Application Note

Full Power Bandwidth and Op Amp Distortion

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ABSTRACT

Full power bandwidth (FPBW) is commonly derived from the slew rate of an operational amplifier and is traditionally used to estimate the frequency at which significant visual waveform distortion occurs. The classical FPBW relationship assumes a single slew rate region and does not define a quantitative distortion limit. This application note introduces measured Total Harmonic Distortion (THD) defined full power bandwidth curves, which define FPBW using specified harmonic distortion limits rather than the visible waveform collapse boundary alone. The relationship between classical slew rate limited FPBW and THD defined FPBW is examined for several operational amplifiers with slew boost architectures. The OPA991 is presented as a unique example of a slew boosted amplifier in which the natural slew rate limit is reached prior to activation of the boosted slew region, resulting in two distinct slew rate limited FPBW boundaries. Measured results demonstrate how slew boost architecture, loop gain, closed loop gain, and open loop gain influence THD defined full power bandwidth and large signal distortion behavior.

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1 Introduction

Full power bandwidth (FPBW) is commonly used to describe the maximum peak to peak output voltage (V_{out_PP}) that an operational amplifier can reproduce at a given frequency without significant large-signal distortion. In the classical form, FPBW is derived from the slew rate of the amplifier and represents the frequency at which a sinusoidal waveform transitions into a triangular waveform due to a limitation in the output rate of change.

Modern operational amplifiers frequently employ slew-boosting architectures to improve large signal performance. Classical FPBW theory assumes a single, constant slew rate and a smooth transition into slew rate limiting. However, real devices can deviate from this assumption depending on the implementation of the slew-boost circuitry.

In this application note, two distinct definitions of full power bandwidth are used. The first is the classical slew rate limited full power bandwidth, which defines the frequency at which a sinusoidal output transitions into a triangular waveform due to the slew rate limit. The second is a THD limited full power bandwidth, which defines the frequency at which the output distortion reaches a specified level. These definitions represent different physical mechanisms and must not be interpreted as the same quantity.

The OPA991 provides a unique example of a slew boosted amplifier in which the natural slew rate limit is reached prior to the activation of the slew boost circuitry. As a result, two distinct slew rate limited full power bandwidth boundaries can be identified: one corresponding to the natural slew rate, which defines the initial onset of waveform distortion, and a second corresponding to the boosted slew rate, which defines the ultimate large signal capability of the amplifier.

This application note presents measured THD limited full power bandwidth curves. The results highlight the limitations of classical FPBW theory and demonstrate that measured THD defined full power bandwidth depends on distortion criterion, loop gain, closed loop gain, open loop gain, and the internal operation of the slew boost circuitry. In contrast, the classical slew rate limited full power bandwidth boundary remains fundamentally determined by the amplifier slew rate.

To understand how full power bandwidth (FPBW) behaves in real world measurements, the following topics are examined in the order shown.

1. Full Power Bandwidth Theory
2. Understanding Slew Rate
3. Understanding Slew Boost
4. Measuring THD Limited Full Power Bandwidth
5. Interpreting the Full Power Bandwidth Curves
6. Impact of Slew Boost Architecture on Full Power Bandwidth Model
7. THD limited full power bandwidth dependence on closed loop and open loop gain

2 Full Power Bandwidth Theory

Full power bandwidth (FPBW) describes the maximum peak to peak voltage (V_{out_PP}) at a given frequency that an op amp can reproduce without significant visual distortion. A theoretical full power bandwidth curve for an op amp is shown in Figure 2-1. Operating inside of the full power bandwidth curve with a pure sine wave input signal results in a visually undistorted output signal, while operating beyond the full power bandwidth boundary results in a visually highly distorted triangle wave that is caused by the slew rate limit. This type of output distortion is known as slew-induced distortion. Total harmonic distortion (THD) is a measurement that provides a figure of merit for the ability of a circuit to accurately output the signal seen at the input. A low THD measurement indicates an accurate reproduction of the input signal, while a high THD value indicates a poor reproduction of the input signal. THD rises sharply once the output crosses the full power bandwidth limit. More information on THD can be found in How to Measure Total Harmonic Distortion of an Op-Amp and THD + N Fundamentals. The typical FPBW curve does not provide a numerical THD value, the curve merely marks the point where large signal distortion begins.

Full power bandwidth is derived from the slew rate (SR) specification and the maximum peak-to-peak output voltage V_{out_pp} of a given operational amplifier (op amp). Equation 1 describes the relationship between full power bandwidth, SR and V_{out_pp}.

$$f_{\mathrm{FPBW}} = \frac{\mathrm{SR}}{\pi V_{\mathrm{out\_pp}}} \tag{1}$$

The derivation of Equation 1 can be found in the Section 10 and assumes the following:

- An undefined Total Harmonic Distortion (THD) level
- Assumes significant visual distortion only, when a pure sine wave turns into a triangle wave
- A single slew rate value
- Linear transition into the slew limit
- No additional distortion mechanisms

The theoretical full power bandwidth curve that is published in op amp data sheets is typically not measured performance. The maximum peak to peak op amp output voltage V_{out_pp} ignores the op amp output swing limitations and assumes the output can reach the power supply rail, V_{supply}.

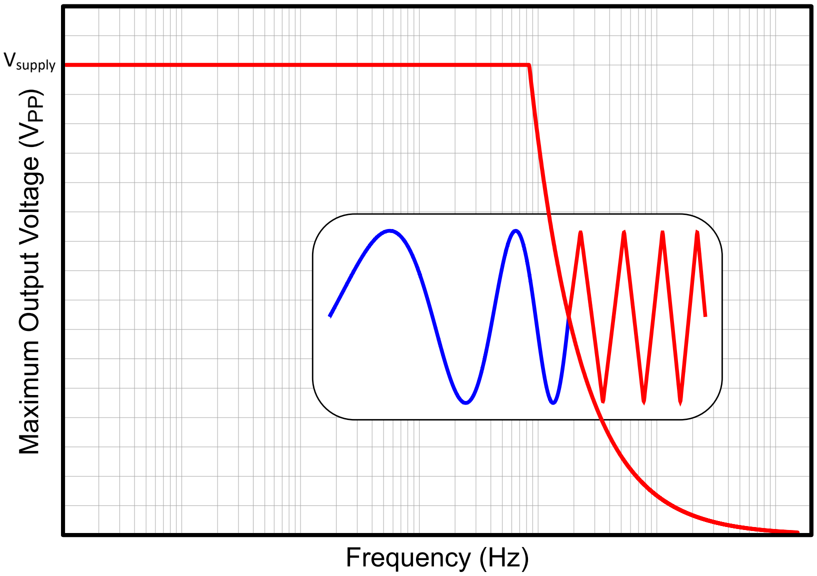

Figure 2-1. Theoretical Full Power Bandwidth Curve

3 Understanding Slew Rate

Figure 3-1 shows a simplified block diagram of an operation amplifier. The first stage is a transconductance (g_m) stage that converts the input differential voltage (V_{id}) into a current, I_M, known as the Miller Current. This current flows into the Miller capacitance (C_M) of the transimpedance stage where the current I_M is converted to a voltage at the output node V_{out}.

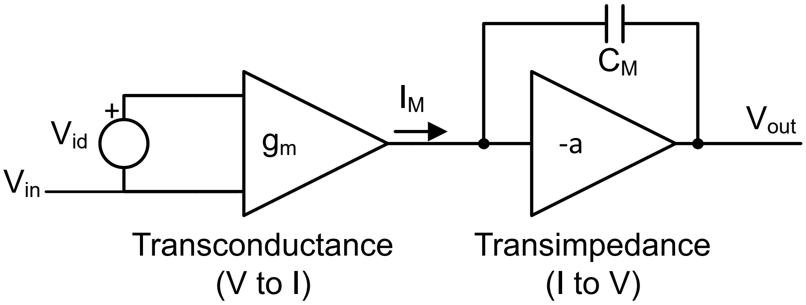

Figure 3-1. Op amp internal block diagram

Figure 3-2 shows the transfer function for an op amp transconductance stage. The small signal response is shown in green and the large signal step response (slew rate limit) is shown in blue.

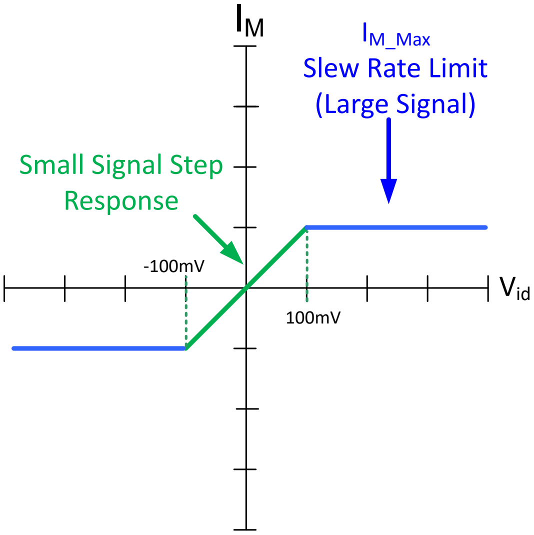

Figure 3-2. Transfer function for op amp transconductance stage

Small signal operation- Small signal operation can be defined as when V_{id} is modest (for example V_{id} < 100mV, see Figure 3-2), and the transconductance stage behaves linearly. Equation 2 describes the small signal relationship between the miller current and input differential voltage.

$$I_M = g_m \times V_{id} \tag{2}$$

During small signal operation, the current I_M is directly proportional to V_{id}. In a closed loop configuration the output voltage is fed back to the inputs with an external feedback network. The feedback forces the voltage difference (V_{id}) between the inverting and non-inverting inputs toward zero. Although the inverting and non-inverting terminals are not electrically connected, the high open loop gain (A_{OL}) of the op amp forces the voltage difference between them to be extremely small; an effect commonly referred to as a virtual short. For example, a 1mV step applied to the inputs generates a brief current pulse into C_M, which makes the output rise. As the Miller capacitor charges, the feedback forces the input differential voltage towards the "virtual short" condition, and when the transient settles V_{id} is essentially zero.

Large signal (slew rate limited) operation- If the input differential voltage exceeds the linear range (for example V_{id} > 100mV, see Figure 3-2), the transconductance stage produces the peak current I_{M_Max} that charges the miller capacitor C_M as shown in Figure 3-3. This constant current continues to charge C_M, producing a linear ramp at the output node V_{out}:

$$SR = \frac{dV_{OUT}}{dt} = \frac{I_{M\_Max}}{C_M} \tag{3}$$

The resulting slope of the output voltage ramp defines the slew rate; the maximum rate which the op amp output can change. With a large step applied, the output initially follows this slew rate limit while the feedback simultaneously reduces the input differential voltage. Once the input differential voltage falls back into the small signal region of operation, I_M falls exponentially towards zero and the output transition changes from a linear ramp to an exponential settling curve. The differential input finally reaches the virtual short condition. Figure 3-3 provides a magnified view of the waveforms, highlighting the moment the device enters small signal mode of operation and illustrates how the input differential voltage decays exponentially toward 0V.

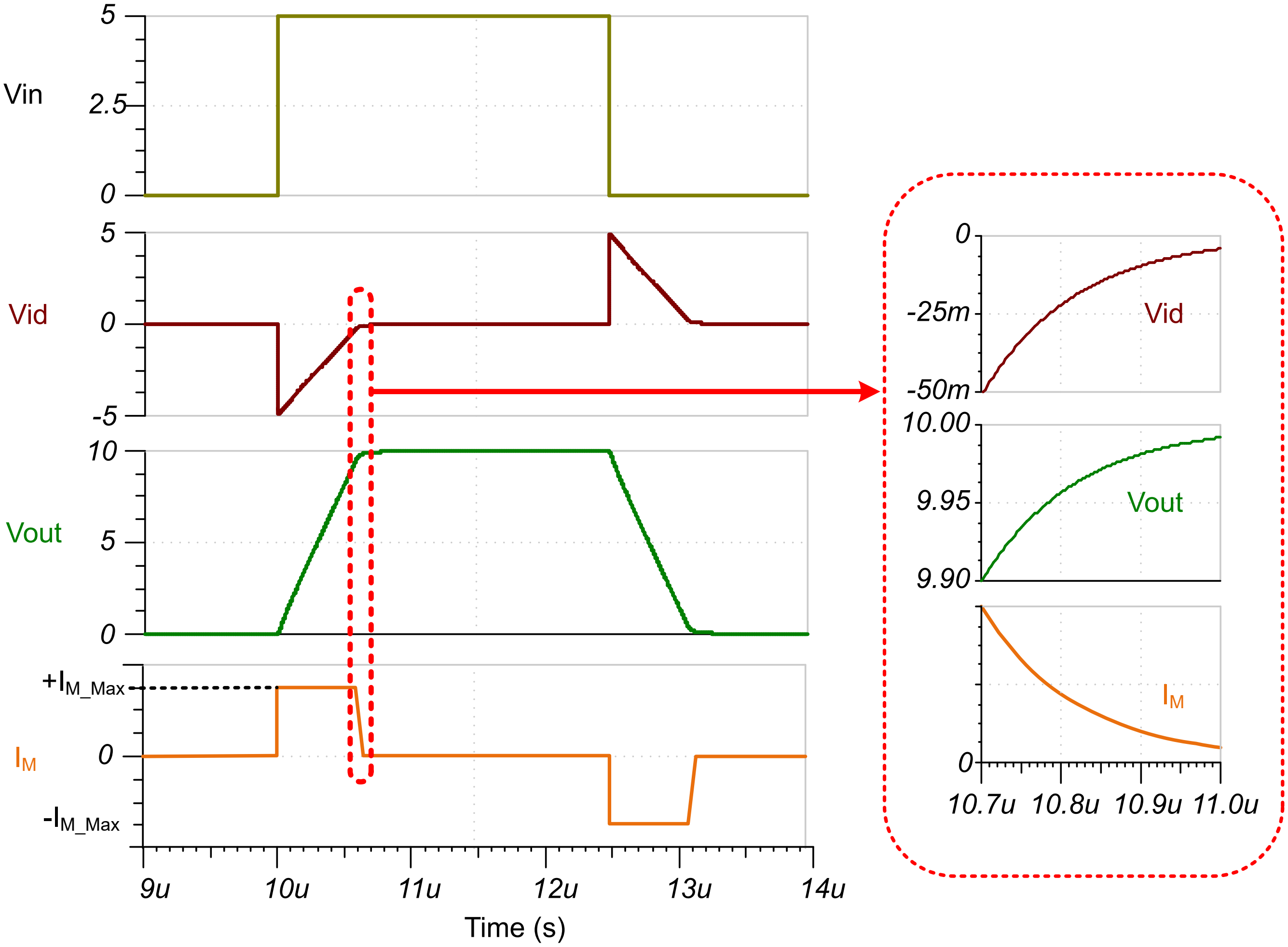

Figure 3-3. V_{id} and I_M for a large signal step

4 Understanding Slew Boost

High performance op amps typically trade quiescent current I_Q for bandwidth, as charging internal compensation capacitors quickly requires a constant, high current draw from the power supply. Slew-boosted architectures break this link, allowing for high, large signal slew rates with significantly lower small signal power. Instead of a constant high quiescent current, slew boosted architectures use "current on demand" circuitry that triggers based on the input differential voltage (V_{id}). By tuning the threshold at which this boost activates, the op amp designer can balance the transition between small signal natural slew mode of operation and large signal slew boosted mode of operation. Table 4-1 shows the tradeoffs between slew rate and quiescent current I_Q for three op amps, the OPA992, OPA197 and OPA991 each with slew boost architectures. The output rate of change vs input differential voltage for each of the three op amps is shown in Figure 4-1.

Table 4-1. Slew Rate vs Quiescent Current (I_Q) Tradeoffs

Op Amp	SR	I_Q
OPA992	$34\ \frac{V}{\mu s}$	2.48mA
OPA197	$27\ \frac{V}{\mu s}$	1mA
OPA991	$28\ \frac{V}{\mu s}$	560µA

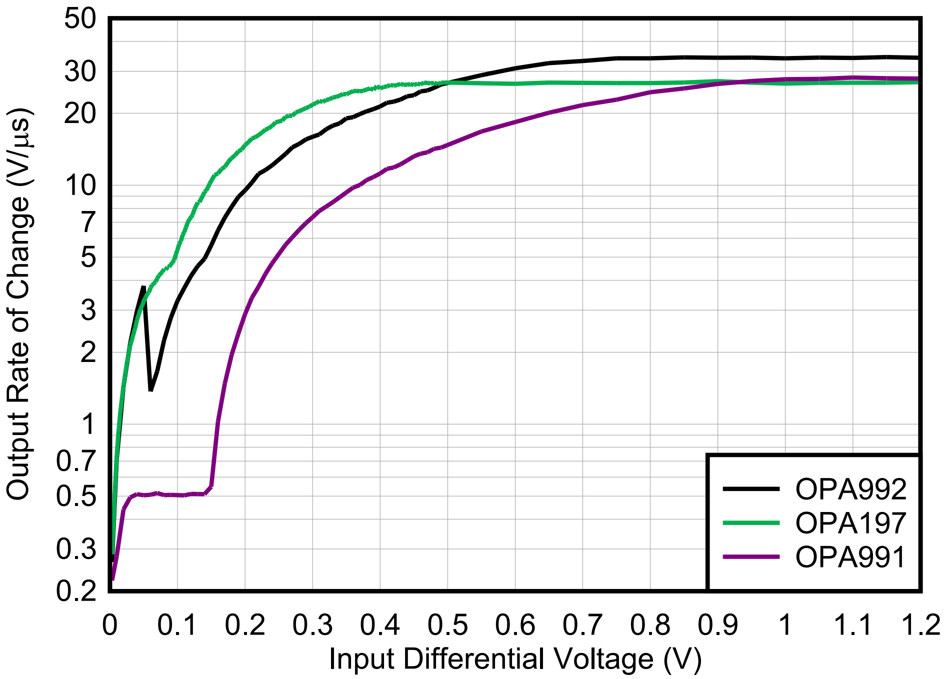

Figure 4-1. Output Rate of Change vs Input Differential Voltage for three slew boost topologies

In conventional op amps, the quiescent current used to bias the input stage generally determines the maximum slew rate. In these designs, the maximum output rate of change is fixed by the available Miller current I_{CM}, that charges the internal compensation capacitor known as the Miller compensation capacitor C_M. Some modern amplifiers use advanced techniques to achieve a higher slew rate while keeping the overall current consumption of the amplifier low. The OPA991 is one such amplifier, specifically engineered to balance high-speed performance with low power draw. In these architectures, additional current is dynamically supplied to the compensation capacitor when large input differential voltages V_{id} are detected. This allows the amplifier to achieve a higher slew rate only when needed.

Figure 4-2 shows the 1V step response of the OPA991. The transition from the slew boost region into natural slew is measured on the output of the op amp, (V_{out}). The supply current I_{supply} is measured with a current probe on the positive power supply (V_{CC}) of the op amp. When slew boost is activated, I_{supply} temporarily increases to approximately 2mA. This measurement highlights the power preservation that is achieved by the OPA991; extra power supply current is only consumed when the slew boost circuitry is activated.

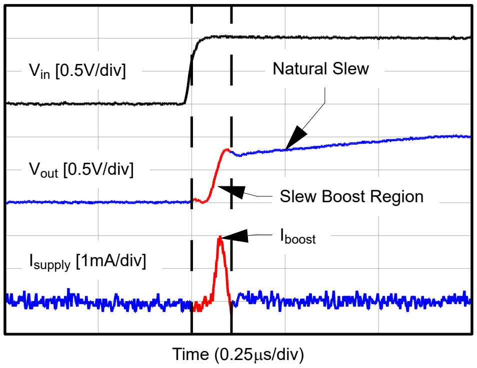

Figure 4-2. OPA991 Step Response

Figure 4-3 shows a simplified representation of the OPA991 slew boost architecture along with measured output rate of change ($\frac{V}{\mu s}$) versus input differential voltage (V).

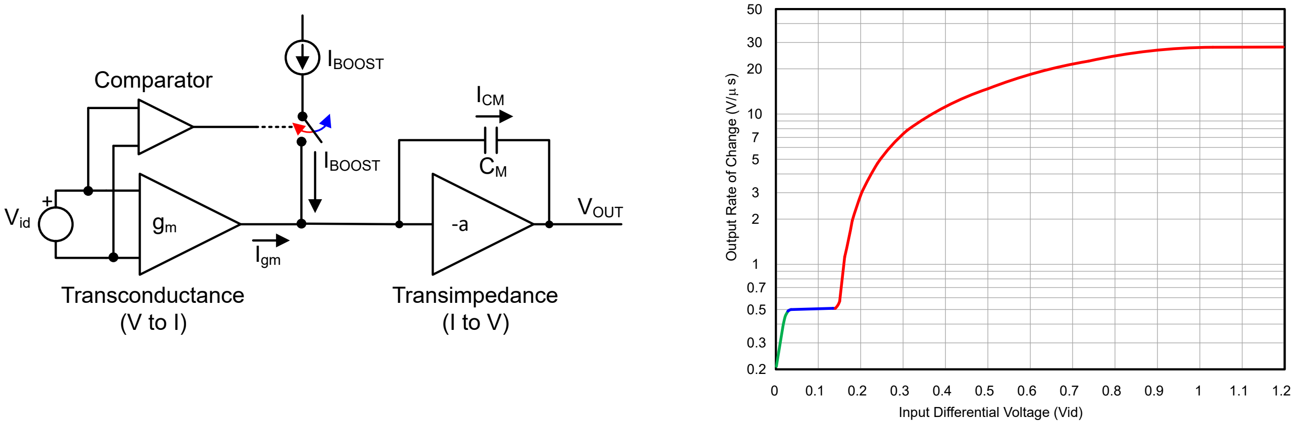

Figure 4-3. Simplified block diagram of a OPA991 with Miller compensation capacitor and measured data of the Output Rate of Change vs Input Differential Voltage

The maximum output rate of change is known as the slew rate and is described by Equation 4

$$\frac{dV_{out}}{dt} \approx \frac{I_{C_M}}{C_M} \tag{4}$$

The Miller current I_{CM} is composed of two components:

- I_{gm}: current from the transconductance stage
- I_{boost}: additional current from the slew boost circuitry

In this slew boost architecture, C_M is charged in three discrete regions with varying current I_{CM} that is described by Equation 5

$$I_{C_M} = I_{gm\_max} + I_{boost} \tag{5}$$

The operation can be divided into three regions:

1. **Small signal output rate of change (Linear Operation):**
    - Input differential voltage V_{id} is small
    - $I_{boost} = 0mA$
    - $I_{gm} < I_{gm\_max}$ and is proportional to V_{id}

    In this region the output rate of change is proportional to V_{id} and is defined as $\frac{dV_{out}}{dt} \approx \frac{I_{gm}}{C_M}$

    - Note that the relationship between V_{id} and I_{gm} is linear in this region. See the green region in Figure 4-3. Typically, small signals are less than 100mV. For this device, the small signal region is approximately 20mV and less.
2. **Natural Slew Region (Current Limited, No Boost):**
    - $I_{gm} = I_{gm\_max}$
    - $I_{boost} = 0\ mA$
    - $SR_{Nat.} \approx \frac{I_{gm\_max}}{C_M}$
    - There is a rising slope as I_{gm} approaches I_{gm_Max}. See the blue region in Figure 4-3. For this device the natural slew is 0.5 $\frac{V}{\mu s}$ when slew boost is not engaged and occurs for input signals of 20mV to 150mV.
3. **Slew Boosted Region (Enhanced Current):**
    - V_{id} increases further
    - Slew Boost circuitry activates
    - $I_{C_M} = I_{gm\_max} + I_{boost}$
    - $SR_{Boost} \approx \frac{I_{gm\_max} + I_{boost}}{C_M}$
    - The slew boost circuitry is activated and additional current I_{boost} helps to quickly charge the compensation capacitor. See the red region in Figure 4-3. For this device the boosted slew rate is 28 $\frac{V}{\mu s}$ and occurs for input signals greater than 150mV. Technically the boosted slew is increasing from approximately 150mV to 1V, and for input signals greater than 1V the max slew boost is achieved.

The activation of the slew boost circuitry depends on the magnitude of the input differential voltage V_{id}. Signals that produce large instantaneous V_{id}, such as step inputs or fast edge transitions, rapidly drive the amplifier into the slew boosted region. In contrast, sinusoidal signals produce a more gradual change in V_{id}, and can enter the natural slew rate limited region before the boost circuitry is engaged. As a result, the OPA991 can exhibit two distinct slew rate limited behaviors depending on the signal characteristics. The initial onset of waveform distortion is governed by the natural slew rate, while the boosted slew rate defines the maximum achievable output rate of change under larger input differential conditions. This behavior is directly reflected in the measured full power bandwidth curves presented later, where the onset of visible distortion aligns with the natural slew rate limit rather than the boosted slew rate. Figure 4-4 presents two theoretical full power bandwidth curves for the OPA991, each corresponding to a distinct slew rate region. The blue curve is derived from the natural slew rate limit of 0.5 $\frac{V}{\mu s}$, while the red curve is derived from the boosted slew rate limit of approximately 28 $\frac{V}{\mu s}$, highlighting the significant difference in large signal performance between the two operating regions. These two curves are referenced later in this application note to demonstrate how the natural and boosted slew rate limits each influence the measured full power bandwidth performance of the OPA991.

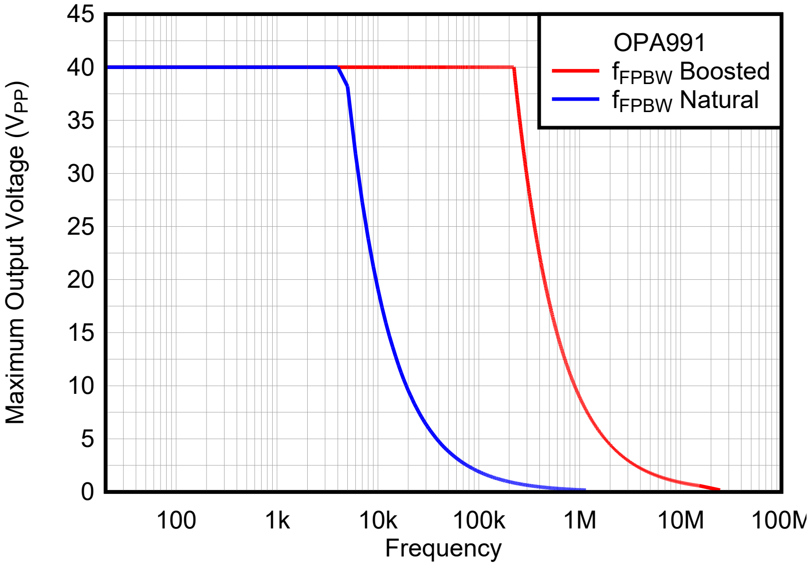

Figure 4-4. Theoretical Full Power Bandwidth curves for the OPA991

5 Measuring THD Limited Full Power Bandwidth

Traditional full power bandwidth theory offers no quantitative THD value, and merely predicts the onset of significant visual (large signal) distortion. The theory also ignores the non linear behavior of slew boost architectures and any other distortion mechanisms present in a real circuit. In contrast, measuring the full power bandwidth of an op amp provides a practical THD boundary, can be performed at any closed loop gain, and inherently captures distortion arising from the device's internal non linearities.

Full power bandwidth of an op amp can be measured to accurately capture the real performance and provides more information than that of the theoretical model from Equation 1. To recap, the derivation of Equation 1 assumes the following:

- An undefined THD level
- Assumes significant visual distortion only, when a pure sine wave turns into a triangle wave
- A constant slew rate value
- Linear Transition into the slew limit
- No additional distortion mechanisms

Measuring the full power bandwidth of an op amp provides the following benefits:

- Can be performed at any closed loop gain
- Can define THD levels
- Captures the differences between theoretical calculations and practical measurements
- The slew rate performance and other distortion mechanisms are naturally captured within the measurement

Figure 5-1 shows the measurement circuits that are used to measure the full power bandwidth. The distortion analyzer is connected to the standard non-inverting and inverting circuits. This application note focuses on the non-inverting measurement. The following procedure is performed:

- Fix output amplitude with a sine wave stimulus
- Sweep frequency
- Measure THD (Measurement Bandwidth = 1.2MHz)
- Repeat for multiple amplitudes, supply and load conditions

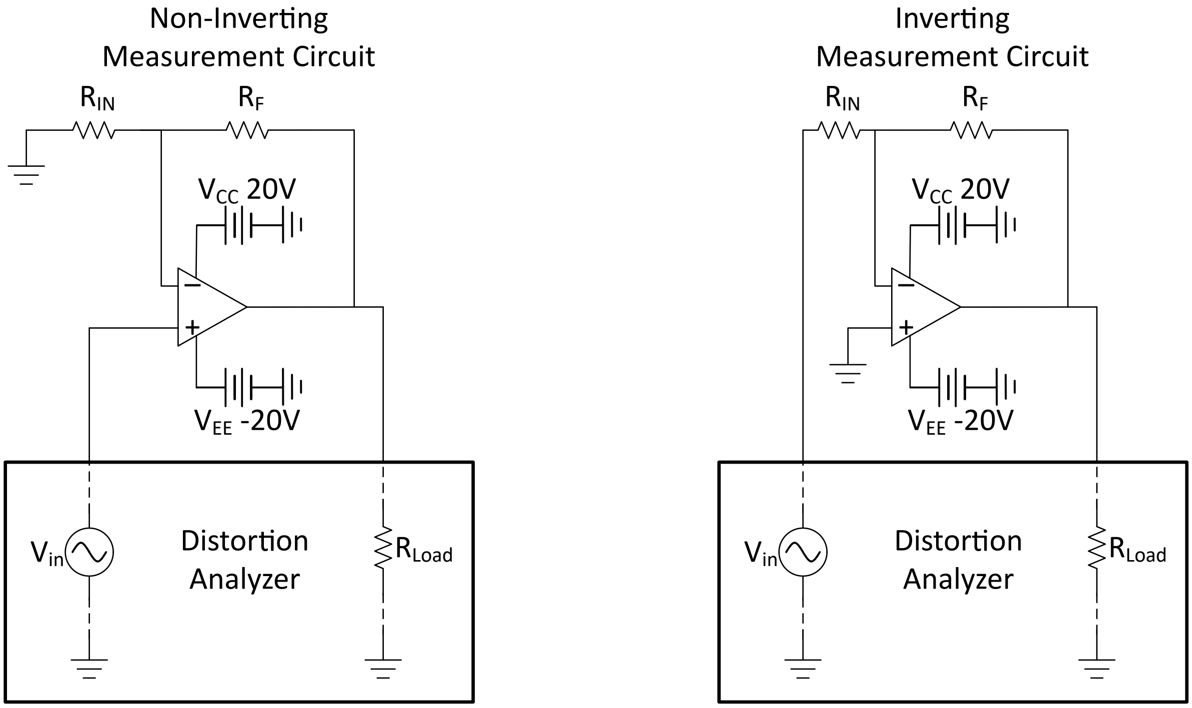

Figure 5-1. Full Power Bandwidth Measurement Circuits

Figure 5-2 shows the theoretical full power bandwidth curves calculated from the natural and boosted slew rate limits of the OPA991. Adjacent to the theoretical curves are measured THD defined full power bandwidth curves in a closed loop gain (A_{CL}) of $A_{\mathrm{CL}} = 1\frac{V}{V}$. While the theoretical full power bandwidth assumes an undefined THD, practical measurements can be plotted against a specific distortion target. Consequently, THD defined full power bandwidth must be interpreted as a measurement dependent boundary rather than a single intrinsic amplifier parameter. Figure 5-2 demonstrates that the full power bandwidth curve calculated from the natural slew limit of the OPA991 is approximately equal to the measured THD curve of -60dB. Operating beyond the natural slew defined full power bandwidth curve with slow moving signals can result in slew induced distortion caused by the natural slew limit of the OPA991.

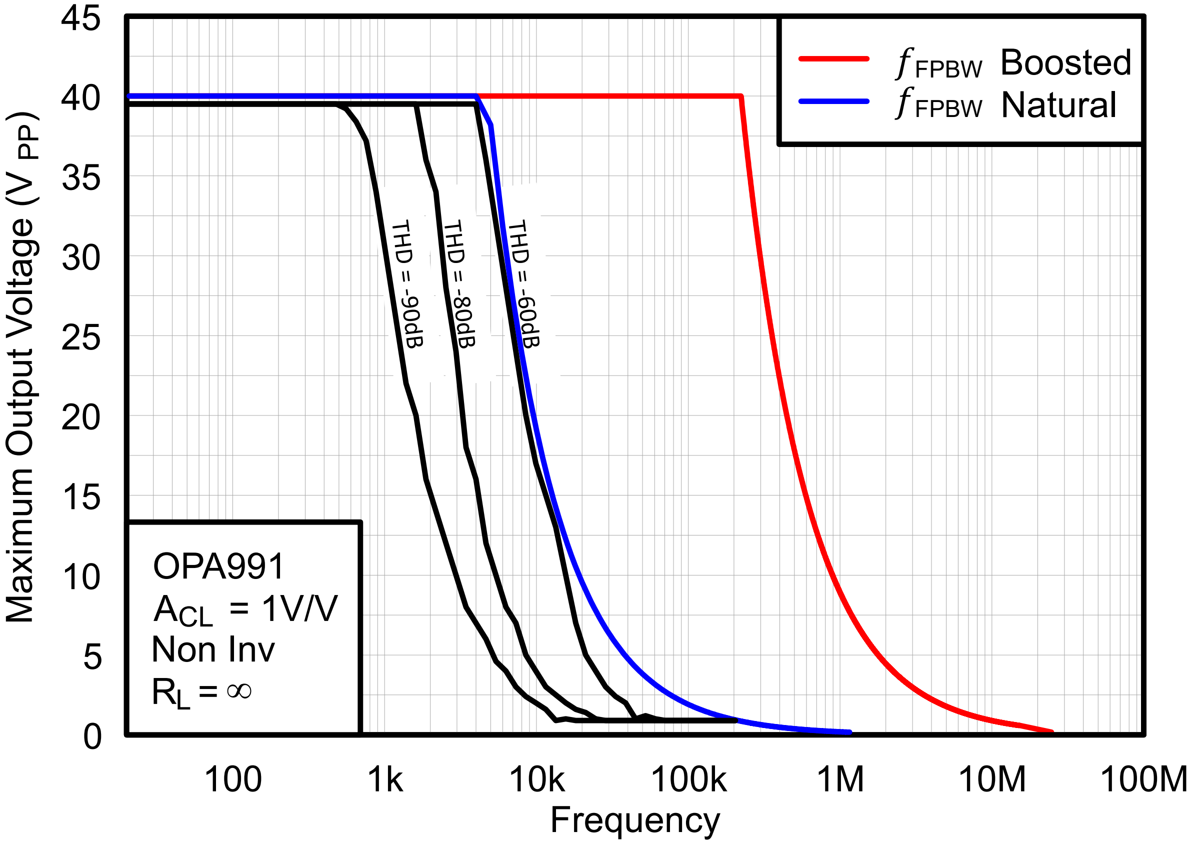

Figure 5-2. Full Power Bandwidth for OPA991 in a gain of 1 $\frac{V}{V}$

6 Interpreting the Full Power Bandwidth Curves

The theoretical full power bandwidth curve indicates the frequency at which the output is still a true sine wave; beyond this point the waveform collapses into a triangular shape. The transition into slew rate limiting is more easily observed at higher output amplitudes. In closed loop configurations, higher gain produces larger output swings for a given input signal, increasing the required output rate of change and making slew induced distortion more apparent.

Figure 6-1 displays a full power bandwidth curve for the OPA991 in a signal gain of $A_{\mathrm{CL}} = 11\frac{V}{V}$, with three color coded dots marking specific data points. Each dot corresponds to the sine wave and Fast Fourier Transform (FFT) shown below the curve, providing insight into how the distortion changes over a fixed amplitude and increasing frequency. At an output amplitude of 10Vpp, each colored dot on Figure 6-1 demonstrates an increase in frequency and a corresponding increase in distortion, as illustrated by the FFTs. While the sine wave appears visually undistorted at 1kHz and 10kHz, significant distortion becomes apparent at 20kHz, where the sine wave transitions to a triangular shape. Note that the theoretical curve does predict this boundary as shown in Figure 5-2.

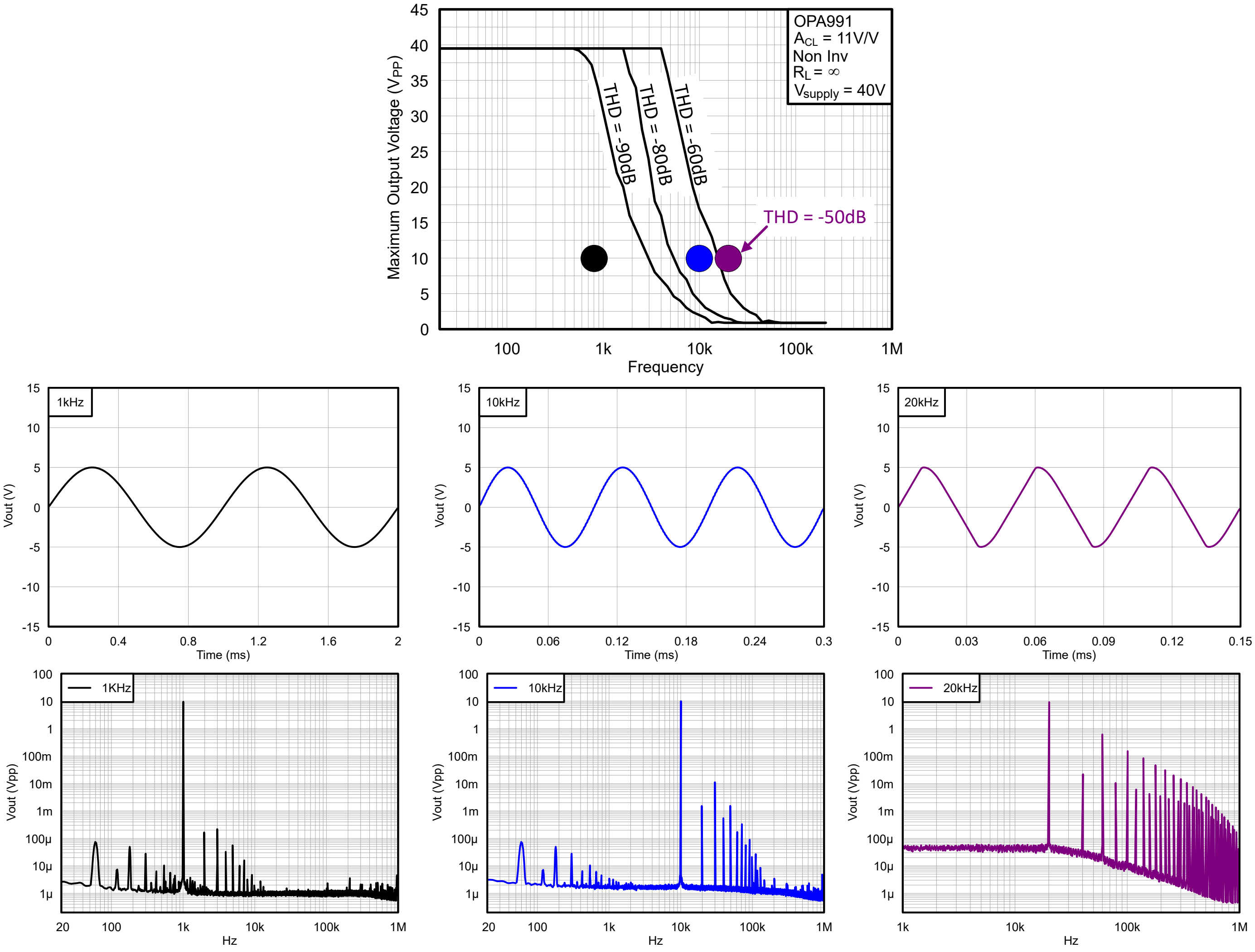

Figure 6-1. Interpreting the full power bandwidth curves

7 Impact of Slew Boost Architecture on Full Power Bandwidth Model

Some slew boosted amplifiers introduce a piecewise transition from natural slew to boosted slew rather than an instantaneous change. The shape and width of this transition region are architecture dependent. Common slew boost designs provide a fast and narrow transition into slew boost which more closely aligns to the constant slew assumption in the theoretical full power bandwidth model. A gradual or wide transition into slew boost results in an intermediate output rate of change and increased large signal distortion. In these regions, distortion rises before the maximum slew rate is reached. As a result, the usable full power bandwidth, when defined by a THD limit, is reduced compared to the maximum theoretical curve. The output rate of change versus input differential voltage curves provide a direct way to visualize this transition behavior. Correlating these curves with the measured THD limited full power bandwidth curves demonstrate that the slew boost implementation, not just the peak slew rate, determines the real large signal performance.

Figure 7-1 compares the theoretical and measured full power bandwidth curves for the OPA992, OPA197, and OPA991 at a closed loop gain of $A_{\mathrm{CL}} = 1\frac{V}{V}$, with the Output Rate of Change ($\frac{V}{\mu s}$) vs Input Differential Voltage (V_{id}) plot included for reference. At a THD limit of -50dB, the OPA992 and OPA197 measured curves closely follow the theoretical predictions due to the quick transition into slew boost mode. The OPA991, however deviates from the theoretical curve derived from the boosted slew rate and instead aligns more closely with the theoretical curve derived from the natural slew limit, a consequence of entering the natural slew rate limit for a range of input differential voltages prior to slew boost being activated. This distinction means that the OPA992 and the OPA197 are governed by a single slew rate limit, whereas the OPA991 exhibits two distinct slew rate regions that each influence large signal distortion behavior.

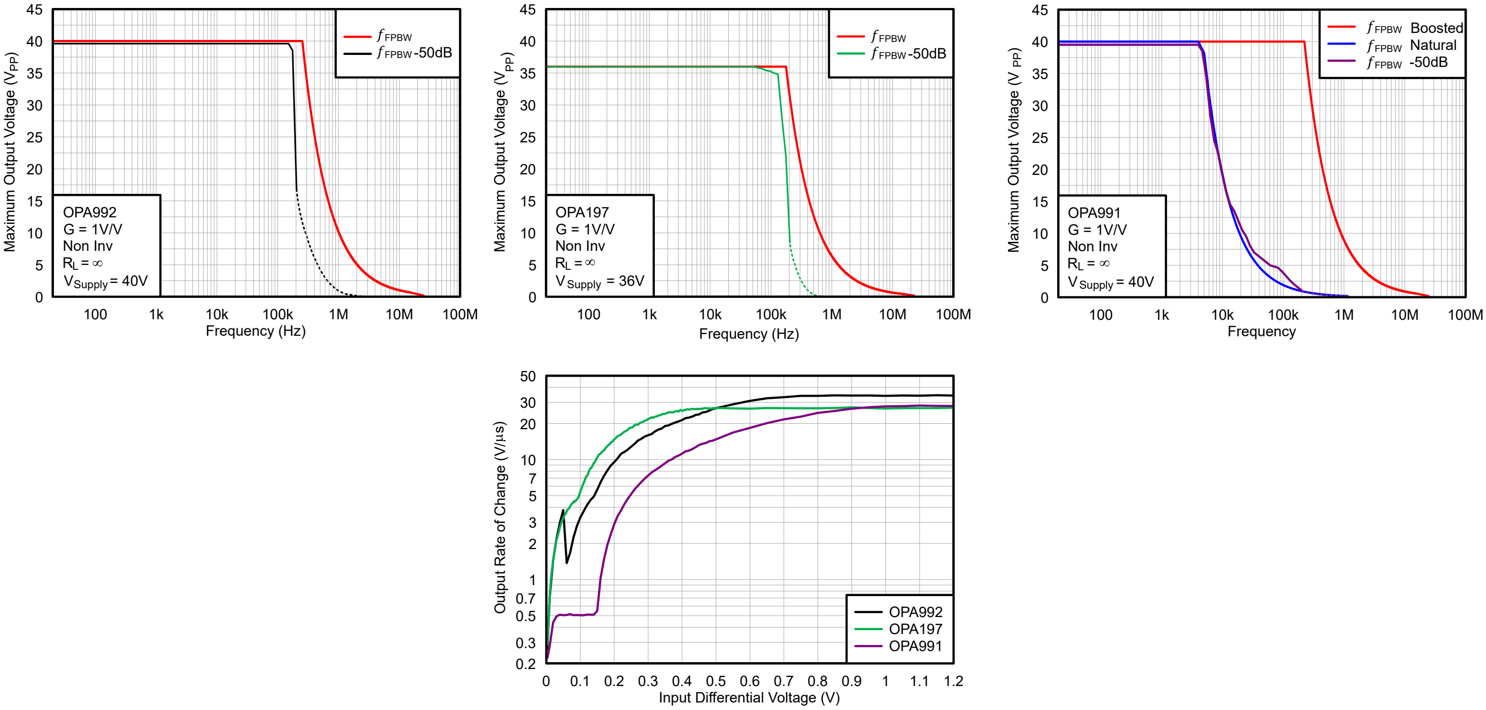

Figure 7-1. Measured vs Theoretical FPBW and Output Rate of Change

8 THD Limited Full Power Bandwidth Dependence on Closed Loop & Open Loop Gain

The mechanisms discussed in this section are distinct from the significant slew induced waveform distortion described earlier. This section instead focuses on how feedback and loop gain influence small signal linearity and harmonic distortion. A fundamentally important point to establish in this section is that the reduction in loop gain with increasing closed loop gain does not directly change the classical slew rate limit full power bandwidth curve for a fixed amplitude.

Figure 8-1 shows the measured full power bandwidth curves for the OPA991 in three different closed loop gain configurations; A_{CL} = $1\frac{V}{V}$, $11\frac{V}{V}$ and $101\frac{V}{V}$. Each curve represents a fixed distortion limit of THD = -60dB. The measured full power bandwidth curves show a clear dependency on closed loop gain, with higher gains exhibiting reduced bandwidth, $f_{\text{FPBW}}\left(A_{\text{CL}} = 101\frac{V}{V}\right) < f_{\text{FPBW}}\left(A_{\text{CL}} = 11\frac{V}{V}\right) < f_{\text{FPBW}}\left(A_{\text{CL}} = 1\frac{V}{V}\right)$. The classic full power bandwidth model, which assumes a single well defined slew rate limit and also ignores the impact of closed loop gain, does not predict this behavior.

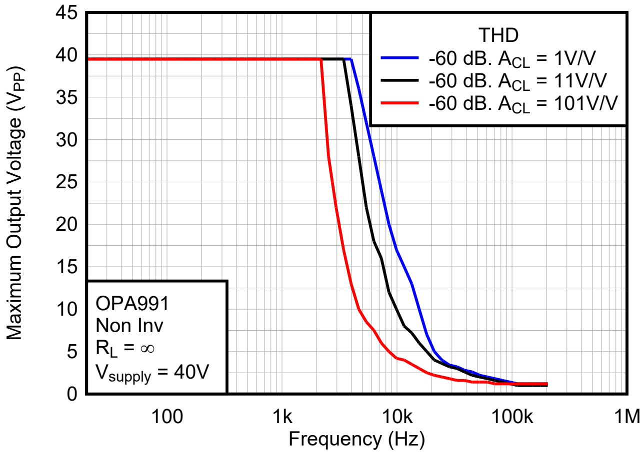

Figure 8-1. OPA991 Full Power Bandwidth (THD = -60dB) at Three Different Signal Gains

Analyzing the feedback equations of an operational amplifier helps explain why increasing the closed loop gain (A_{CL}) reduces the THD defined full power bandwidth curve.

Figure 8-2 shows the block diagram for an operational amplifier in a closed loop configuration.

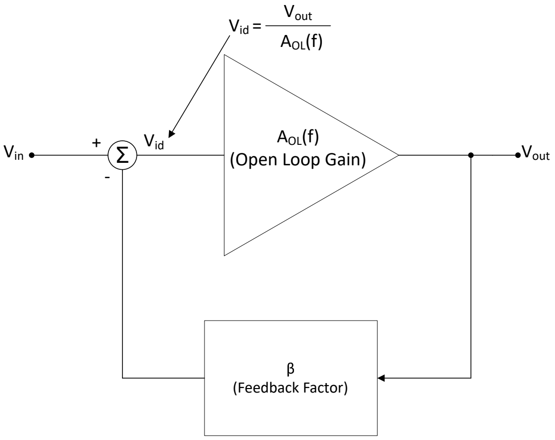

Figure 8-2. Feedback Control Theory Block Diagram

Recall that the closed loop gain equation for an operational amplifier is:

$$A_{CL}(f) = \frac{V_{out}(f)}{V_{in}(f)} = \frac{A_{OL}(f)}{1 + A_{OL}(f)\beta(f)} \approx \frac{1}{\beta(f)},\ A_{OL}(f) \cdot \beta(f) \gg 1 \tag{6}$$

Where:

$A_{OL}(f)$	open loop gain
$\beta(f)$	external feedback factor
$A_{OL}(f)\beta(f)$	Loop Gain

For further details on the derivation of this equation please visit the Texas Instruments Precision Labs Series.

Rewriting Equation 6 and solving for β results in Equation 7.

$$\beta(f) = \frac{A_{\mathrm{OL}}(f) - A_{\mathrm{CL}}(f)}{A_{\mathrm{OL}}(f) \cdot A_{\mathrm{CL}}(f)} \tag{7}$$

One observation to make when analyzing Equation 7 is that higher A_{CL} results in a reduced β since these parameters are inversely proportional. This in turn lowers the loop gain $A_{OL}\beta$. The loop gain is the parameter that controls the error voltage V_{id} between the op amp inputs. Since loop gain directly controls the input error voltage (V_{id}), understanding the relationship between V_{id} and loop gain is crucial.

To start, rewriting Equation 6 and solving for V_{out} results in:

$$V_{out}(f) = V_{in}(f)\frac{A_{OL}(f)}{1 + A_{OL}(f)\beta(f)} \tag{8}$$

As seen in Figure 8-2:

$$V_{id}(f) = \frac{V_{out}(f)}{A_{OL}(f)} \tag{9}$$

Substituting Equation 8 into Equation 9 results in:

$$V_{id}(f) = \frac{V_{in}(f)}{1 + A_{OL}(f)\beta(f)} \tag{10}$$

The inverse relationship between V_{id} and $A_{OL}\beta$ shown in Equation 10 demonstrates that a reduction in loop gain results in an increase in the error voltage V_{id} at the inputs of the op amp. Because loop gain is the mechanism that linearizes the amplifier transfer function, a lower loop gain diminishes the ability of the system to correct internal nonlinearities. This increase in error voltage results in greater signal distortion and higher THD. As THD increases, the measured bandwidth of the THD defined full power bandwidth curve is reduced. In summary, the relationship between higher A_{CL} and reduced THD defined full power bandwidth performance follows this progression:

$$A_{CL} \uparrow \ \Rightarrow \beta \downarrow \ \Rightarrow \text{Loop Gain} \downarrow \ \Rightarrow V_{id}\ \text{Nonlinearity} \uparrow \ \Rightarrow \text{THD} \uparrow \ \Rightarrow \text{Measured THD Defined } \mathrm{f_{FPBW}} \downarrow$$

Loop gain is also dependent on the op amp open loop gain A_{OL}, which is finite and rolls off with frequency. Consequently, as A_{OL} declines, loop gain decreases and as a result the total harmonic distortion (THD) increases.

The reduction in loop gain with increasing closed loop gain does not directly change the slew rate limit full power bandwidth boundary of the amplifier. Instead, reduced loop gain increases the input error voltage V_{id}, which increases small signal nonlinear distortion and raises THD prior to the onset of significant visual slew induced waveform collapse. As a result, the THD defined full power bandwidth curve contracts with increasing closed loop gain even though the underlying slew rate limit full power bandwidth boundary of the amplifier remains unchanged.

More information on THD can be found in How to Measure Total Harmonic Distortion of an Op-Amp and THD + N Fundamentals and the Texas Instruments Precision Labs video series on op amp distortion.

9 Summary

Full power bandwidth (FPBW) describes the maximum peak-to-peak voltage (V_{PP}) that an operational amplifier can reproduce at a given frequency before the onset of significant visual distortion caused by slew rate limiting. The classical FPBW relationship derived from slew rate provides a useful estimate for the frequency at which a sinusoidal waveform transitions into a triangular waveform due to slew rate limiting. However, the classical model assumes a single slew rate region and does not define a quantitative distortion limit.

This application note demonstrated that measured THD defined full power bandwidth and classical slew rate limited full power bandwidth represent different physical mechanisms and must not be interpreted as the same quantity. The slew rate limited FPBW boundary defines the onset of significant visual waveform distortion, while the THD defined FPBW boundary identifies the frequency at which harmonic distortion exceeds a specified limit.

Modern operational amplifiers frequently employ slew boost architectures to improve large-signal performance. The details of the transition between natural slew operation and boosted slew operation can significantly influence measured distortion behavior. Amplifiers with a sharp transition into slew boost closely follow the classical FPBW model derived from a single slew rate value, while amplifiers with wider or piecewise slew transitions can exhibit increased distortion prior to reaching the maximum boosted slew rate.

The OPA991 provides a useful case study of a slew boosted amplifier in which the natural slew rate limit is reached prior to activation of the boosted slew region. Measurements demonstrate that the onset of significant visual waveform distortion closely aligns with the theoretical FPBW curve derived from the natural slew rate limit, while the boosted slew rate limit defines the amplifier’s ultimate large signal capability under larger input differential conditions.

Measured THD defined full power bandwidth curves additionally show a dependence on loop gain. Increasing closed loop gain reduces feedback factor and loop gain, which increases the input error voltage V_{id} and raises small signal nonlinear distortion prior to the onset of significant visual slew induced waveform distortion. As a result, the THD defined full power bandwidth contracts with increasing closed loop gain even though the underlying slew rate boundary of the amplifier remains unchanged.

The measured results demonstrate that measured THD defined full power bandwidth is not always represented by a single fixed boundary, but instead depends on several factors including:

- Slew boost architecture
- Natural versus boosted slew rate regions
- THD criterion
- Closed loop gain and loop gain
- Open loop gain rolloff

When distortion requirements are stringent, relying solely on the classical FPBW equation cannot fully characterize real-world large-signal behavior. Measured THD defined full power bandwidth curves provide additional insight into amplifier linearity, distortion mechanisms, and slew-boost operation across practical operating conditions.

10 Appendix

Deriving the full power bandwidth formula is accomplished by starting with the output sinusoidal signal shown in Equation 11.

$$v_{\mathrm{out}}(t) = \frac{V_{\mathrm{out\_pp}}}{2}\sin(2\pi f t) \tag{11}$$

The rate of change of the output signal is found by taking the first order derivative of Equation 11 resulting in Equation 12.

$$\frac{dv_{\mathrm{out}}}{dt} = \pi f V_{\mathrm{out\_pp}}\cos(2\pi f t) \tag{12}$$

The greatest instantaneous rate of change for the output voltage occurs when the cosine term reaches a peak value of 1. This peak rate of change is called the slew rate (SR), and under these conditions the familiar slew rate equation is obtained, Equation 13 . The frequency the slew limit occurs is known as the full power bandwidth frequency, f_{FPBW}

$$\mathrm{SR} = \pi \cdot f_{\mathrm{FPBW}} \cdot V_{\mathrm{out\_pp}} \tag{13}$$

Rearranging Equation 13 and solving for f_{FPBW} results in:

$$f_{\mathrm{FPBW}} = \frac{\mathrm{SR}}{\pi V_{\mathrm{out\_pp}}} \tag{14}$$

11 References

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