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.

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

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.

$$f_u = 1.8 \text{ MHz} \quad (1)$$

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

$$A_{OL\ DC} = 20 \times \log_{10} \frac{V_{\text{OUT}}}{V_{\text{OS}}}$$

$$A_{OL\ DC} = 195 \text{ dB} \quad (2)$$

The frequency behavior of $A_{OL}(s)$ is largely defined by the low-frequency dominant pole located at frequency $\omega_1$ 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 $-45^\circ$.

$$f_1 = 0.37 \text{ mHz} \quad (3)$$

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

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

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.

$$f_{XP1} = 142 \text{ kHz} \quad (5)$$

$$f_{XZ1} = 274 \text{ kHz} \quad (6)$$

$$f_{XZ2} = 1.24 \text{ MHz} \quad (7)$$

$$f_{XP2} = 4.88 \text{ MHz} \quad (8)$$

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

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 $A_{\text{OL}}(s)$ curve as shown in Figure 2.

![Figure 2. PGA900 $A_{\text{OL}}(s)$ vs Temperature](image)

Figure 2 shows the temperature effects on $A_{\text{OL,DC}}$. Over the operating temperature range, $A_{\text{OL,DC}}$ can vary from 214 to 149 dB. The 65-dB change in $A_{\text{OL,DC}}$ results in changes in the accuracy of the closed-loop gain at low-frequencies.

![Figure 3. PGA900 $A_{\text{OL,DC}}$ vs Temperature](image)

Figure 3 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 $A_{\text{OL}}(s)$ curve as shown in Figure 5.

![Figure 5. PGA900 $A_{\text{OL}}(s)$ vs Output Load](image)

Figure 5 shows the output load effects on $A_{\text{OL,DC}}$. Over the operating output load range, $A_{\text{OL,DC}}$ can vary from 195 to 141 dB.

![Figure 6. PGA900 $A_{\text{OL,DC}}$ vs Output Load](image)

Figure 6 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 $A_{\text{OL}}$

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 $A_{\text{OL}}(s)$ as shown in Figure 8.

![Figure 8. PGA900 $A_{\text{OL}}(s)$ vs Power Supply Voltage](image1)

$A_{\text{OL,DC}}$ 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 $A_{\text{OL,DC}}$ vs Power Supply](image2)

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\textsubscript{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\textsubscript{OL}(s) are displayed in Figure 11.

![Figure 11. PGA900 A\textsubscript{OL}(s) vs Process Variation](image)

Over the process corners, A\textsubscript{OL\_DC} changes from 188.9 dB to 196.2 dB as shown in Figure 12.

![Figure 12. PGA900 A\textsubscript{OL\_DC} Change vs Process Variation](image)

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.
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°.
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

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

7. Miroslav Oljaca, Henry Surtihadi, *Operational amplifier gain stability, Part 2: DC gain-error analysis* SLYT374
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