Application Report
SLDA031–April 2015

Understanding Open Loop Gain of the PGA900 DAC Gain Amplifier

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ABSTRACT

The open-loop gain (A_{OL}) of an operational amplifier is one of the most important specifications. Proper understanding of A_{OL} at DC and over frequency is crucial for the understanding of closed-loop gain, bandwidth, and stability analysis.

This application note provides an in-depth understanding of the PGA900 A_{OL} magnitude and phase over frequency. The effects of temperature, power supply voltage, and semiconductor process variation on the A_{OL} curve were observed. The variation over these parameters was used to develop a worst-case model that can be used to create robust designs.

Contents

List of Figures

1 PGA900 A_{OL}

Figure 1 shows the typical frequency behavior of the PGA900 A_{OL} magnitude ($A_{OL}(s)$) and phase ($\varphi(s)$).

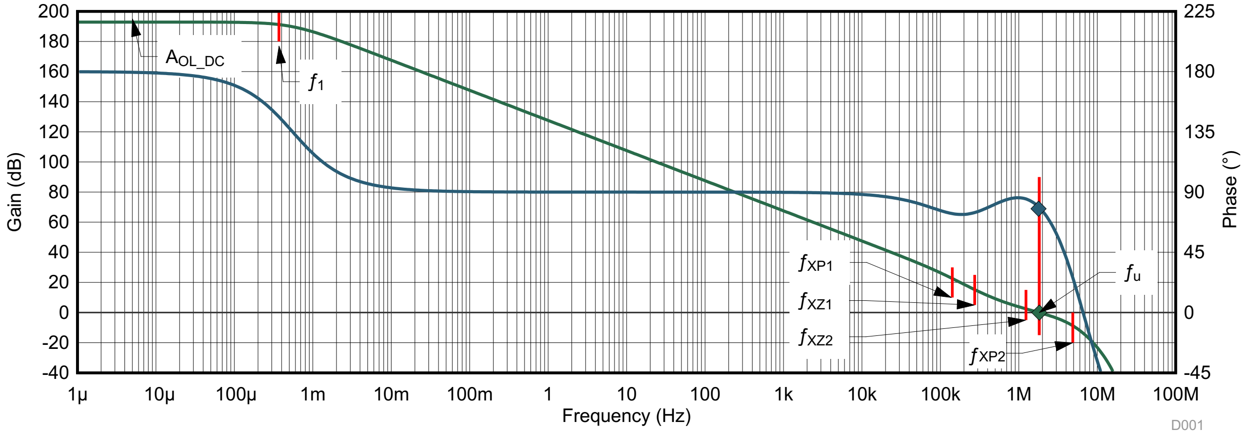

Figure 1. PGA900 Typical $A_{OL}(s)$ and Phase Response ($\varphi(s)$) over Frequency

The frequency where $A_{OL}(s)$ = 1 V/V or 0 dB, is marked as f_u in Figure 1; f_u is defined in Equation 1.

$$f_u = 1.8 \text{ MHz} \tag{1}$$

A_{OL_DC} is the DC change in output voltage (V_{OUT}) versus the change in input offset voltage (V_{OS}) as defined in Equation 2.

$$A_{OL_{DCdB}} = 20 \times \log_{10} \frac{V_{OUT}}{V_{OS}}$$
$$A_{OL_{DCdB}} = 195 \text{ dB} \tag{2}$$

The frequency behavior of $A_{OL}(s)$ is largely defined by the low-frequency dominant pole located at frequency ω_1 or f_1. At the dominant pole frequency, $A_{OL}(s)$ has decreased 3 dB from A_{OL_DC} and the phase has shifted by –45°.

$$f_1 = 0.37 \text{ mHz} \tag{3}$$

A single-pole Laplace approximation to the A_{OL} curve can be defined based on f_1, as shown in Equation 4.

$$A_{OL}(s) = \frac{A_{OL\_DC}}{1 + \frac{s}{\omega_1}}$$

where

- $s = j\omega$
- $\omega_1 = 2\pi f_1$ (4)

The complete frequency behavior of the PGA900 A_{OL} curve is additionally shaped by a midfrequency pole-zero pair, f_{XP1} and f_{XZ1}, an additional zero at f_{XZ2} and a high-frequency triple-pole, f_{XP2}. These frequencies are listed below for the PGA900. The location of these poles and zero in the $A_{OL}(s)$ transfer function determines the unity-gain crossover frequency (f_u) of 1.8 MHz.

$$f_{XP1} = 142 \text{ kHz} \tag{5}$$
$$f_{XZ1} = 274 \text{ kHz} \tag{6}$$
$$f_{XZ2} = 1.24 \text{ MHz} \tag{7}$$
$$f_{XP2} = 4.88 \text{ MHz} \tag{8}$$

The complete analytical expression of $A_{OL}(s)$ and $\varphi(s)$ are shown in Equation 9 and Equation 10.

$$A_{OL}(s) = A_{OL\_DC} \frac{\left(1 + \frac{s}{\omega_{XZ1}}\right)\left(1 + \frac{s}{\omega_{XZ2}}\right)}{\left(1 + \frac{s}{\omega_1}\right)\left(1 + \frac{s}{\omega_{XP1}}\right)\left(1 + \frac{s}{\omega_{XP2}}\right)^3} \quad (9)$$

$$\psi(s) = -\arctan\left(\frac{s}{\omega_1}\right) - \arctan\left(\frac{s}{\omega_{XP1}}\right) + \arctan\left(\frac{s}{\omega_{XZ1}}\right) + \arctan\left(\frac{s}{\omega_{XZ2}}\right) - 3 \times \arctan\left(\frac{s}{\omega_{XP2}}\right) \quad (10)$$

To create a robust design, it is important to understand how $A_{OL}(s)$ changes as the system operating conditions change. System operating conditions that affect the performance of the $A_{OL}(s)$ curve include: temperature, output load, power supply voltage, and process variation.

2 Temperature Effects on PGA900 A_{OL}

The PGA900 is specified over an extended operating temperature range of –40ºC to 150ºC. The operating temperature affects both the DC and the frequency behavior of the PGA900 $A_{OL}(s)$ curve as shown in Figure 2.

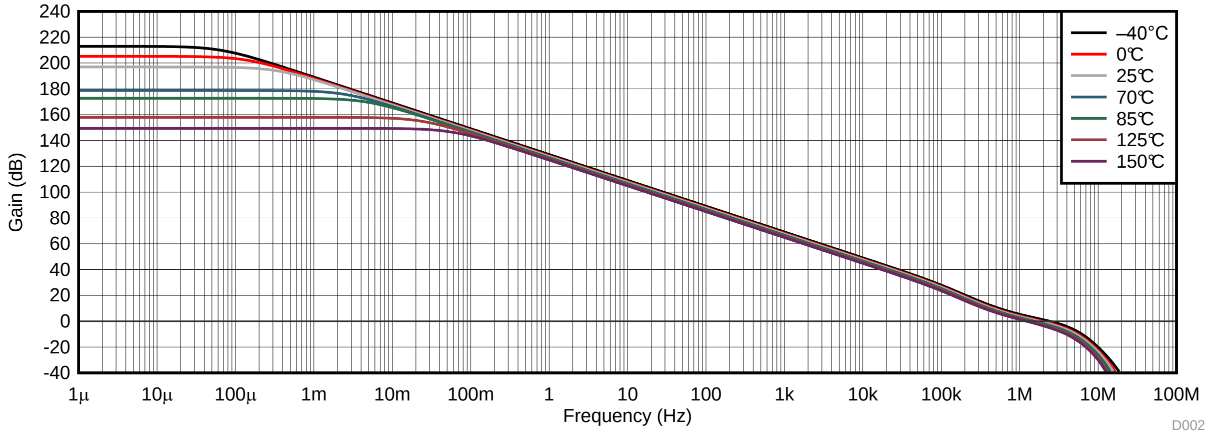

Figure 2. PGA900 $A_{OL}(s)$ vs Temperature

Figure 3 shows the temperature effects on A_{OL_DC}. Over the operating temperature range, A_{OL_DC} can vary from 214 to 149 dB. The 65-dB change in A_{OL_DC} results in changes in the accuracy of the closed-loop gain at low-frequencies.

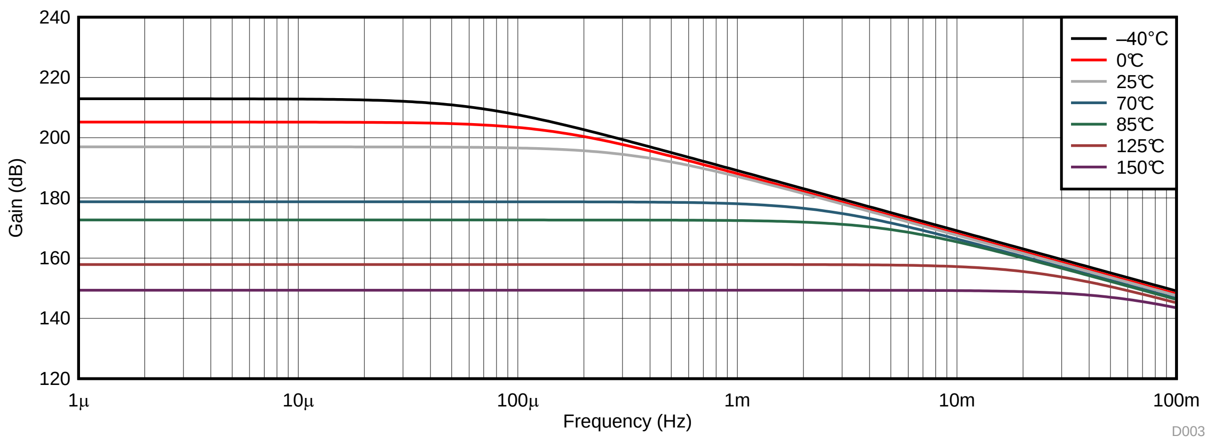

Figure 3. PGA900 A_{OL_DC} vs Temperature

Figure 4 shows the variation of the unity-gain frequency, f_u, over the operating temperature range. Over the operating temperature of the PGA900, f_u can vary from 1.26 to 2.75 MHz.

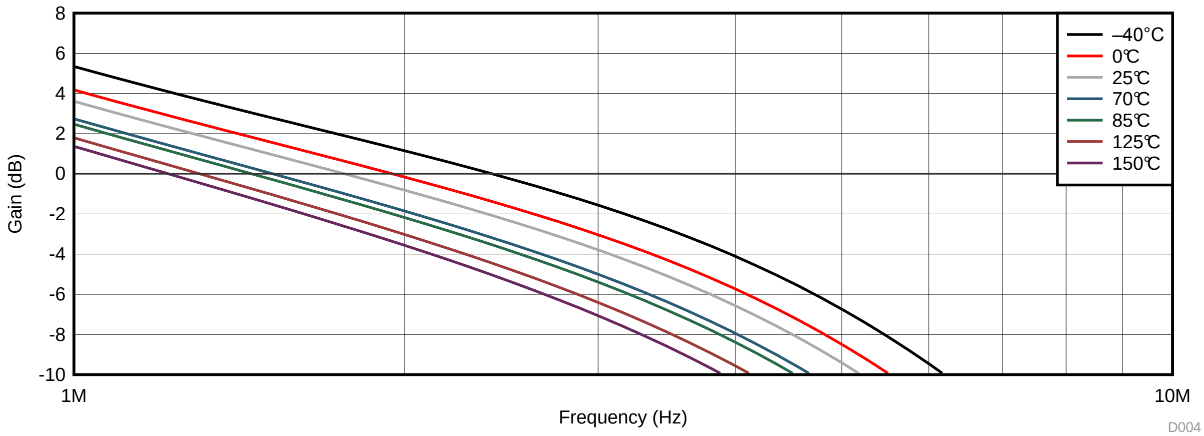

Figure 4. PGA900 Unity-Gain Frequency vs Temperature

3 Output Load Effects on PGA900 AOL

The PGA900 is specified to drive output loads with up to 2.5 mA of source and sink current. The operating output current, or better output load, affects both the DC and the frequency behavior of the PGA900 $A_{OL}(s)$ curve as shown in Figure 5.

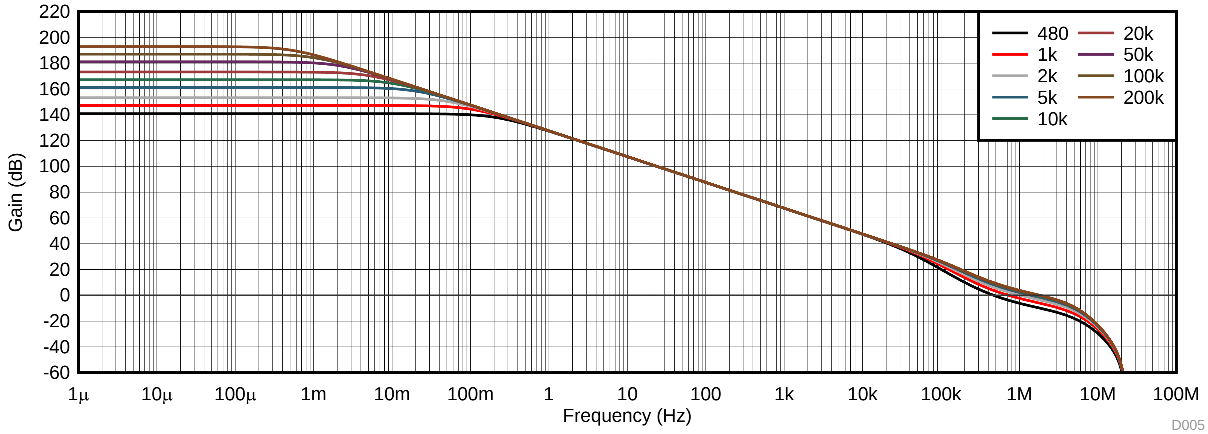

Figure 5. PGA900 $A_{OL}(s)$ vs Output Load

Figure 6 shows the output load effects on A_{OL_DC}. Over the operating output load range, A_{OL_DC} can vary from 195 to 141 dB.

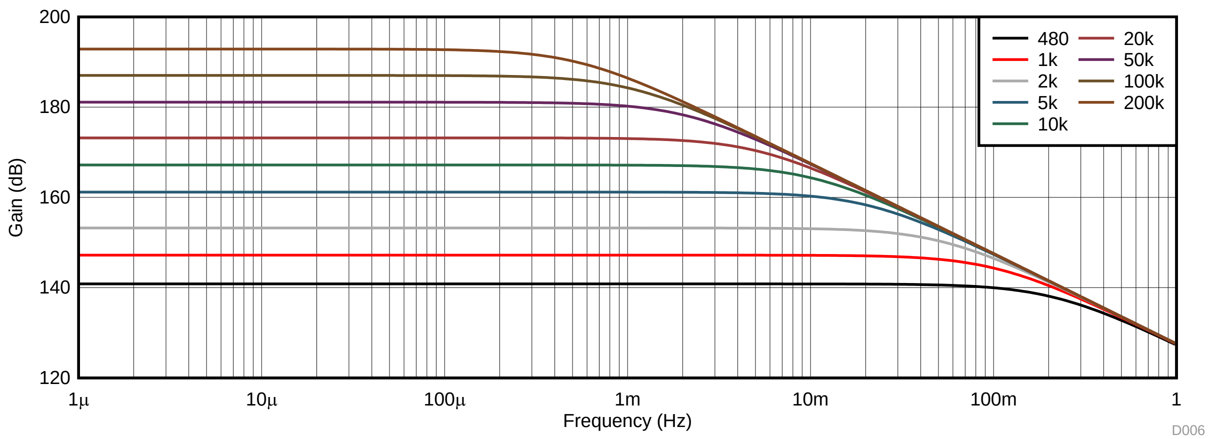

Figure 6. PGA900 A_{OL_DC} vs Output Load

Figure 7 shows the variation of the unity-gain frequency, f_u, over the operating output load range. Over the operating output load of the PGA900, f_u can vary from 0.48 to 1.8 MHz.

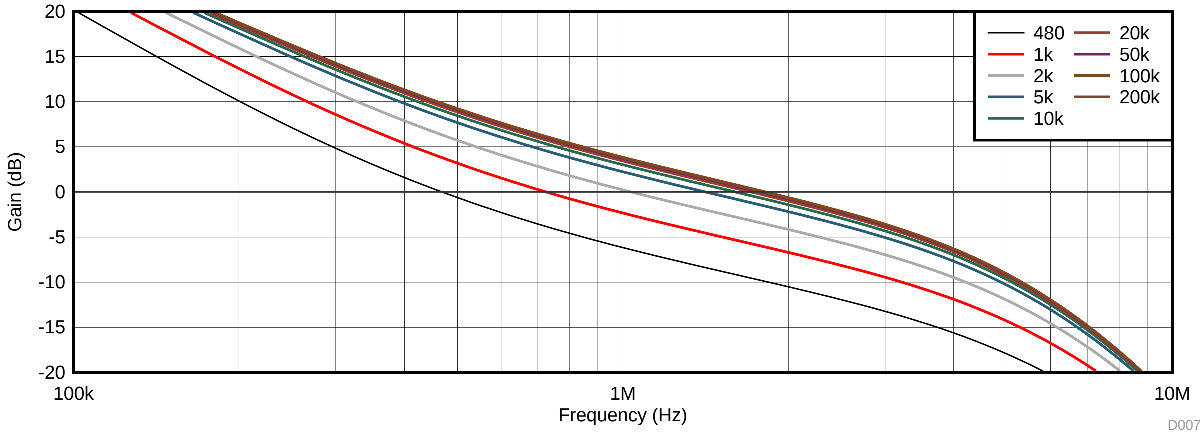

Figure 7. PGA900 Unity-Gain Frequency vs Output Load

Lower values of load resistance cause a greater impact on A_{OL} due to the interaction of the open-loop output impedance and the output load.

4 Power Supply Voltage Effects on PGA900 A_{OL}

The PGA900 can operate over a wide range of the power supply voltages from 3.3 to 30 V. The power supply voltage has minimal impact on $A_{OL}(s)$ as shown in Figure 8.

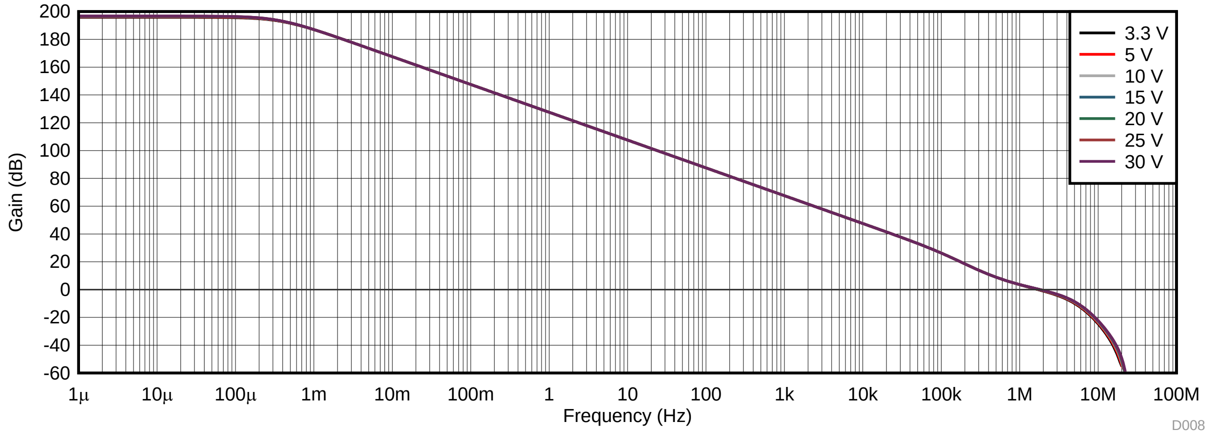

Figure 8. PGA900 $A_{OL}(s)$ vs Power Supply Voltage

A_{OL_DC} changes by less than 1 dB from 195.9 to 196.8 dB over the full power-supply voltage range, as shown in Figure 9.

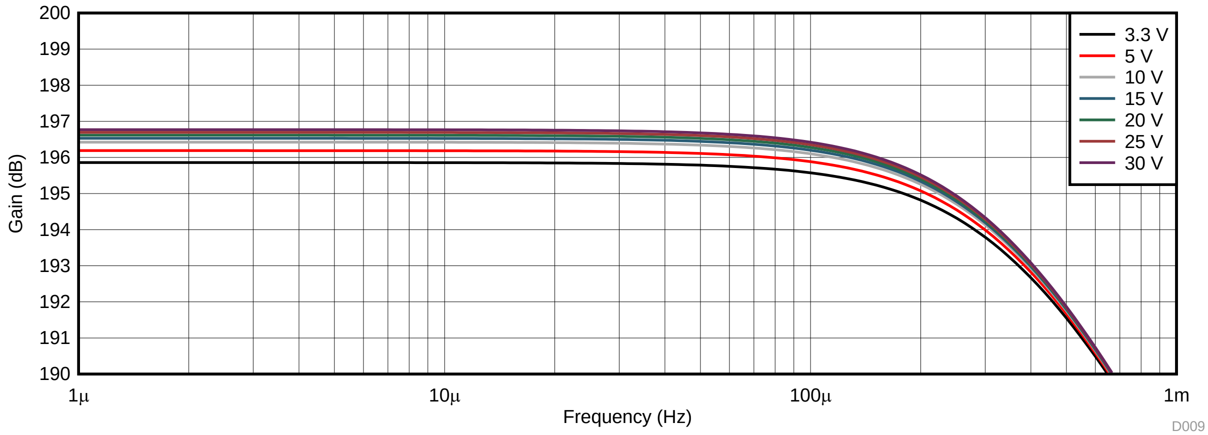

Figure 9. PGA900 A_{OL_DC} vs Power Supply

Over the full power-supply voltage range, f_u only changes from 1.7 to 1.8 MHz as shown in Figure 10.

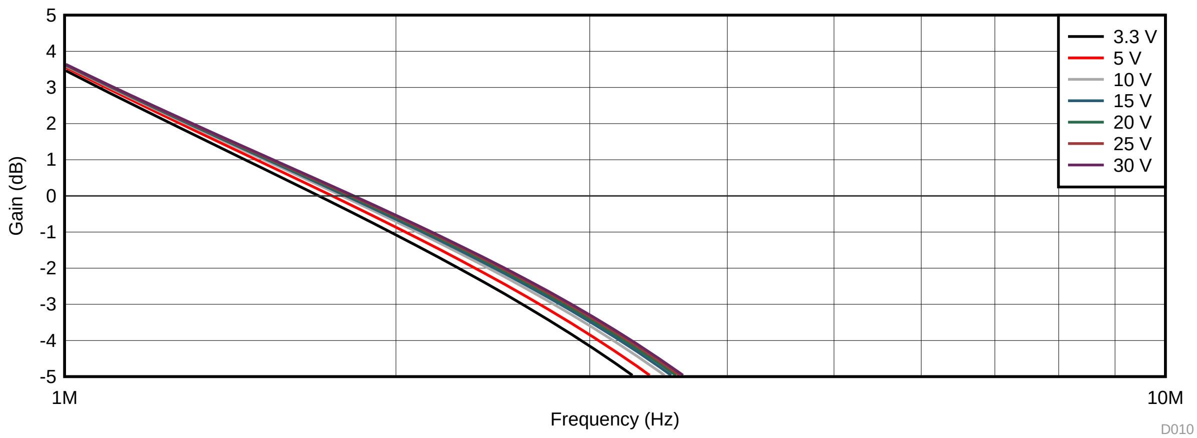

Figure 10. PGA900 Unity Gain Frequency vs Power Supply

5 Process Variation Effects on PGA900 A_{OL}

During manufacturing, semiconductor process parameters are subjected to variations that result in performance differences in the final integrated circuits. Process corners represent the worst-case variations of these semiconductor parameters. The effects of the manufacturing process corners on the PGA900 A_{OL}(s) are displayed in Figure 11.

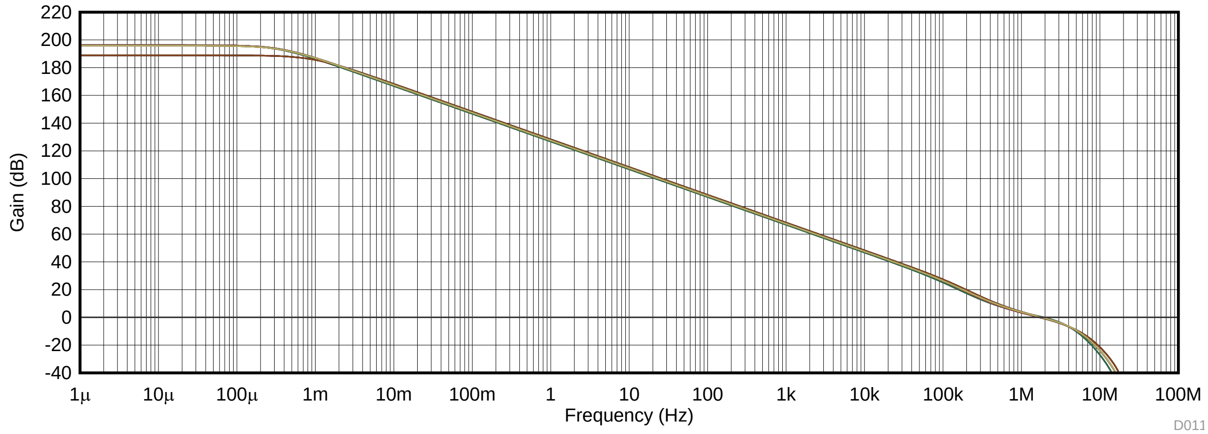

Figure 11. PGA900 A_{OL}(s) vs Process Variation

Over the process corners, A_{OL_DC} changes from 188.9 dB to 196.2 dB as shown in Figure 12.

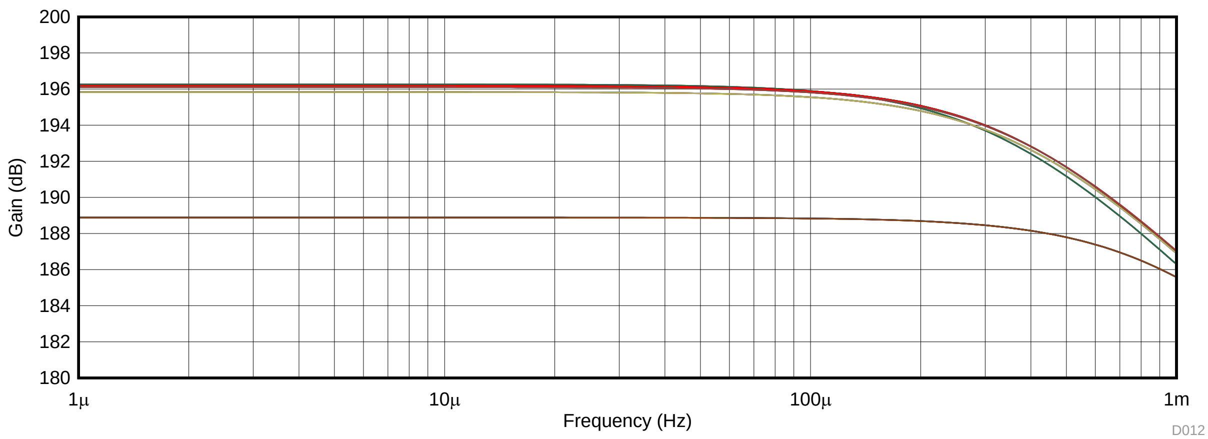

Figure 12. PGA900 A_{OL_DC} Change vs Process Variation

Process variations result in changes of f_u from 1.66 to 1.9 MHz as shown in Figure 13.

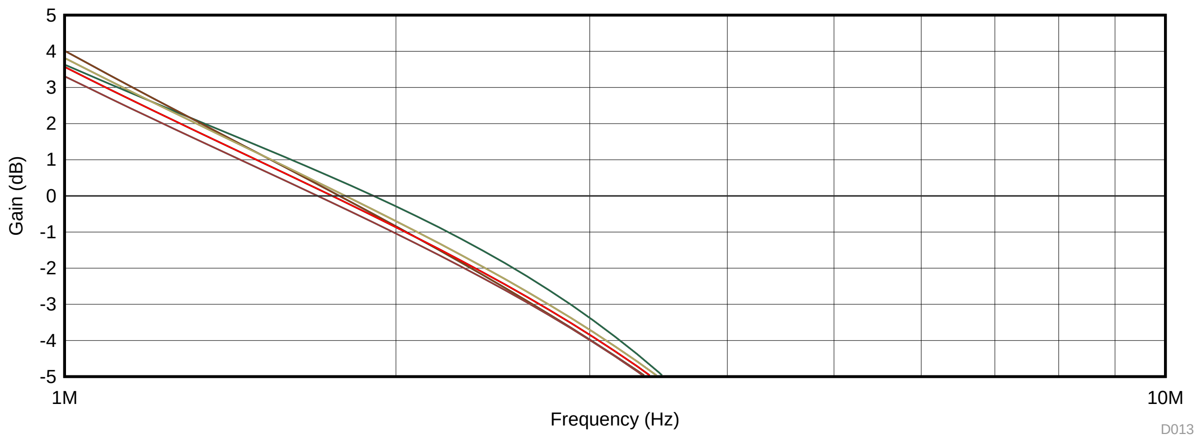

Figure 13. PGA900 Unity Gain Frequency vs Process Variation

6 Worst-Case PGA900 A_{OL} Variations

The variations in the PGA900 A_{OL}(s) due to temperature, power-supply voltage, and process variations for a 200-kΩ load resistor can be combined together to understand the worst-case variations that may occur in an application. The operating temperature results in the largest variations of A_{OL}(s), while the power-supply voltage results in the smallest variations. Observe the worst-case PGA900 A_{OL}(s) in Figure 14.

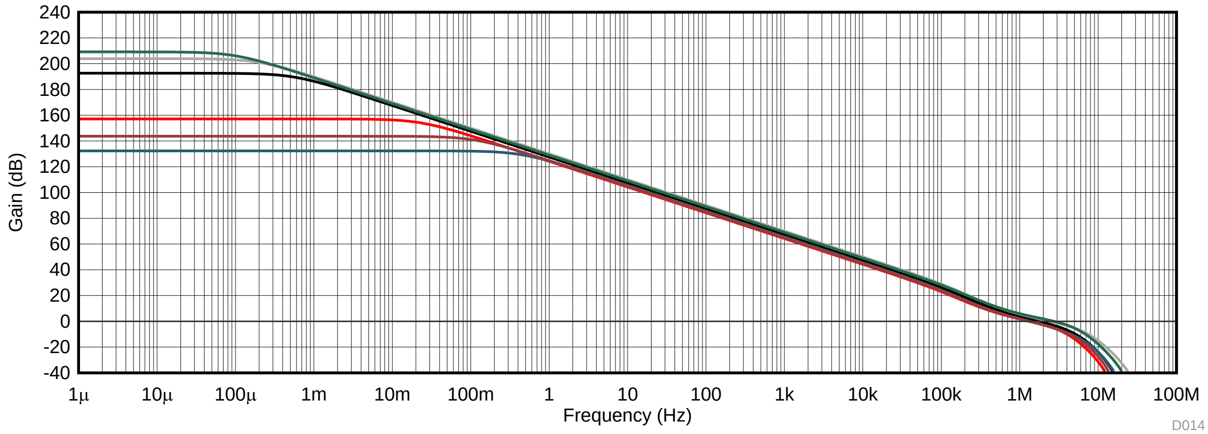

Figure 14. PGA900 Worst-Case A_{OL}(s) vs Frequency

Over all of the possible system variations, A_{OL_DC} can change from 135 to 213 dB as shown in Figure 15.

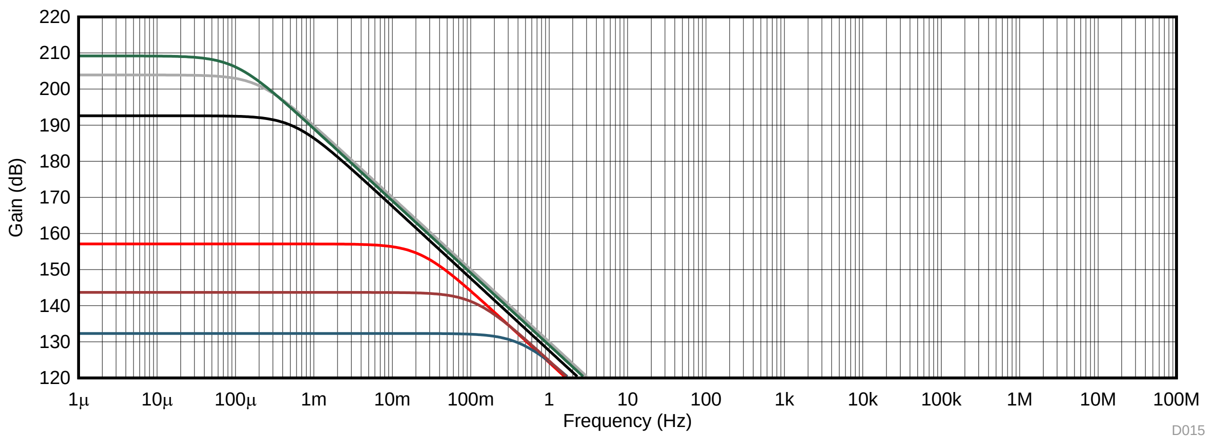

Figure 15. PGA900 Worst-Case A_{OL_DC}

As shown in Figure 16, the system variations result in a worst-case change in f_u from 1.2 to 3 MHz. This variation can significantly impact the stability analysis of the PGA900 and must be taken into account during the design process.

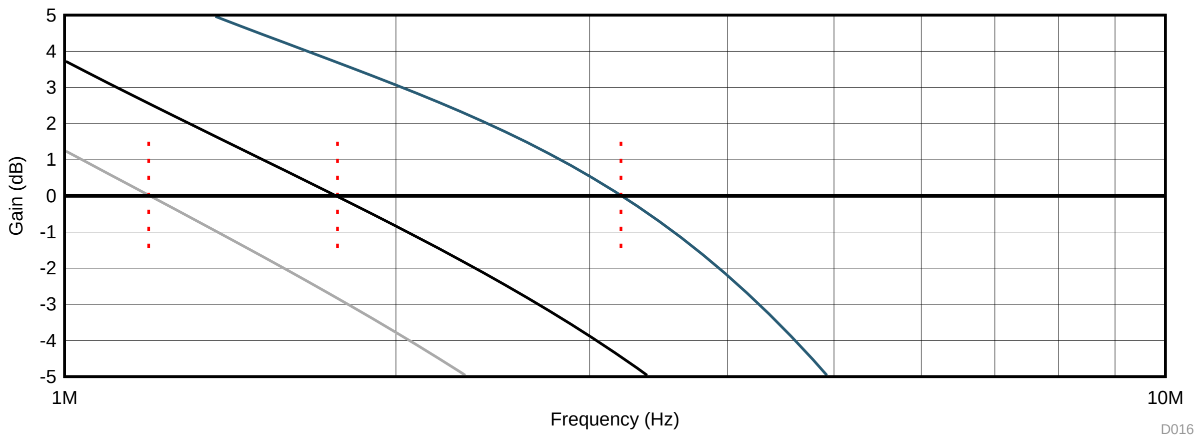

Figure 16. PGA900 Worst-Case Unity Gain Frequency

The corresponding phase responses for the curves shown in Figure 16 have been plotted in Figure 17. The phase margin is the measure of the phase at f_u for each of the curves. The worst-case system variations cause the phase margin to change from the nominal value of 77.6° up to 79° and down to 56°.

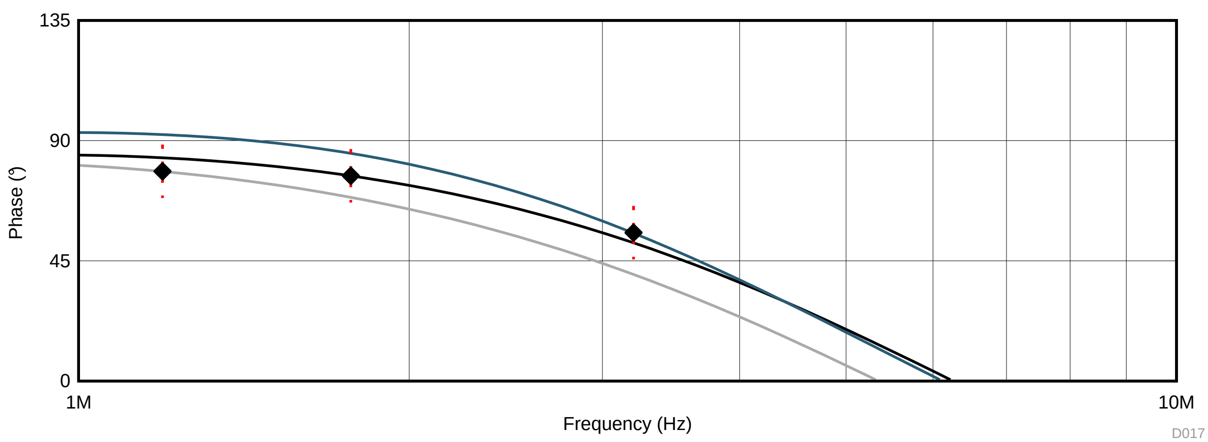

Figure 17. PGA900 Worst-Case Phase Margin

7 Conclusion

The PGA900 A_{OL} curve is shaped by a low-frequency dominant pole, a midfrequency pole-zero pair, an additional zero, and a high-frequency triple pole. The complete PGA900 A_{OL} curve is shown in Figure 1 and defined in Equation 1.

The typical magnitude and phase response of the A_{OL} curve changes due to variations in the system operating temperature, output load, power-supply voltage, and semiconductor processing. The changes in A_{OL} due to these varying application factors were presented in this note over the full operating range of the PGA900. The results from the individual parameters were used to determine the worst-case changes that may occur in a harsh industrial application. Table 1 lists the results of the individual application factors along with the worst-case analysis. System designers can use this information to create a robust design over the expected application operating conditions. The A_{OL} characteristics and typical variations shown in this application note are valid for any semiconductor operational amplifier on a CMOS process.

Table 1. Summary of PGA900 A_{OL} and f_u Shifts

Application Factor	Conditions	A_{OL}		f_c	
		MIN (dB)	MAX (dB)	MIN (MHz)	MAX (MHz)
Temperature	–45°C to 150°C	149	214	1.26	2.75
Output load	470 Ω to 200 kΩ	140	195	0.48	1.8
Power supply	3.3 to 30 V	195.9	196.8	1.7	1.8
Process variation	Weak-strong	188.9	196.2	1.66	1.9
Worst case	Power supply, temperature, process	135	213	1.2	3.0

8 References

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