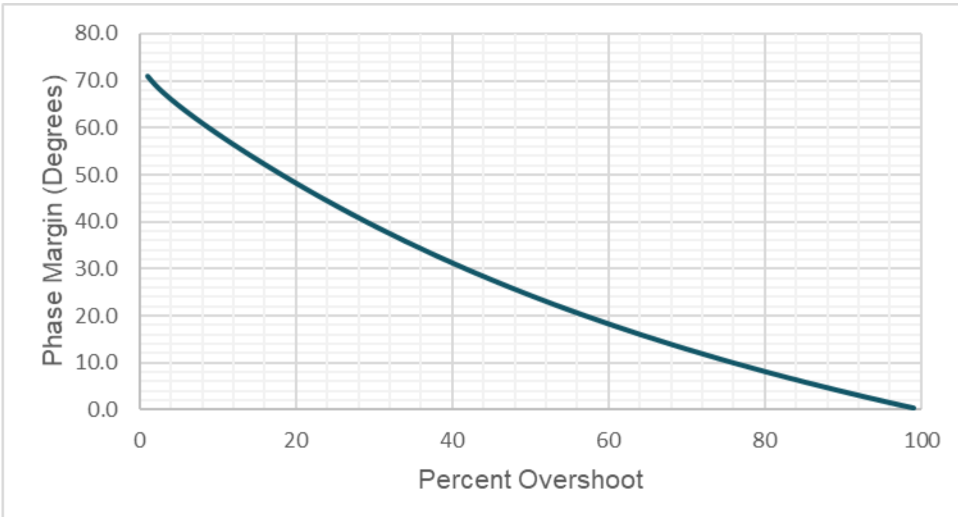

Figure 4-3. Phase Margin vs Percent Overshoot of a Second Order System

Table 4-1 lists some examples of expected percent overshoot at each phase margin.

Table 4-1. Phase Margin vs Overshoot

Phase Margin	Overshoot
15°	65.9%
30°	41.6%
45°	23.3%
60°	8.8%
75°	0.0%

4.5 Phase Margin Represented by Gain Peaking

In frequency response of a standard second order system, a resonance exists only if $\zeta<1/\sqrt{2}$. The resonant peak, M_r, at the resonant frequency is given by:

$$M_r = \frac{1}{2\zeta\sqrt{1-\zeta^2}} \quad (49)$$

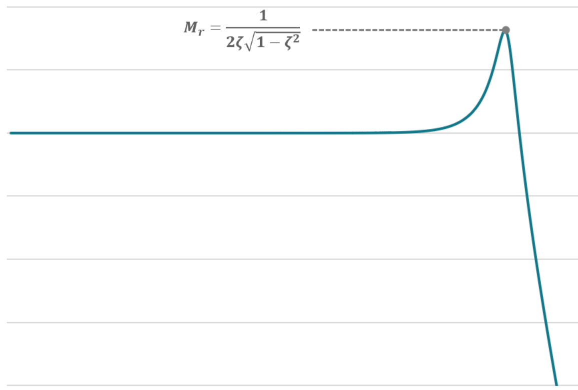

Figure 4-4. Gain Peaking

SolvingEquation 49 for ζ yields Equation 50.

$$\zeta^4 - \zeta^2 + \frac{1}{4M_r^2} = 0 \tag{50}$$

Let ζ^2 be y. Then, Equation 50 can be written as:

$$y^2 - y + \frac{1}{4M_r^2} = 0 \tag{51}$$

Solving for y yields:

$$y = \zeta^2 = \frac{1 \pm \sqrt{1 - \frac{1}{M_r^2}}}{2} \tag{52}$$

Since the range of $\zeta<1/\sqrt{2}$ is assumed, take the smaller value.

$$\zeta^2 = \frac{1 - \sqrt{1 - \frac{1}{M_r^2}}}{2} \tag{53}$$

$$\zeta = \sqrt{\frac{1 - \sqrt{1 - \frac{1}{M_r^2}}}{2}} \tag{54}$$

By substituting Equation 54 into Equation 46

$$\phi_{PM(Degrees)} = \frac{180}{\pi}\tan^{-1}\sqrt{\frac{2}{\sqrt{1 + \frac{1}{\left(1 - \sqrt{1 - \frac{1}{M_r^2}}\right)^2}} - 1}} \tag{55}$$

From Equation 55, Figure 4-5 can be drawn.

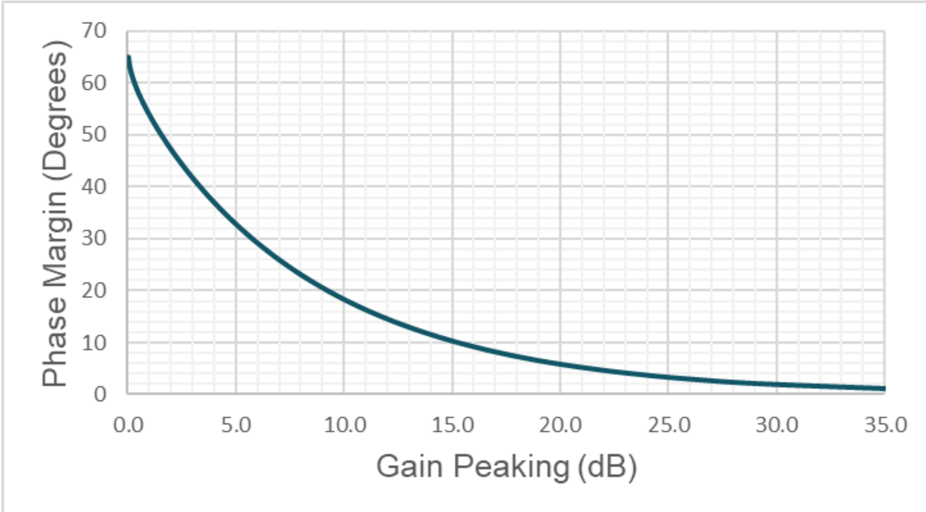

Figure 4-5. Phase Margin vs Gain Peaking

Table 4-2 lists some examples of an expected ac-gain peaking at each phase margin.

Table 4-2. Phase Margin vs Gain Peaking

Phase Margin	Gain Peaking
15°	11.7dB
30°	5.7dB
45°	2.3dB
60°	0.28dB

5 Simulation of Ideal Second Order System

The relationship between phase margin and overshoot, as well as phase margin and gain peaking, was confirmed using the Laplace transform part of PSPICE for TI. Figure 5-1 shows a model of a non-inverting amplifier with an ideal second-order system designed to have a 120dB DC gain, a 1MHz crossover frequency, and a 50% feedback factor, which is equal to a noise gain of 2V/V (6.02dB). For the step response, a 0.5V input is applied, and the target settled output magnitude is 1V.

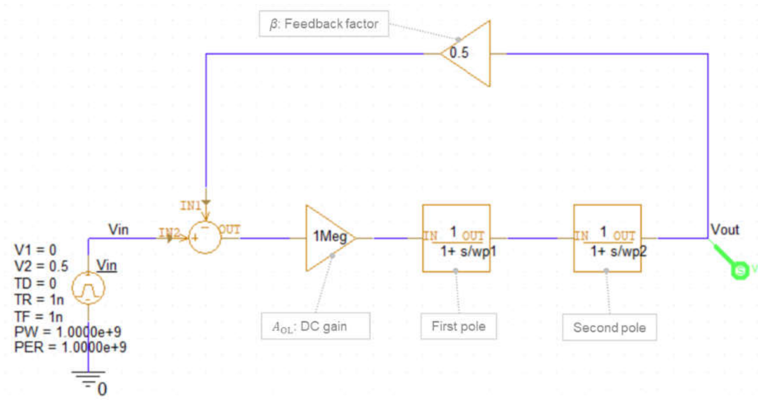

Figure 5-1. Ideal Second Order System Emulating Non-Inverting Amplifier with 2V/V Gain

To achieve the intended phase margin under the conditions mentioned above, the first pole and the second pole were set to the values listed in the table below.

Table 5-1. Setting of the First Pole and the Second Pole

Phase Margin	ω_{P1} [rad/s]	ω_{P2} [Mrad/s]
30°	25.13	3.63
45°	17.77	6.28
60°	14.51	10.88
75°	13.01	23.45

Step response and gain peaking were simulated with four different phase margins. The simulation results are substantially consistent with Table 4-1 and Table 4-2.

5.1 Phase Margin: 30 Degrees

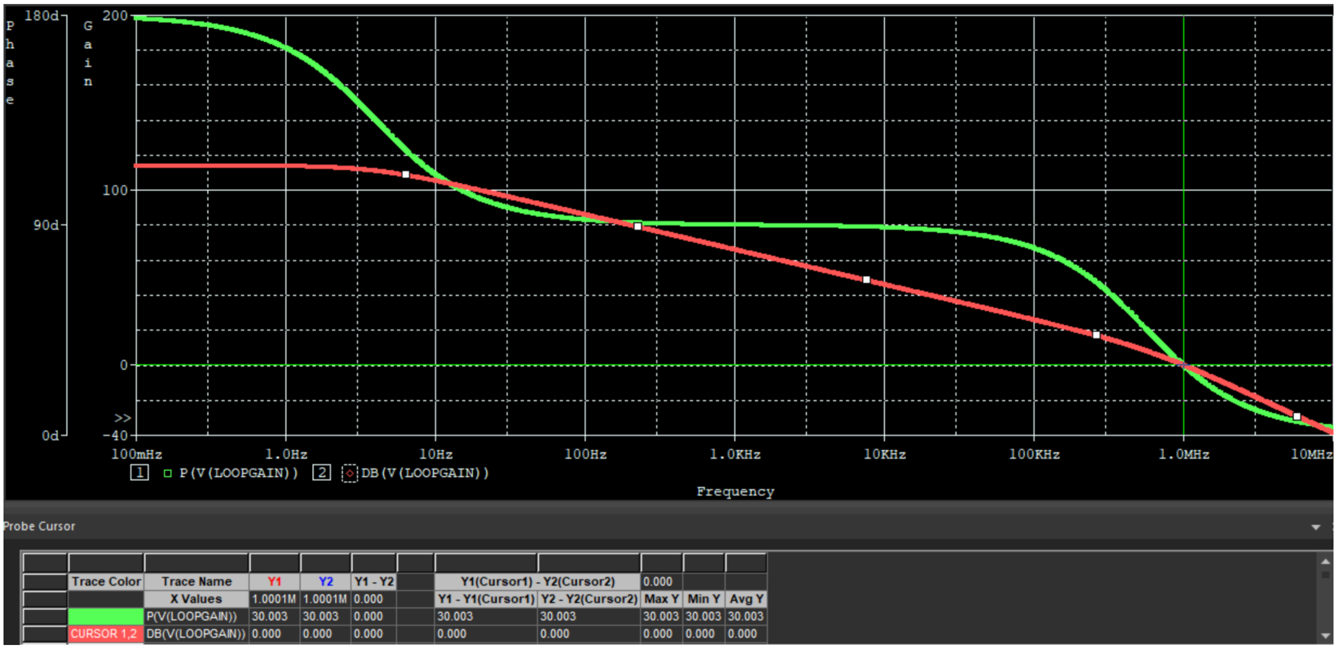

Figure 5-2. Bode Plot of Loop Gain at a Phase Margin of 30°

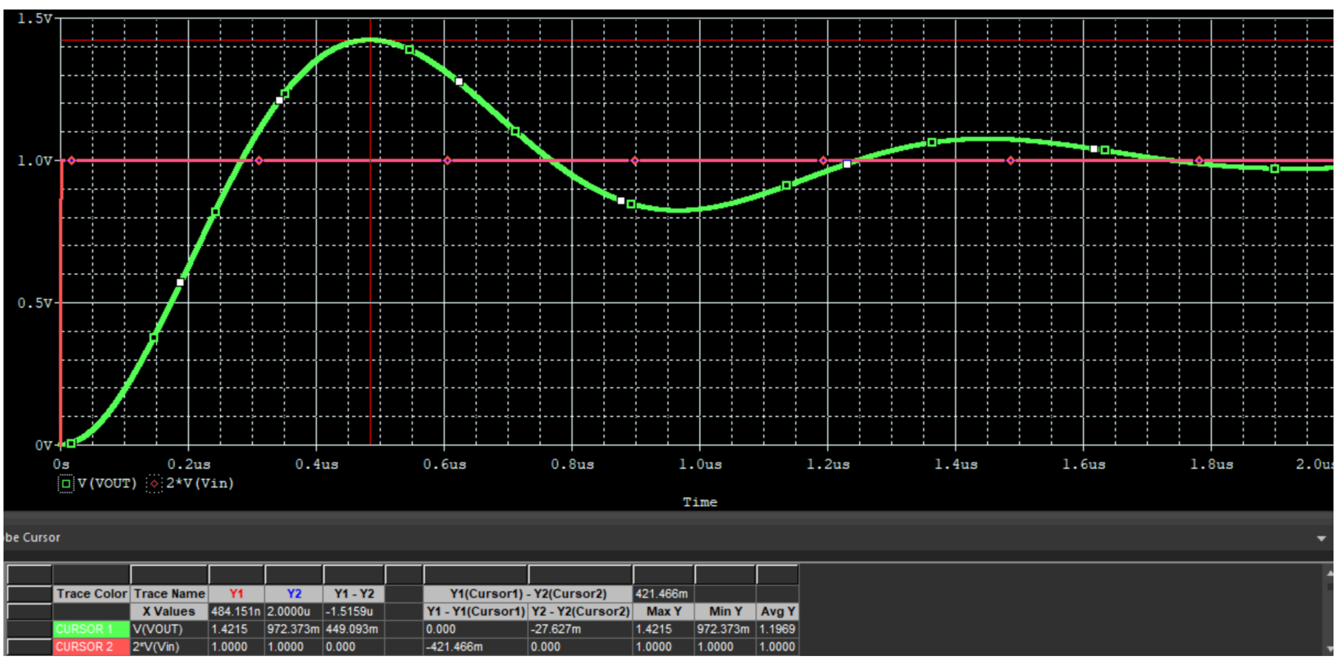

Figure 5-3. Step Response at a Phase Margin of 30°, 42.1% Overshoot

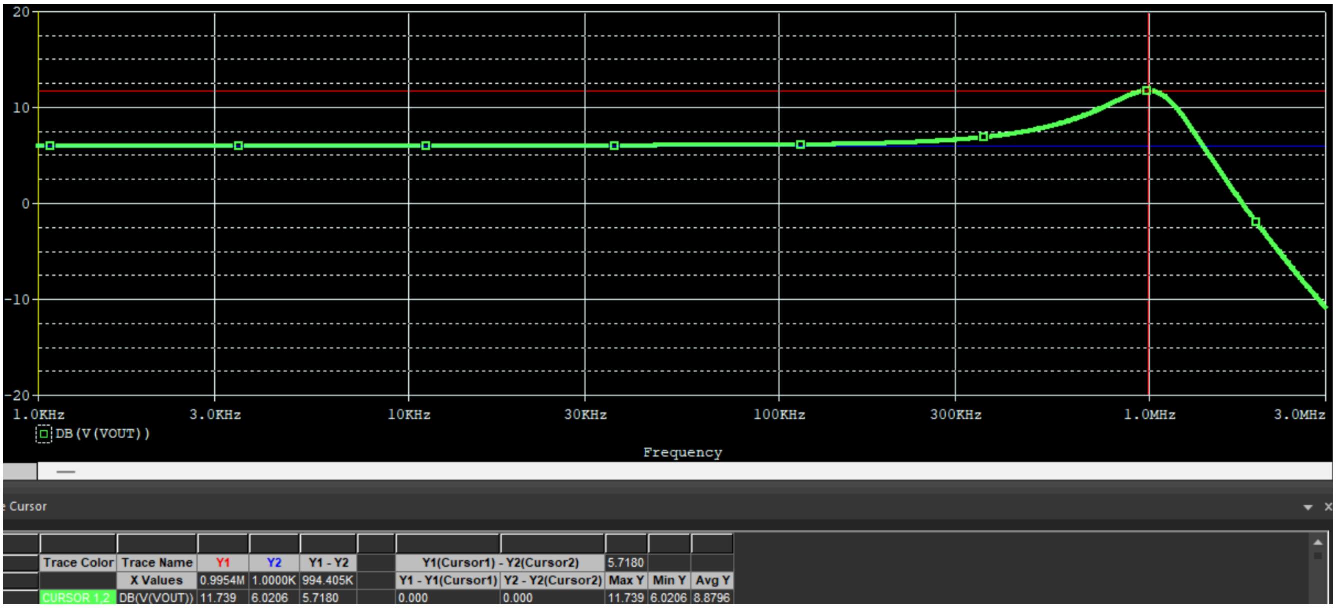

Figure 5-4. Gain peaking at a Phase Margin of 30°, 5.7dB

5.2 Phase Margin: 45 Degrees

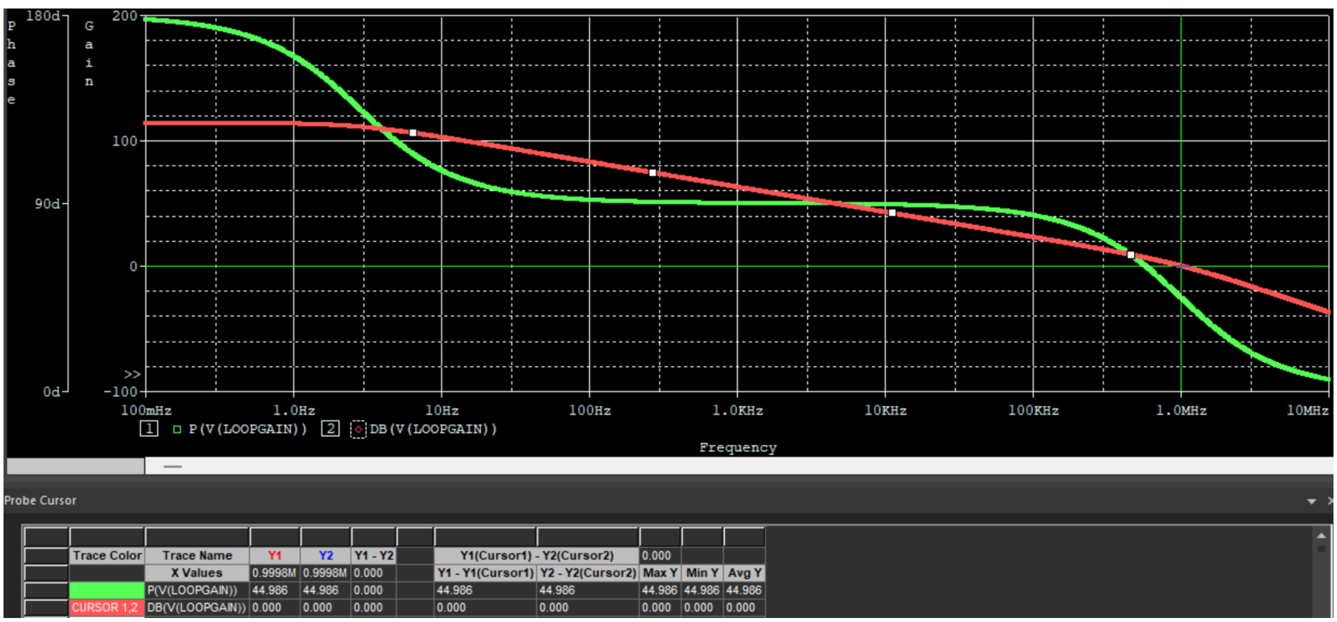

Figure 5-5. Bode Plot of Loop Gain at a Phase Margin of 45°

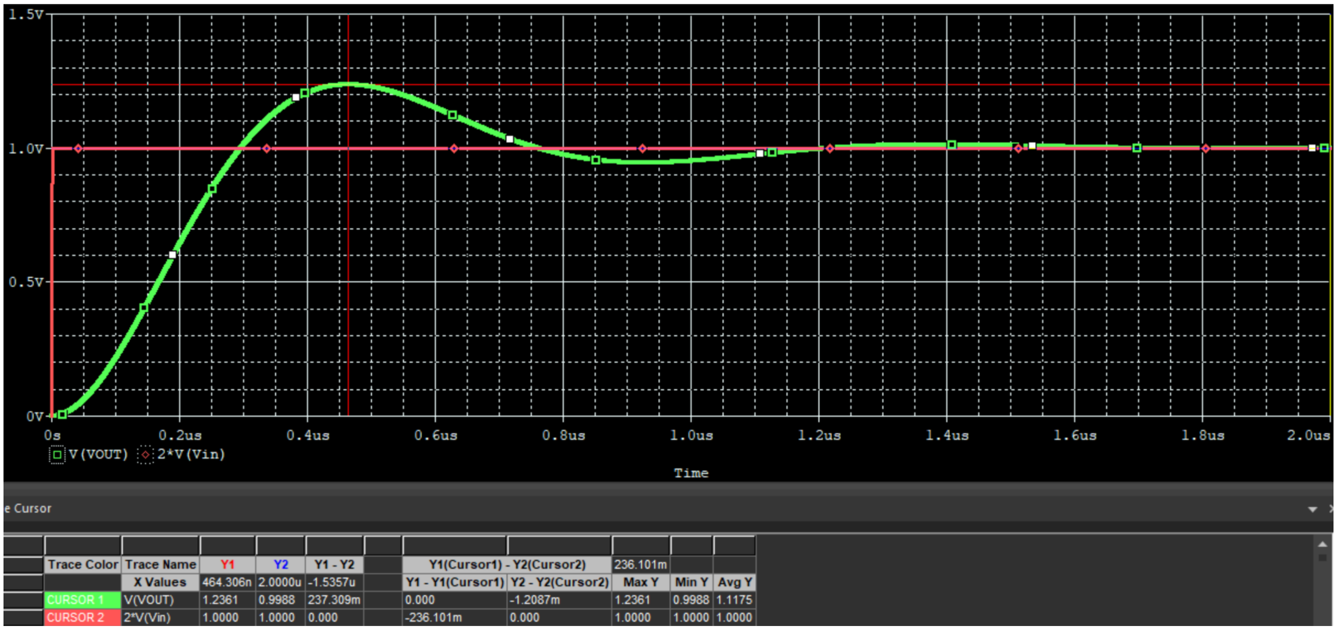

Figure 5-6. Step Response at a Phase Margin of 45°, 23.6% Overshoot

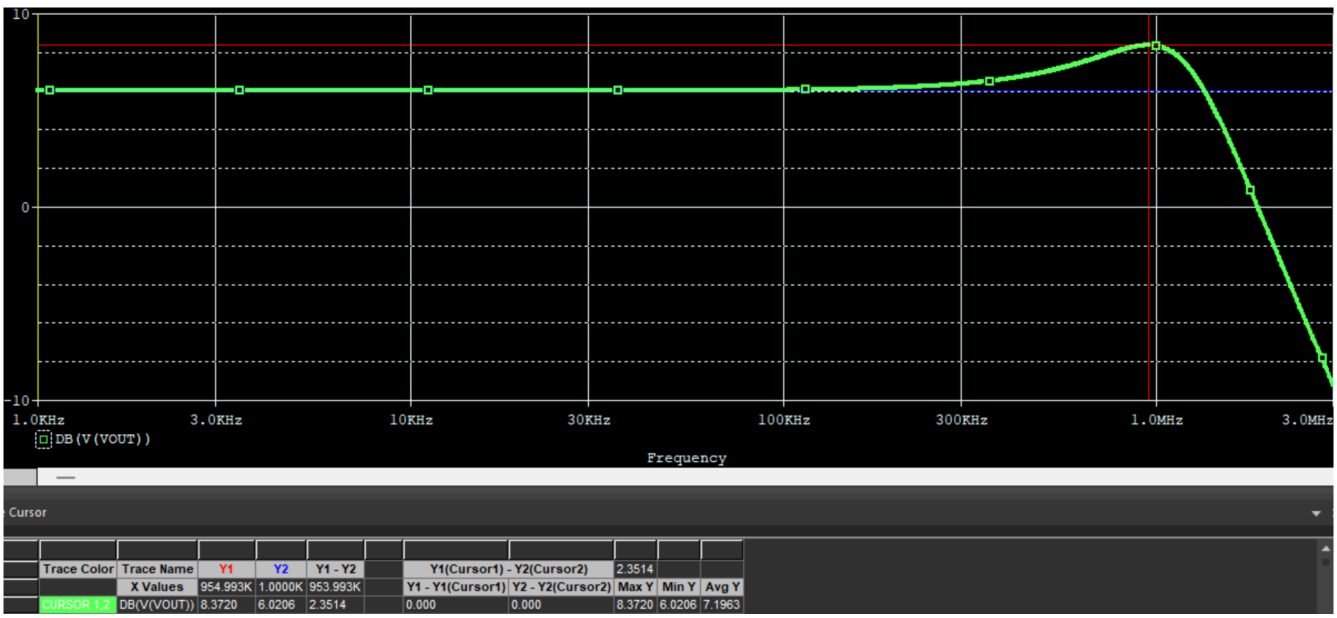

Figure 5-7. Gain Peaking at a Phase Margin of 45°, 2.3dB

5.3 Phase Margin: 60 Degrees

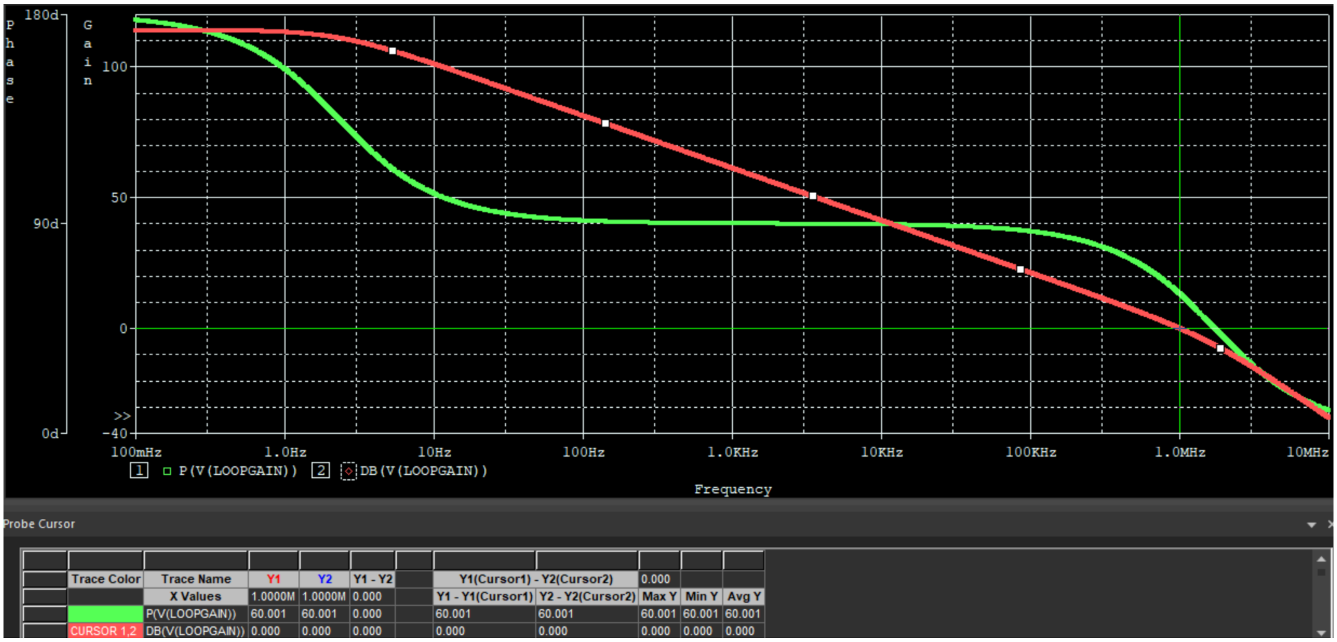

Figure 5-8. Bode Plot of Loop Gain: Phase Margin of 60°

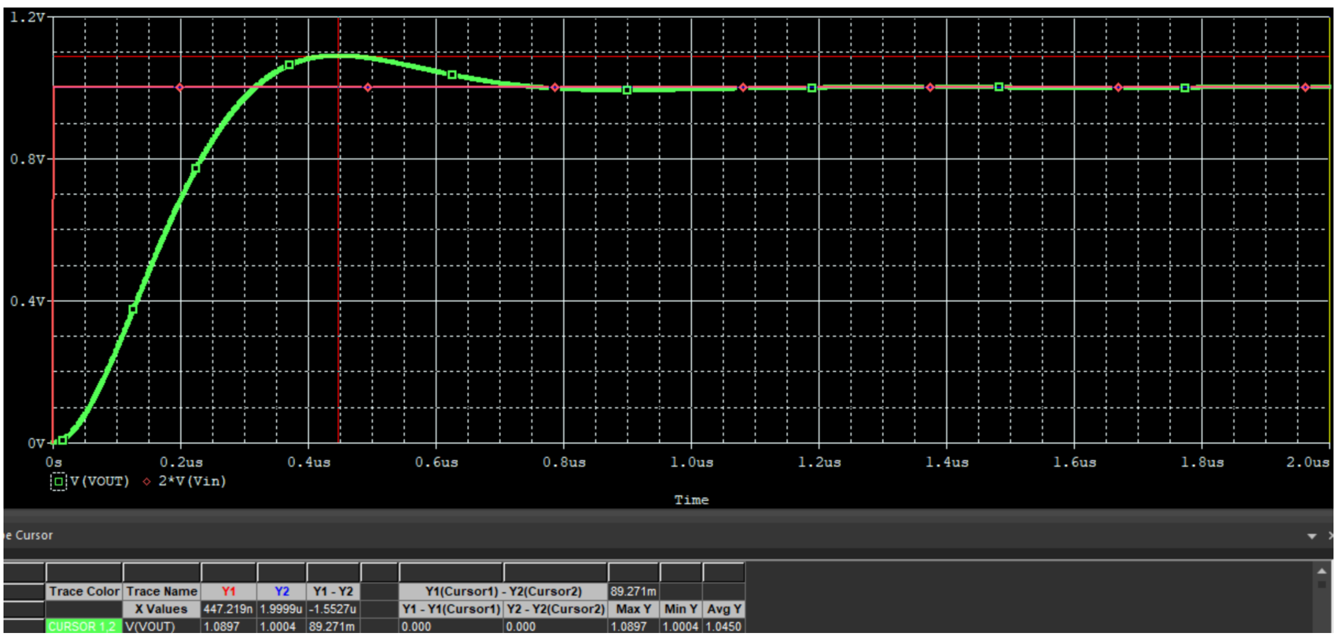

Figure 5-9. Step Response at a Phase Margin of 60°, 8.9% Overshoot

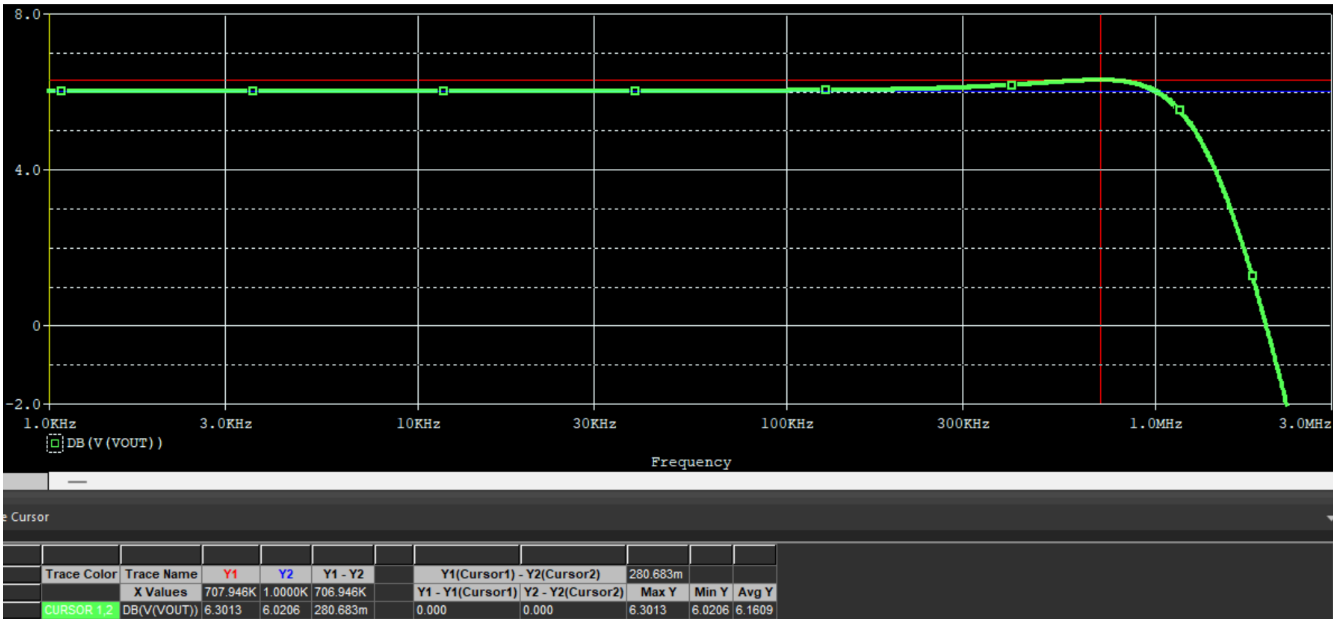

Figure 5-10. Gain Peaking at a Phase Margin of 60°, 0.28dB

5.4 Phase Margin: 75 Degrees

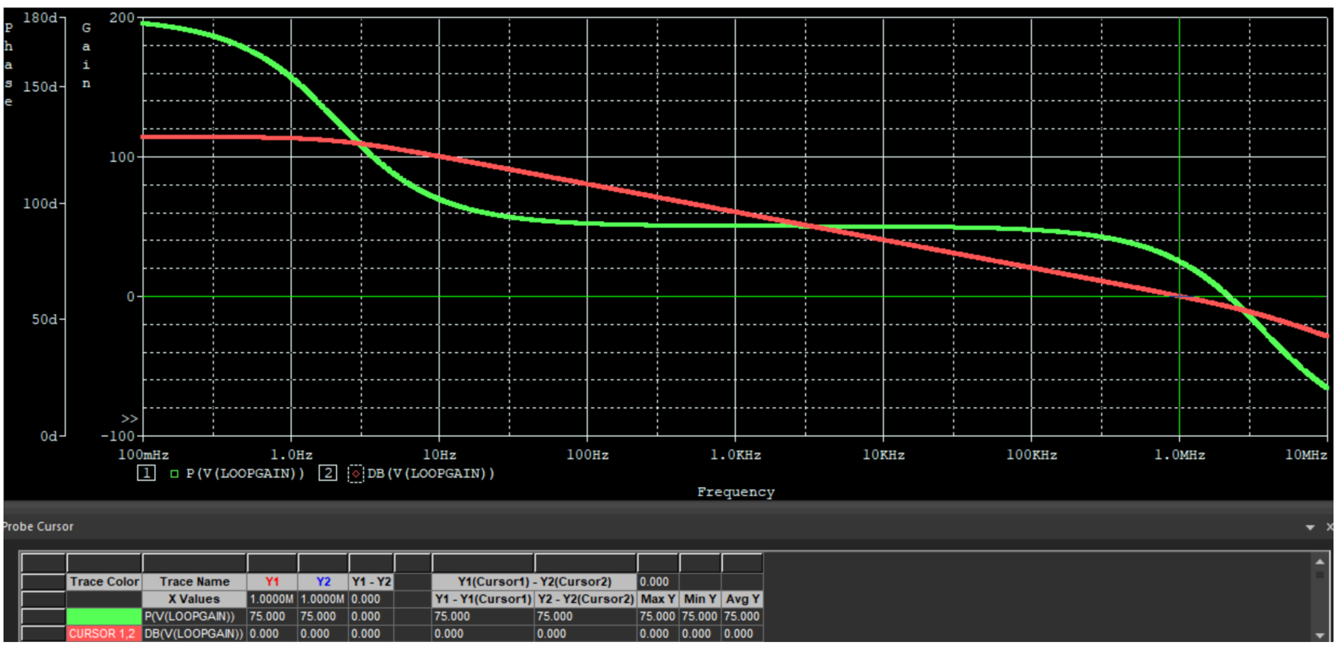

Figure 5-11. Bode Plot of Loop Gain: Phase Margin of 75°

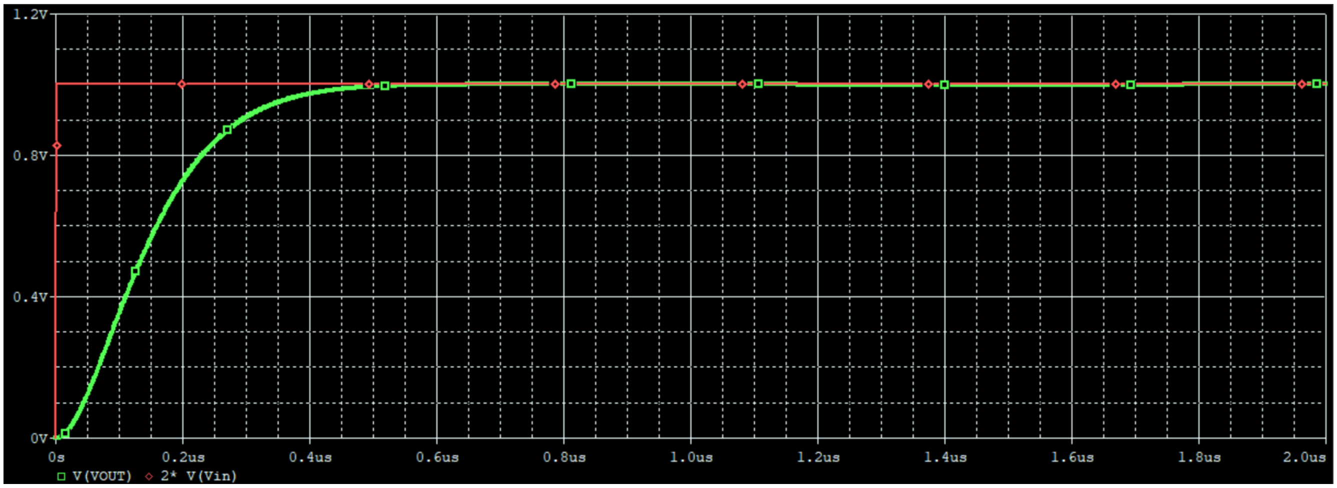

Figure 5-12. Step Response at a Phase Margin of 75°, No Overshoot

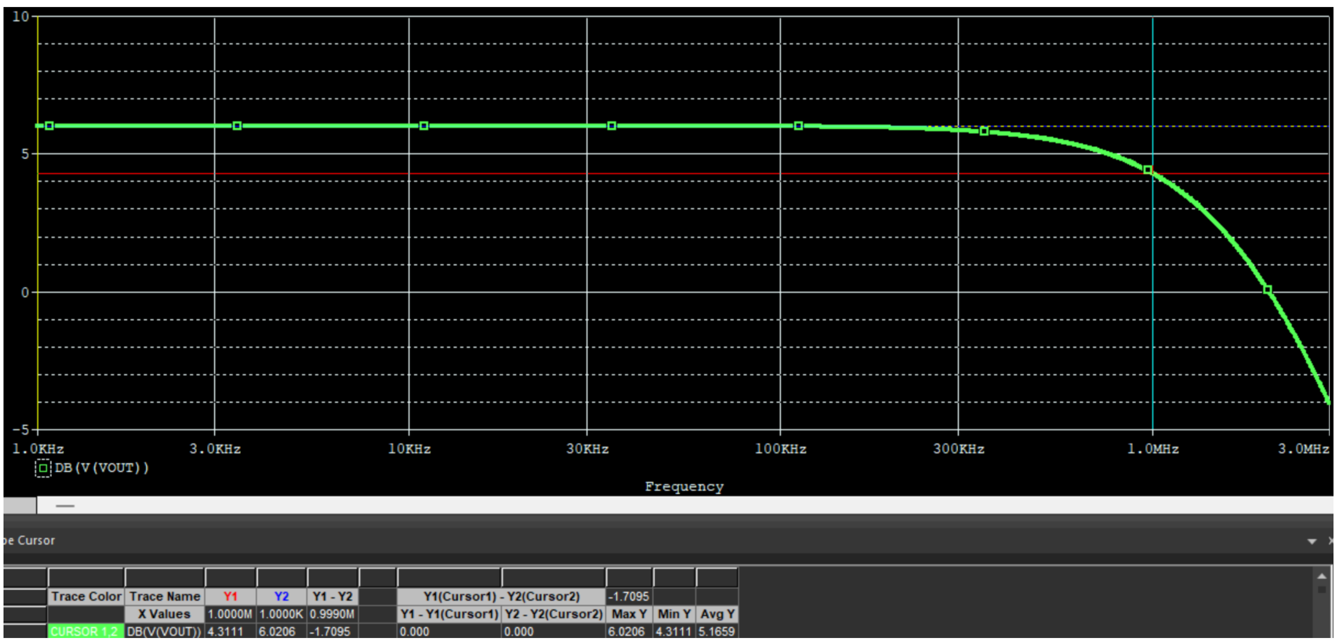

Figure 5-13. Gain Peaking at a Phase Margin of 75°, No peaking

5.5 Step Response with Different Phase Margin (Damping Ratio)

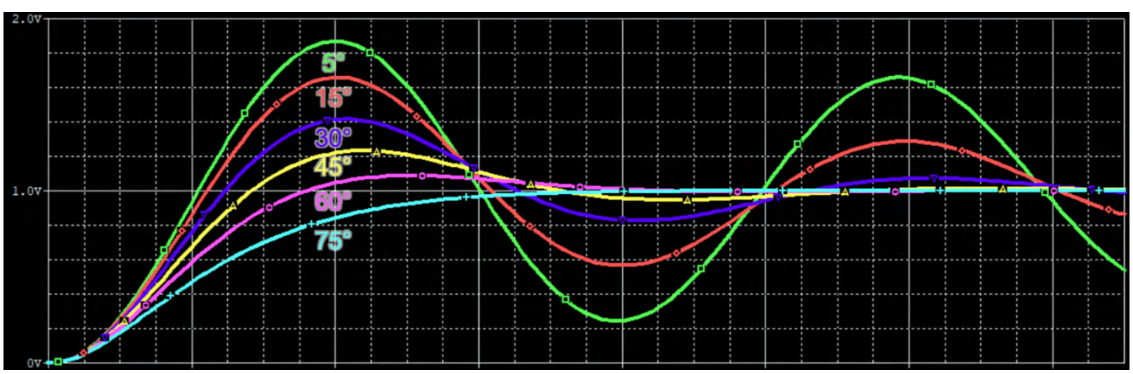

Figure 5-14. Step Response with Different Phase Margin

5.6 Gain Peaking with Different Phase Margin (Damping Ratio)

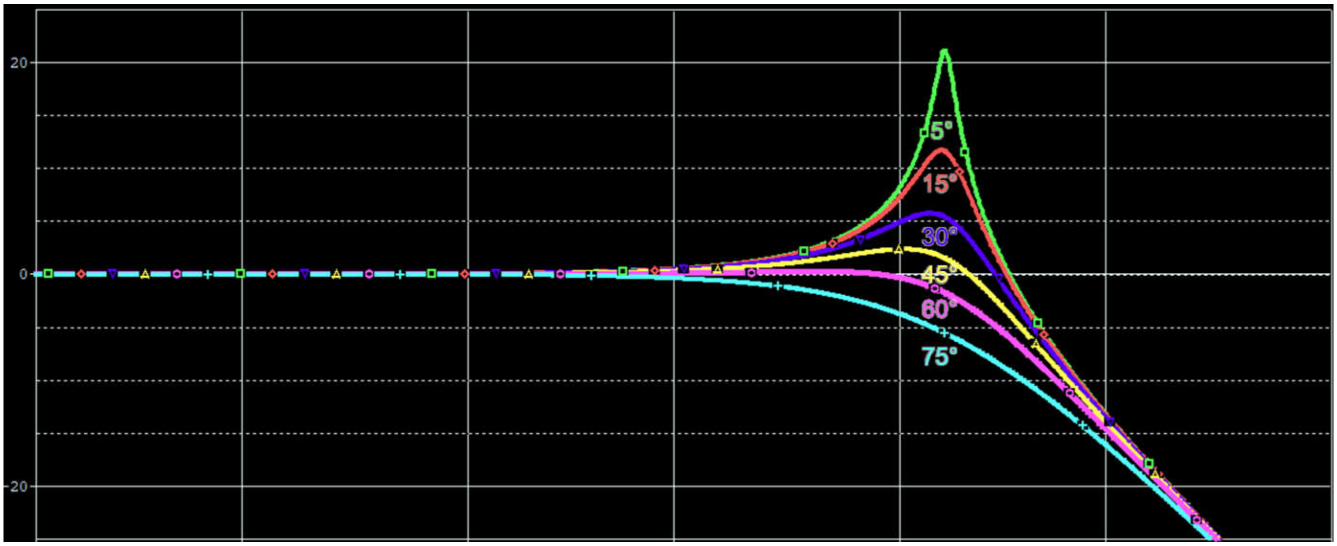

Figure 5-15. Gain Peaking with Different Phase Margin

6 Simulation Example Using an Op-Amp

6.1 OPA392 With Non-Inverting Amp Configuration

As an example of a simulation using actual op-amp, the OPA392 is used with a noise gain of 2V/V.

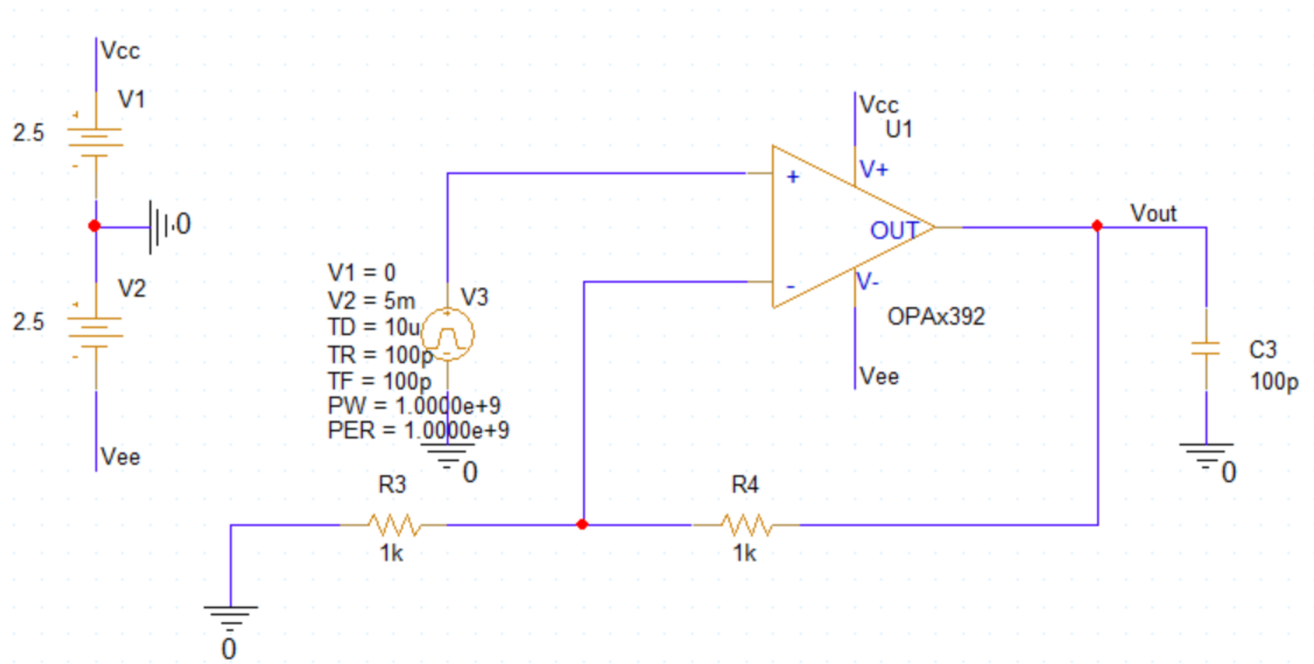

Figure 6-1. OPA392 with Non-Inverting Amplifier Configuration

6.1.1 Step Response Simulation

Figure 6-2 shows the step response of the circuit mentioned in Figure 6-1. The percent overshoot is calculated as 1mV/10mV ×100 = 10%, which corresponds to a phase margin of 58.6 degrees.

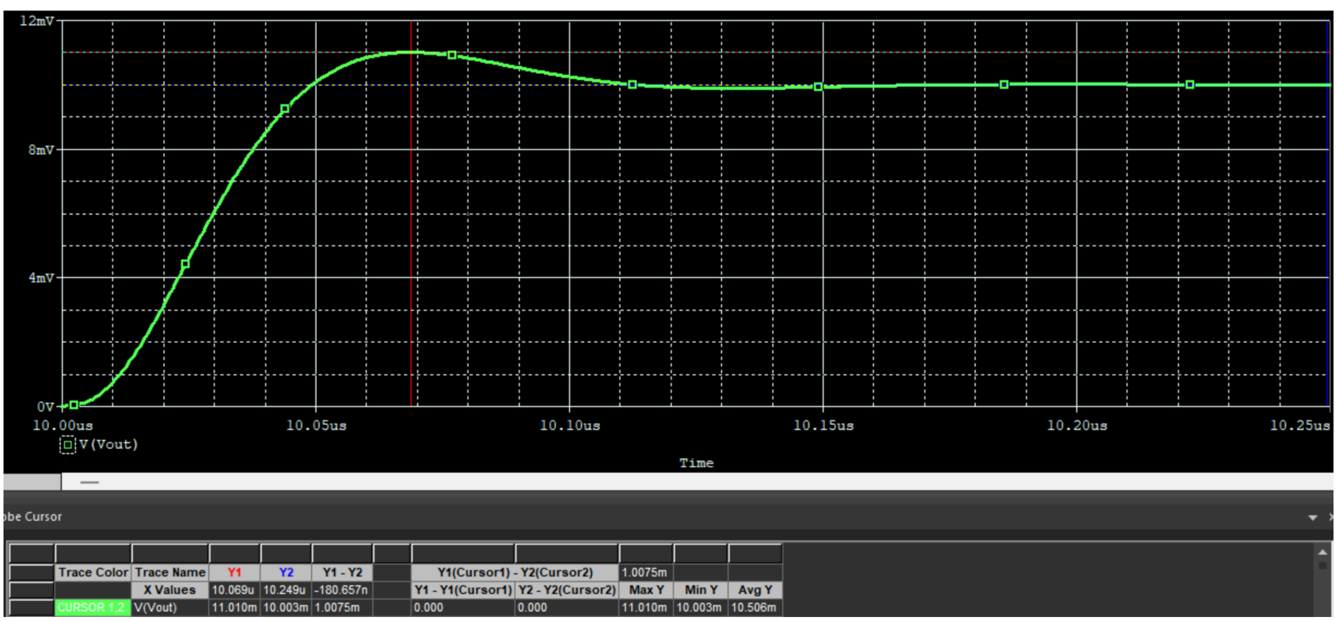

Figure 6-2. Step Response: OPA392 with Noninverting Amp Configuration

6.1.2 Gain Peaking Simulation

The gain peaking was 0.38dB, which corresponds to 58.9 degrees phase margin.

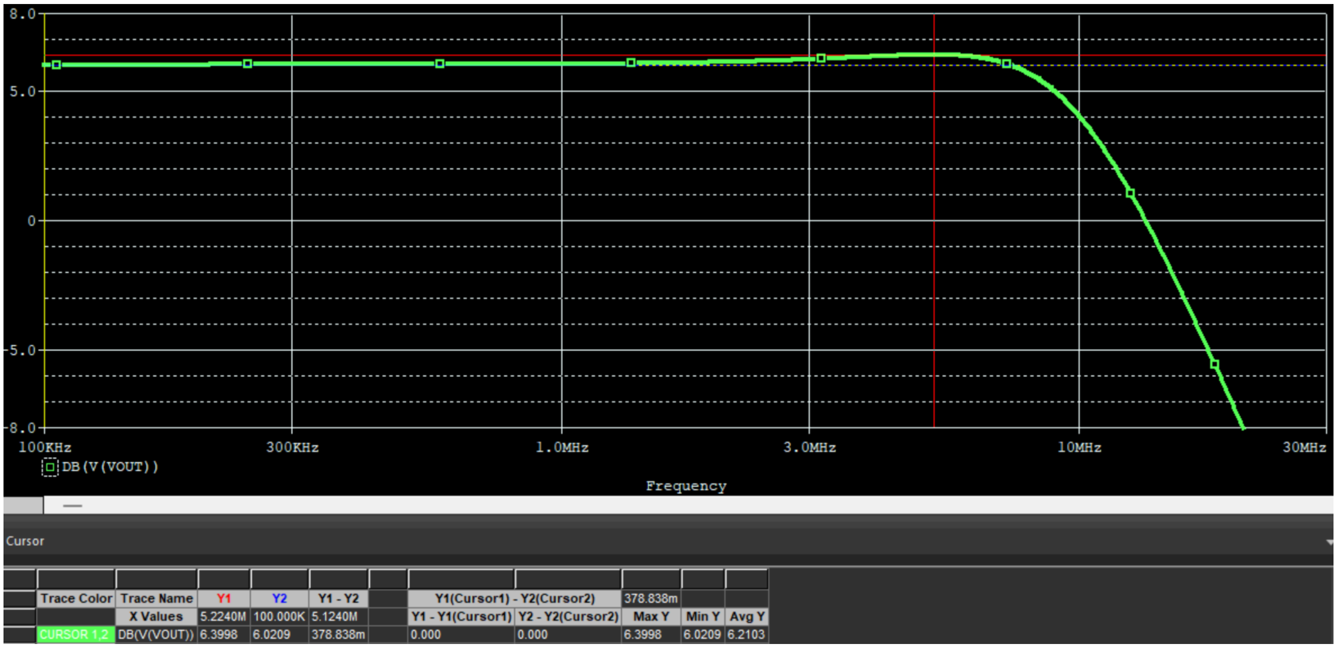

Figure 6-3. Gain Peaking: OPA392 with noninverting amp configuration

6.1.3 Loop Gain Simulation

To obtain a true loop gain, Middlebrook's loop gain measurement method was used, as shown in Equation 56. This method allows the user to measure the loop gain T without breaking the loop, using Equation 56 and the test circuit shown in Figure 6-4.

$$T = \frac{-\frac{V_y}{V_x} \times \frac{I_y}{I_x} - 1}{-\frac{V_y}{V_x} + \frac{I_y}{I_x} + 2} \quad (56)$$

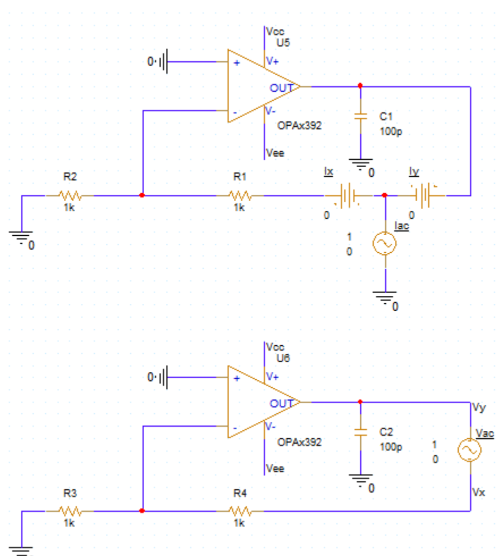

Figure 6-4. Middlebrook's Loop Gain Measurement

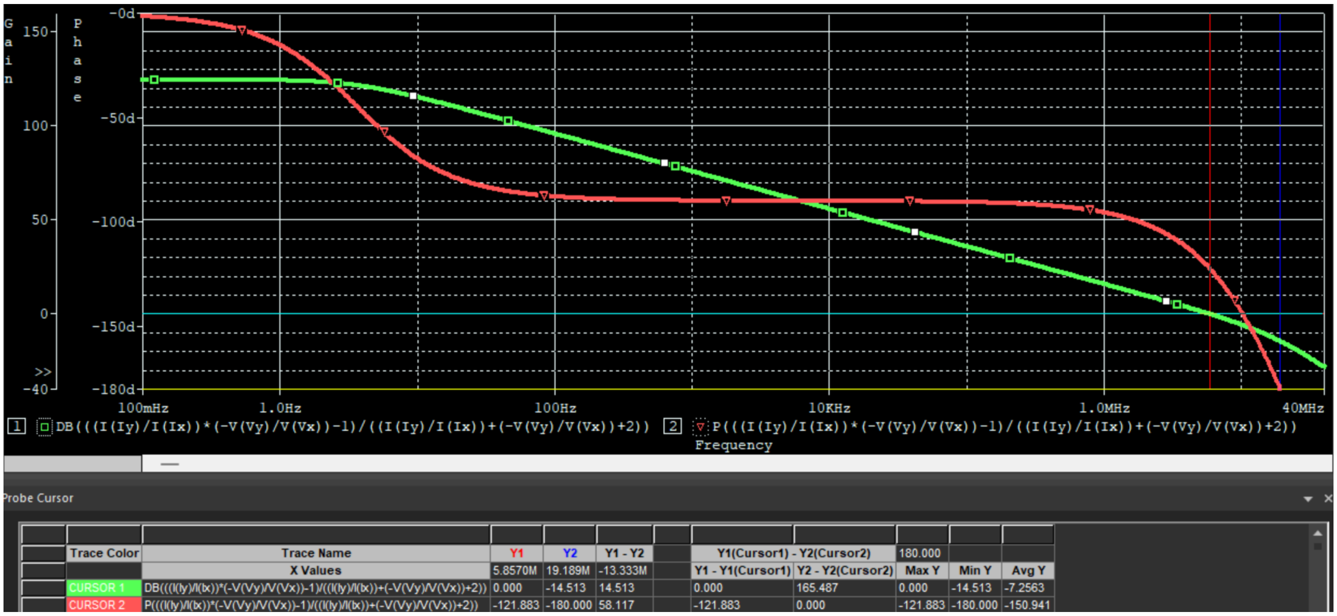

Figure 6-5. Bode Plot of Loop Gain: OPA392 with Noninverting Amp Configuration

The phase margin was 58.1 degrees, which is very close to the expected phase margin associated with overshoot and gain peaking.

6.2 TLV9052 with Unity Gain Buffer Configuration

Another example is using TLV9052 with unity gain buffer configuration and 470pF capacitive load.

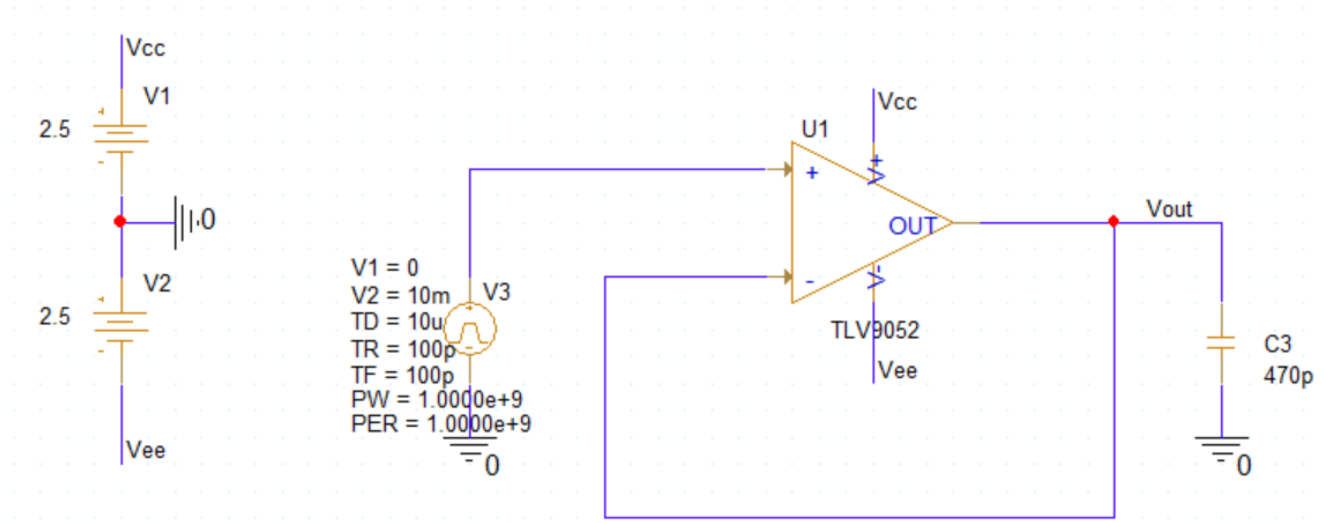

Figure 6-6. TLV9052 Buffer with 470pF Capacitive Load

6.2.1 Step Response Simulation

The overshoot was 6.37mV/10mV×100=63.7%, which represents phase margin of 16.2 degrees.

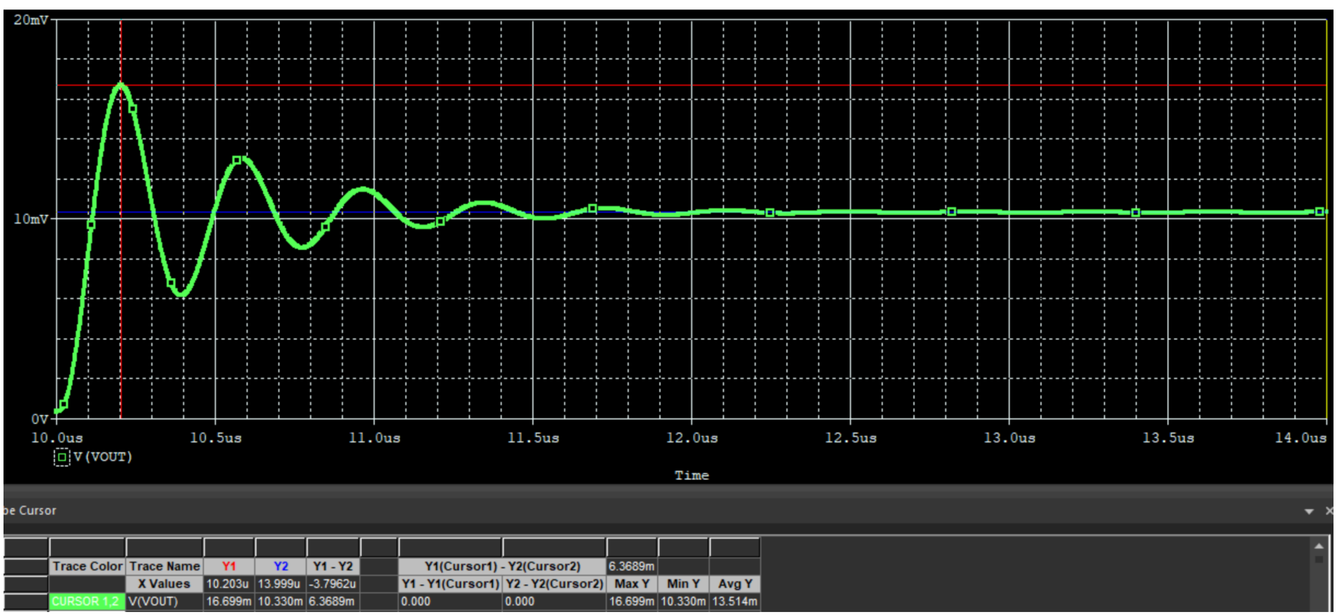

Figure 6-7. Step Response: TLV9052 with buffer configuration

6.2.2 Gain Peaking Simulation

The gain peaking was 11.2dB, which represents phase margin of 15.8 degrees.

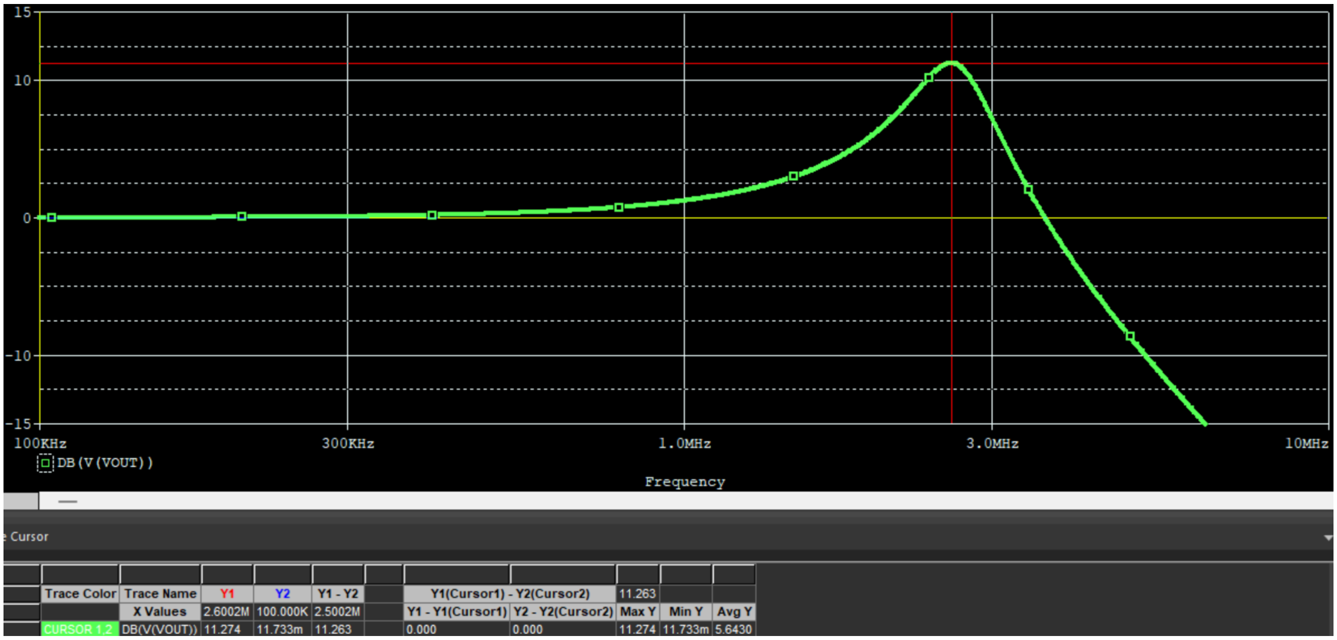

Figure 6-8. AC Peaking: TLV9052 with Buffer Configuration

6.2.3 Loop Gain Simulation

Figure 6-9 is the result of Middlebrook loop gain measurement. The phase margin was 16 degrees, which is very close to the expected phase margin associated with overshoot and gain peaking.

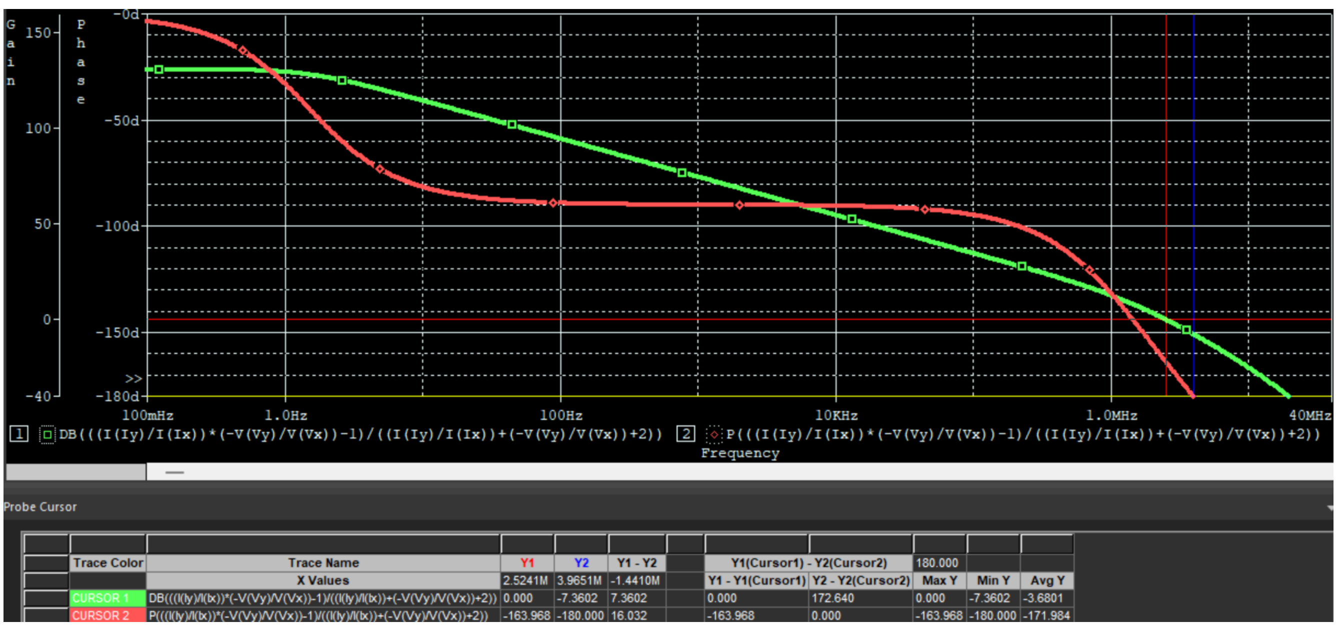

Figure 6-9. Bode Plot of Loop Gain: TLV9052 with Buffer Configuration

6.3 OPA206 with Unity Gain Buffer Configuration

Another example is using OPA206 with unity gain buffer configuration and 100pF capacitive load.

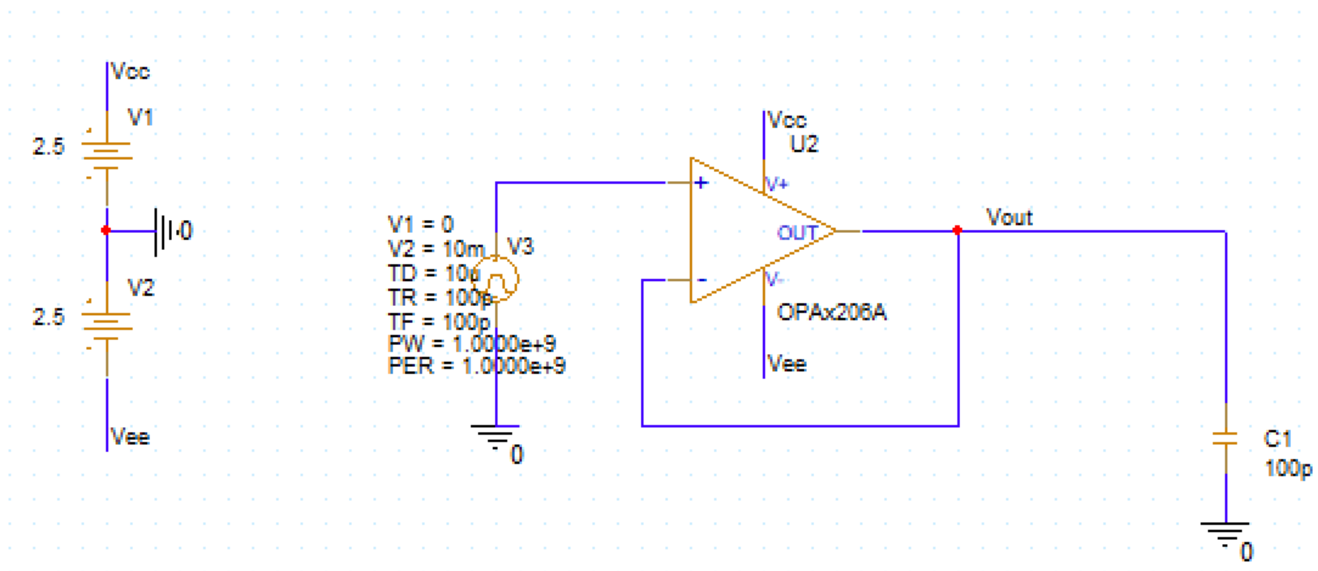

Figure 6-10. OPA206 Buffer with 100pF Capacitive Load

6.3.1 Step Response Simulation

The overshoot was 2.48mV/10mV×100=24.8%, which represents phase margin of 43.6 degrees.

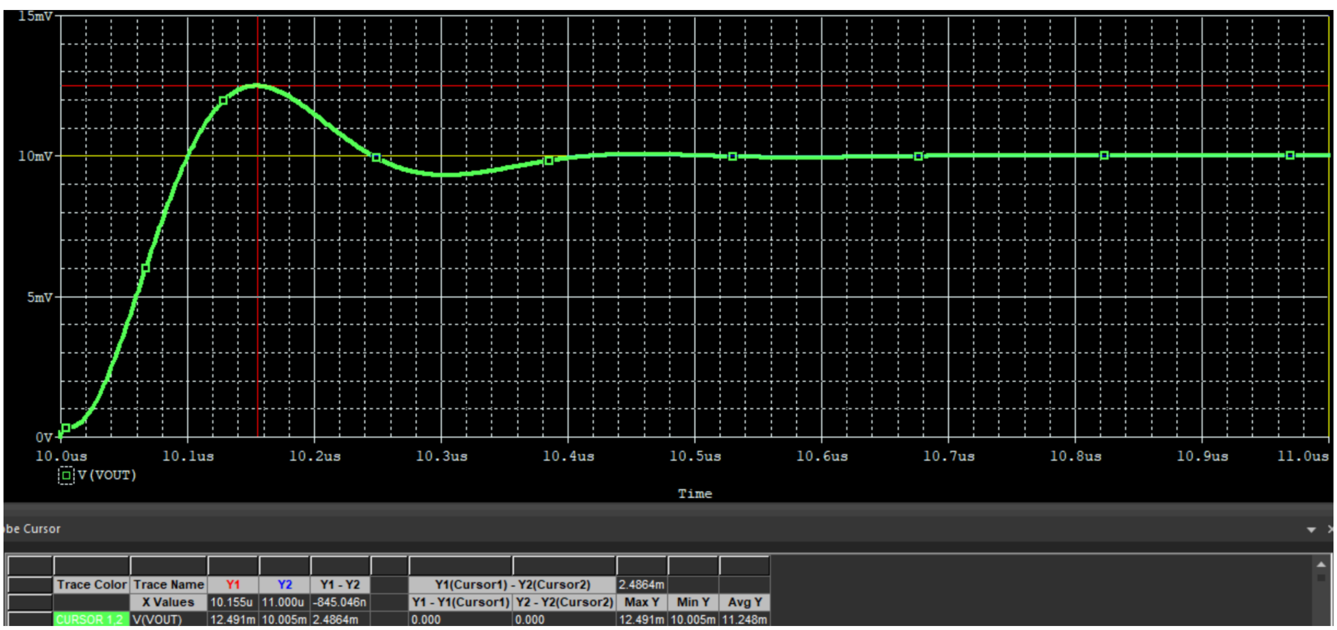

Figure 6-11. Step Response: OPA206 with Buffer Configuration

6.3.2 Gain Peaking Simulation

The gain peaking was 2.5dB, which represents phase margin of 44.2 degrees.

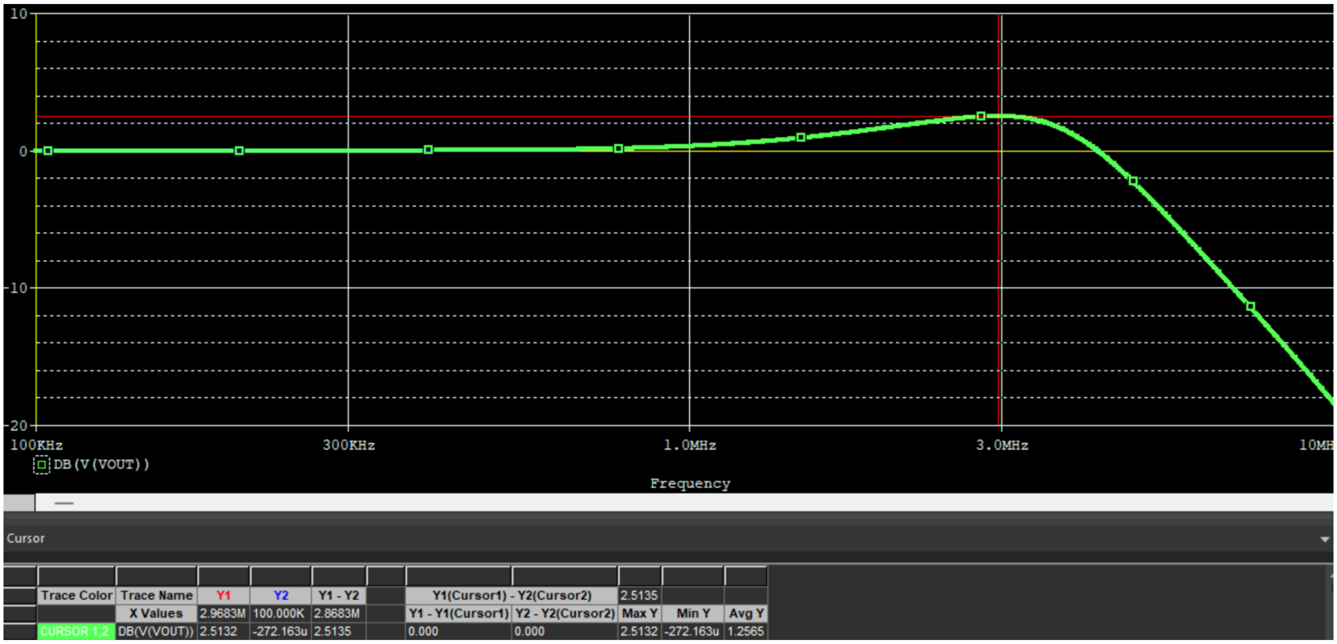

Figure 6-12. AC Peaking: OPA206 with Buffer Configuration

6.3.3 Loop Gain Simulation

Figure 6-13 is a result of Middlebrook loop gain measurement. The phase margin was 44.6 degrees, which is very close to the expected phase margin associated with overshoot and gain peaking.

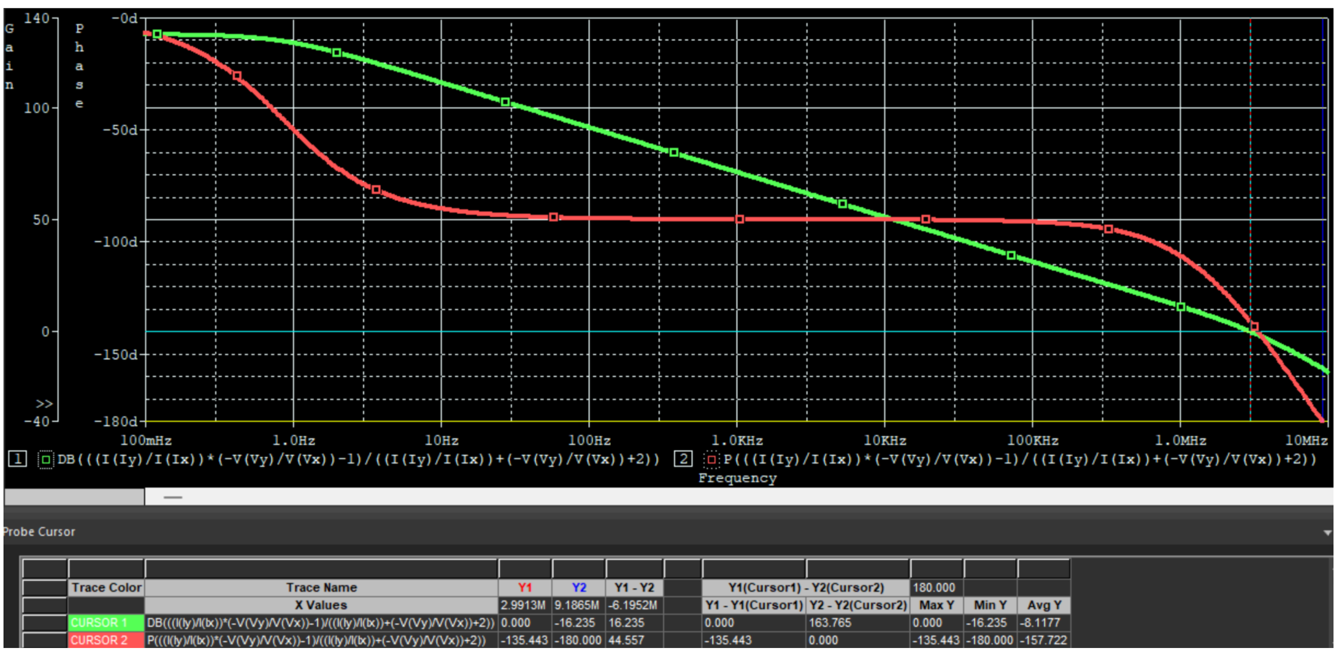

Figure 6-13. Bode Plot of Loop Gain: OPA206 with Buffer Configuration

7 Causes of the Mismatch of Phase Margin Between Step Response and AC Analysis

7.1 The Transfer Function is not a Second Order System

Figure 4-3 and Figure 4-5 were derived under the assumption of a second order system, which consists of two poles and no zero. If the system includes additional poles or zeros, it can lead to some errors.

7.2 Amplifier Showing Large-Signal Behavior

If the output voltage is too large, it leads to large signal behavior, which can mask small signal behavior, resulting in an error. In general, a step response output change of 10mV to 20mV is recommended.

The simulation result of the circuit is shown in Figure 6-6, but with a different input amplitude. Previously, a 10mV step was applied, but for this simulation, a 1V step is applied. As a result, the overshoot decreased compared to the condition where a 10mV step was applied (from 63.7% to 58.7%), even though the circuit configurations are identical.

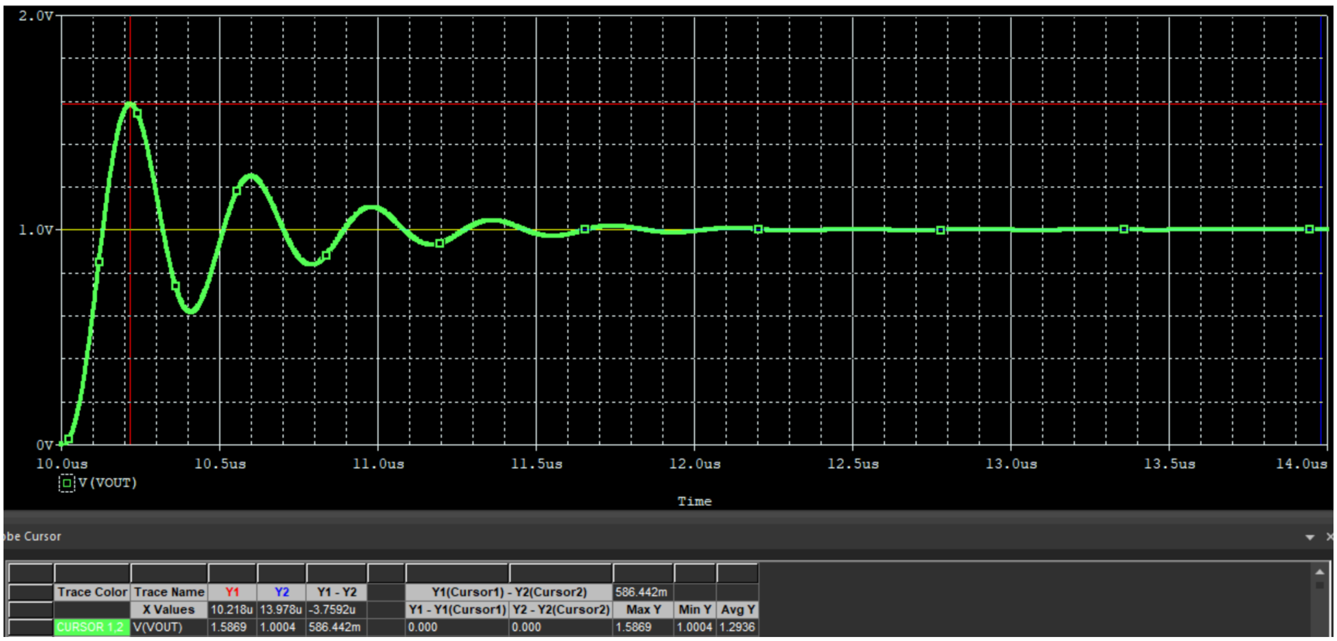

Figure 7-1. Step Response with Large Signal Behavior

7.3 Noise Gain is Not Flat Within Crossover Frequency

If the noise gain is not flat within the crossover frequency, the overshoot is likely to differ from the expected result. When the feedback factor (noise gain) is not constant across frequency, it can lead to change gain peaking. For example, if a zero caused by a large feedback resistor and parasitic input capacitance exists within the crossover frequency in noise gain, the noise gain at high frequency increases. This invalidates the graph of Figure 4-3 and Figure 4-5, even when the system is second order.

Below is an example case, where even if the phase margin is the same in a second-order system, the overshoot can be different.

Figure 7-3 shows step response of Figure 7-2. The simulated percent overshoot is 37.4%, which represents 33.1 degrees expected phase margin. Figure 7-4 is AC analysis simulation, showing 33.3 degrees phase margin.

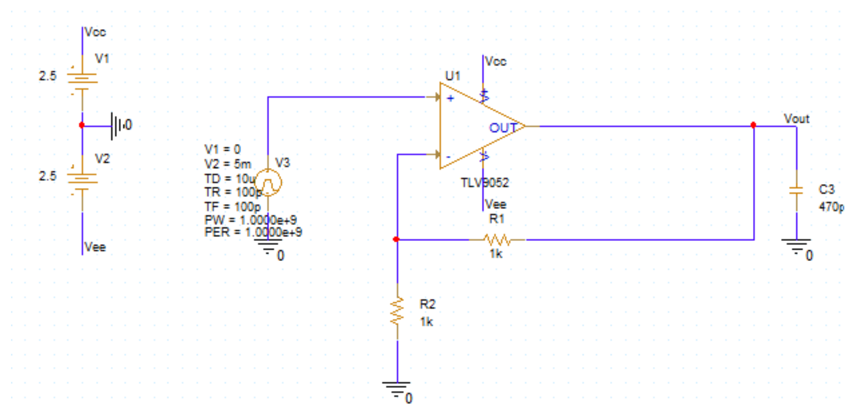

Figure 7-2. Noninverting Amplifier with Low Feedback Resistors with a Capacitive Load

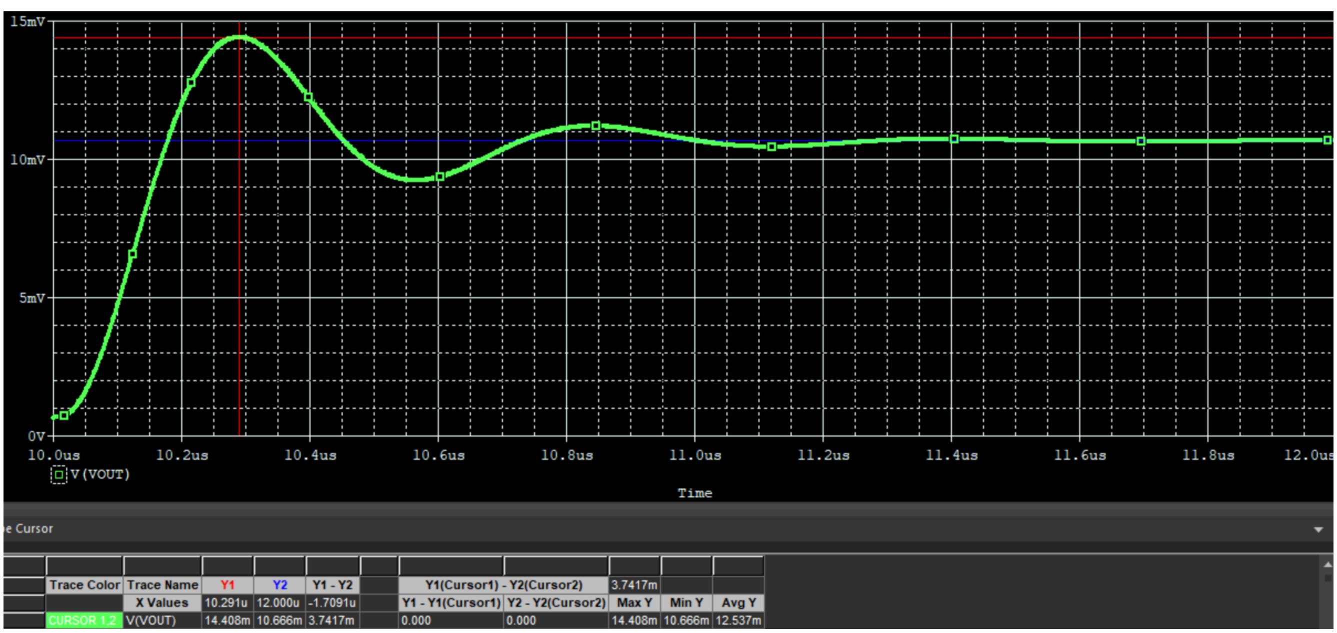

Figure 7-3. Step Response (Low Feedback Resistors with a Capacitive Load)

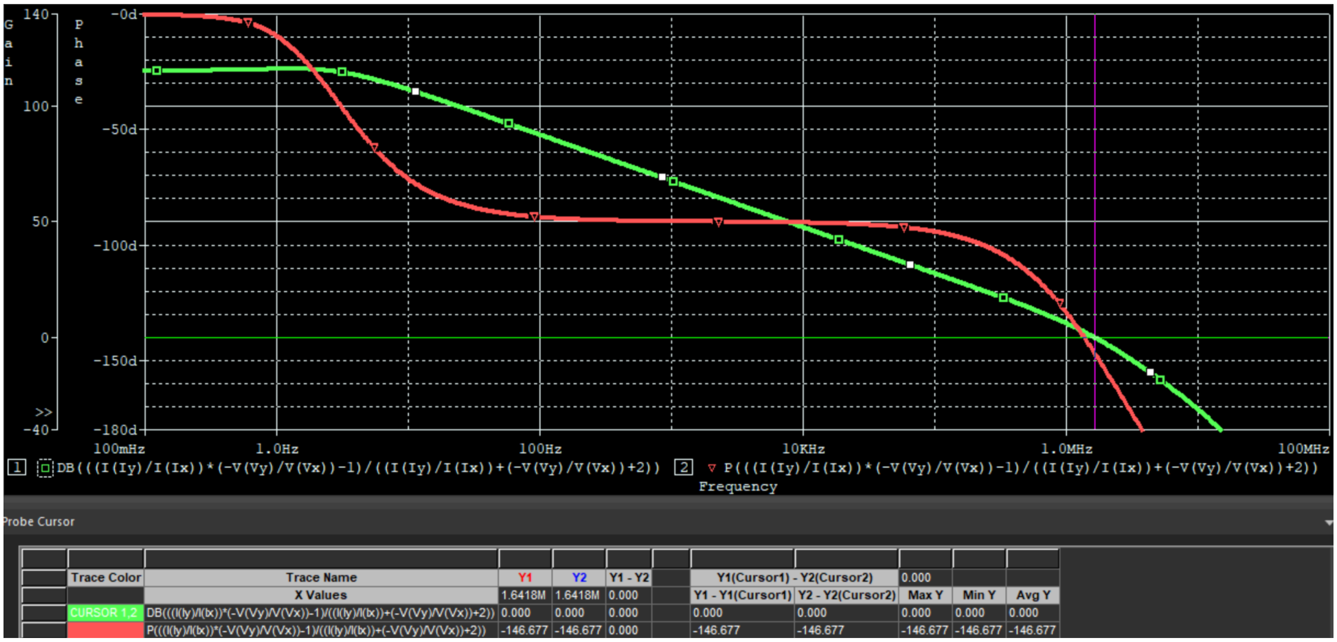

Figure 7-4. Loop Gain: 33°Phase Margin (Low Feedback Resistors with a Capacitive Load)

While, Figure 7-5 also has about 33 degrees phase margin as shown in Figure 7-6 which is same as Figure 7-2. However, step response of Figure 7-7 showed 53% overshoot, which is much larger than Figure 7-3, even though Figure 7-2 and Figure 7-5 have same phase margin.

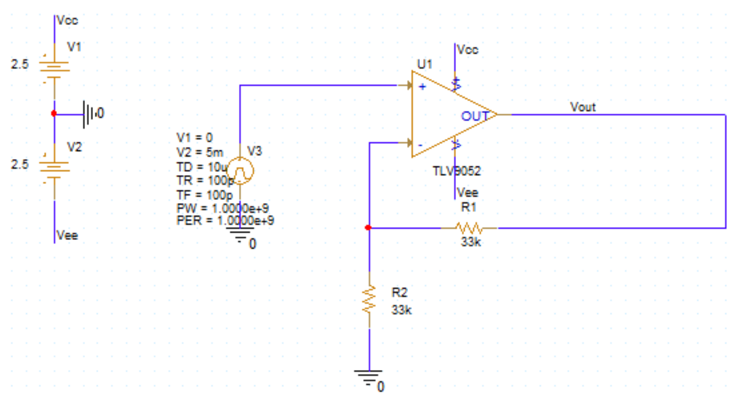

Figure 7-5. Noninverting Amplifier with Large Feedback Resistors

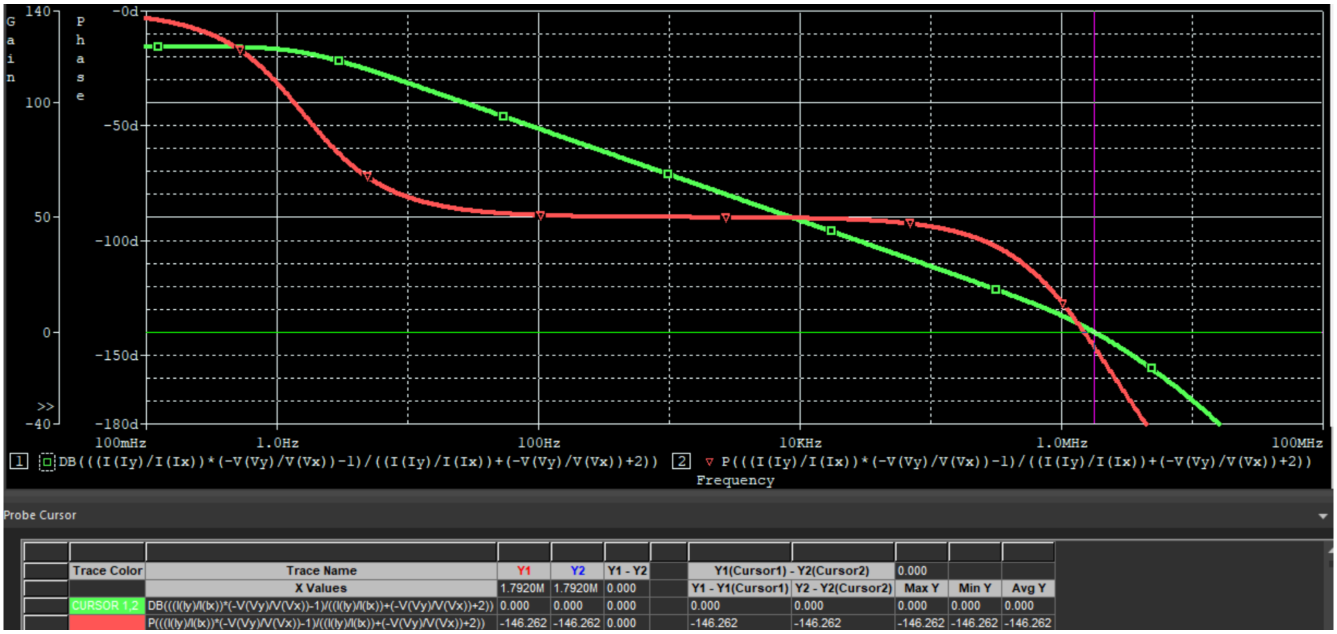

Figure 7-6. Loop Gain: 33°Phase Margin (Large Feedback Resistors)

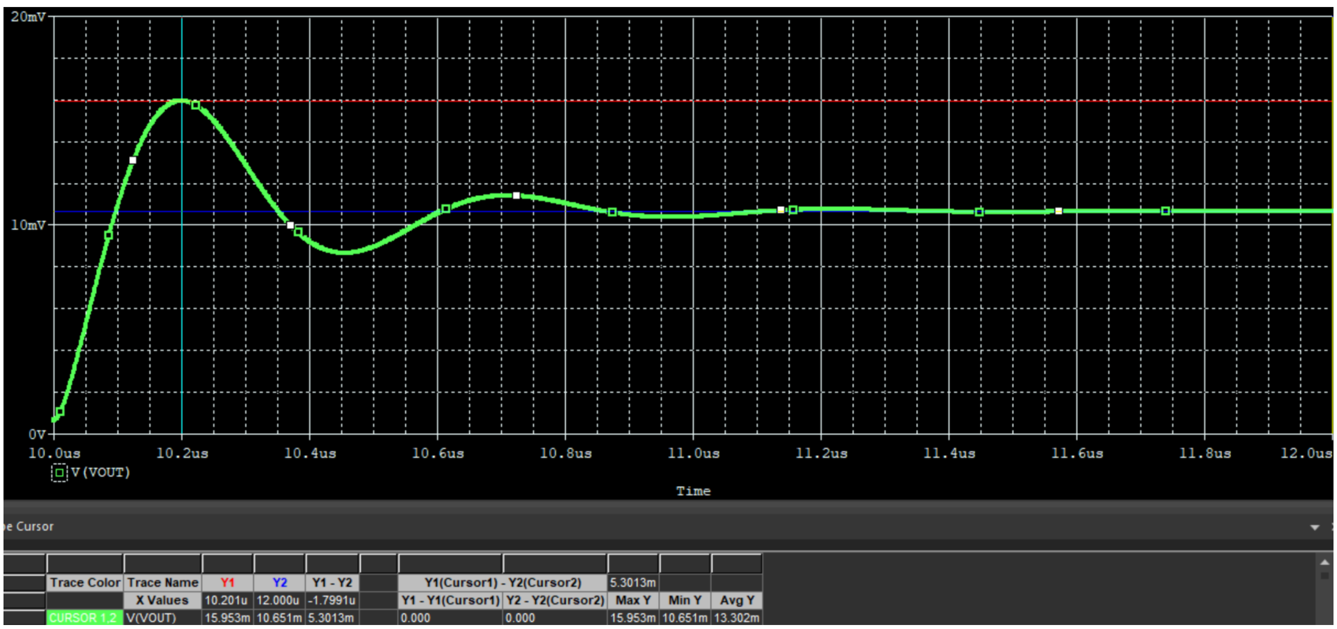

Figure 7-7. Step Response (Large Feedback Resistors)

Figure 7-8 shows a simplified schematic of Figure 7-2. The second pole is caused by the output impedance of the op-amp and the capacitive load. Meanwhile, Figure 7-5 does not have a capacitive load, but it uses larger feedback resistors, which makes it more sensitive to input capacitance like Figure 7-9. In this case, the second pole is caused by feedback resistors and input capacitance.

For Figure 7-5, the noise gain at high frequency increases due to the input capacitance as shown in Figure 7-10, while the noise gain of Figure 7-2 remains flat across frequency as shown in Figure 7-11. This leads to a boost of gain peaking as shown in Figure 7-12, resulting in larger overshoot even if phase margin is same.

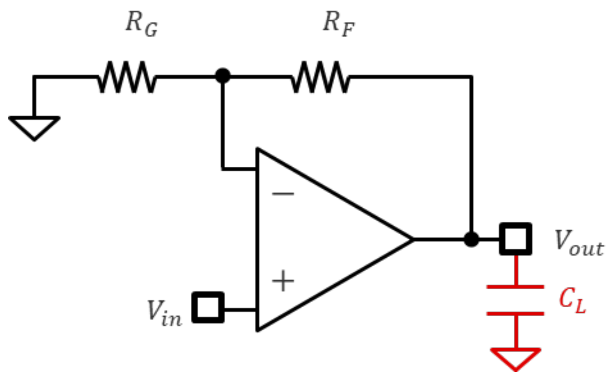

Figure 7-8. Second Pole is Caused By Capacitive Load

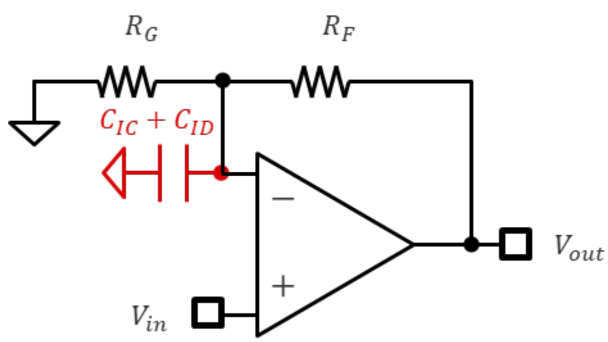

Figure 7-9. Second pole is Caused by Parasitic Input Capacitance

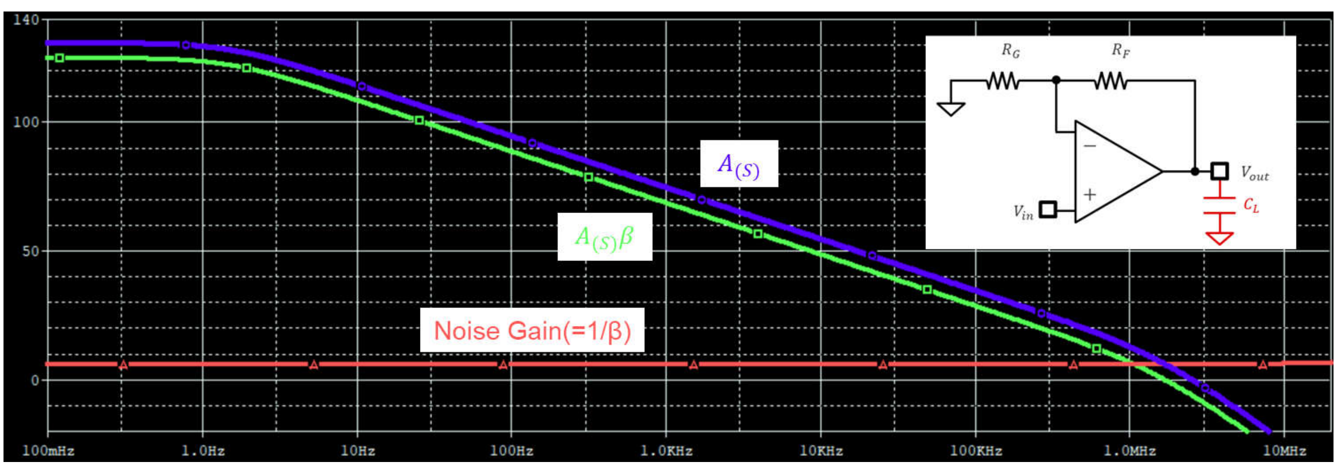

Figure 7-10. Frequency Response (Low Feedback Resistors with a Capacitive Load)

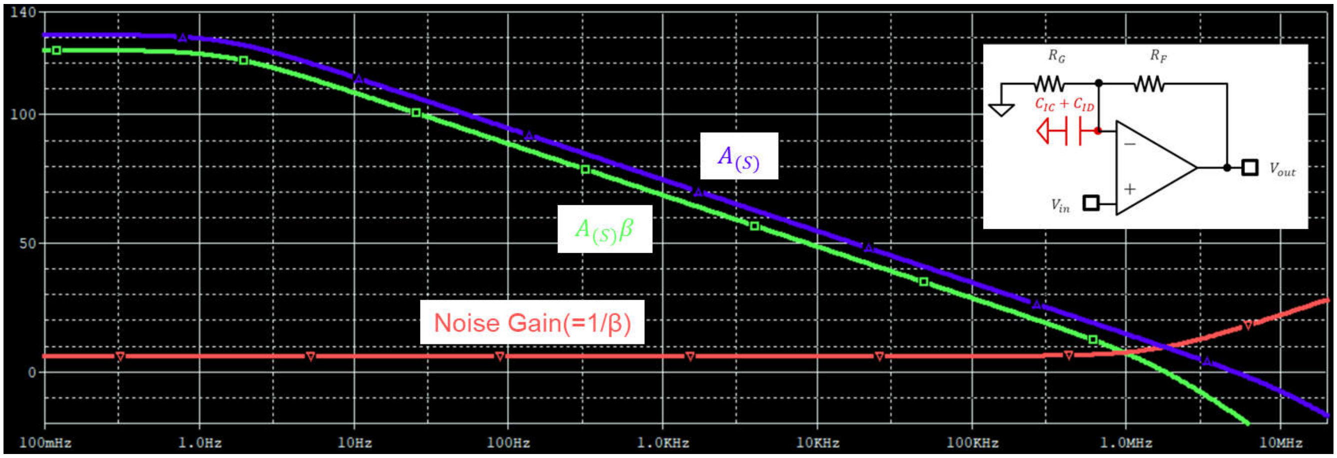

Figure 7-11. Frequency Response (Large Feedback Resistors)

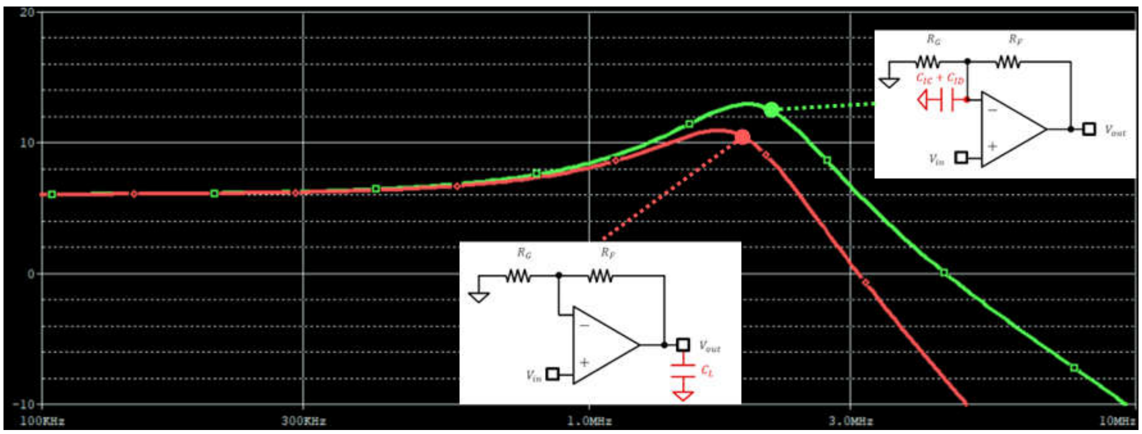

Figure 7-12. Gain Peaking Difference

8 Summary

This document confirms that the phase margin can be indirectly estimated from the percentage of overshoot in the step response or from gain peaking in a second-order system, through theoretical calculations and simulations using PSPICE for TI.

9 References

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2. Texas Instruments, OPA206 Input-Overvoltage-Protected, 4μV, 0.08μV/°C, Low-Power Super Beta, e-trim™ Operational Amplifiers, data sheet.
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5. Texas Instruments, Modeling the output impedance of an op amp for stability analysis, analog application journal.
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7. Texas Instruments, PSPICE for TI, simulation tool.