

# Application Note

## Ramping Up on Slew Rate



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### ABSTRACT

This application note discusses the discrepancy between the slew rate in applications and the slew rate specifications in op amp data sheets. The virtual ground (or virtual zero) concept simplifies op amp design by assuming the voltage difference between the inputs,  $V_{ID}$ , is zero.  $V_{ID}$  must increase to generate slew rate. Just over 100 mV are needed to reach the maximum natural slew rate that is listed in many data sheets. Some op amps have a data sheet slew rate greater than natural slew rate by incorporating a slew boost circuit. The  $V_{ID}$  needed to reach boosted slew rate may be several hundreds of millivolts. Most data sheets do not state the presence of slew boost; however, there are methods to determine the presence of slew boost by examining the data sheet figures with waveforms.

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## 1 Slew Rate Definition

Slew rate is the fastest output voltage change over time in operational amplifiers, typically measured in units of volts per microsecond,  $V/\mu s$ . Some low-power op amps express slew rate in volts per millisecond,  $V/ms$ . The data sheet slew rate (SR) parameter is the rate of change of the output voltage with a large input signal and unity gain setup (unless specifically stated otherwise). This single value is often the only obvious information about slew rate in the data sheet. It is important to know that not all applications experience this magnitude of slew rate. Additionally, it is important to note that slew rate is not a constant value for all inputs and configurations.

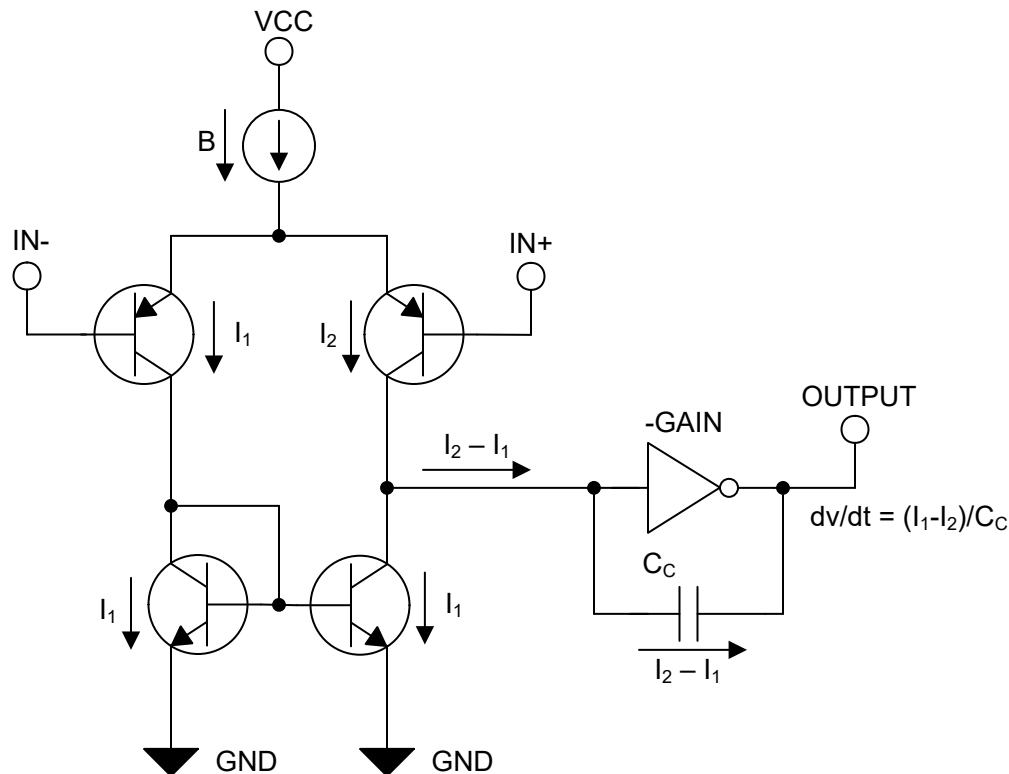
### 1.1 Virtual Ground and Slew Rate

Op amp circuits are easy to create and understand due to the ‘virtual ground’ mental concept. In closed loop circuits, the large gain of the op amp drives the input voltages ( $IN+$  and  $IN-$ ) to be the same. Input voltage difference ( $V_{ID}$ ) is assumed to be zero. This assumption makes op amp circuit math simple. In reality, there are three effects that degrade this virtual ground concept. The first effect is DC offset voltage ( $V_{OS}$ ). The second effect is small signal gain.  $V_{ID}$  for a small signal is simply  $V_{OUT}$  divided by  $A_{OL}$  (open-loop gain). The third effect is slew rate generation. This application note focuses solely discussing on slew rate.

$V_{ID}$  must be non-zero to generate slew rate. The greater the  $V_{ID}$ , the greater the slew rate. At some point, increasing  $V_{ID}$  no longer increases slew rate. The data sheet value is the slew rate where a larger  $V_{ID}$  has no effect.

## 2 Bipolar Op Amp Slew Rate Example

Many bipolar op amp input stages simplify to the circuit in [Figure 2-1](#). The  $V_{ID}$ ,  $[IN+] - [IN-]$  voltage, controls how the bias current ( $B$ ) is split between current paths  $I_1$  and  $I_2$ . Current  $I_1$  is mirrored 1:1, to create an output current,  $I_2 - I_1$ , that can vary from  $-B$  to  $+B$ . This output current charges the compensation capacitor ( $C_C$ ) and this charge rate is inverted to become the output slew rate.



**Figure 2-1. Simplified Bipolar Input Stage Schematic**

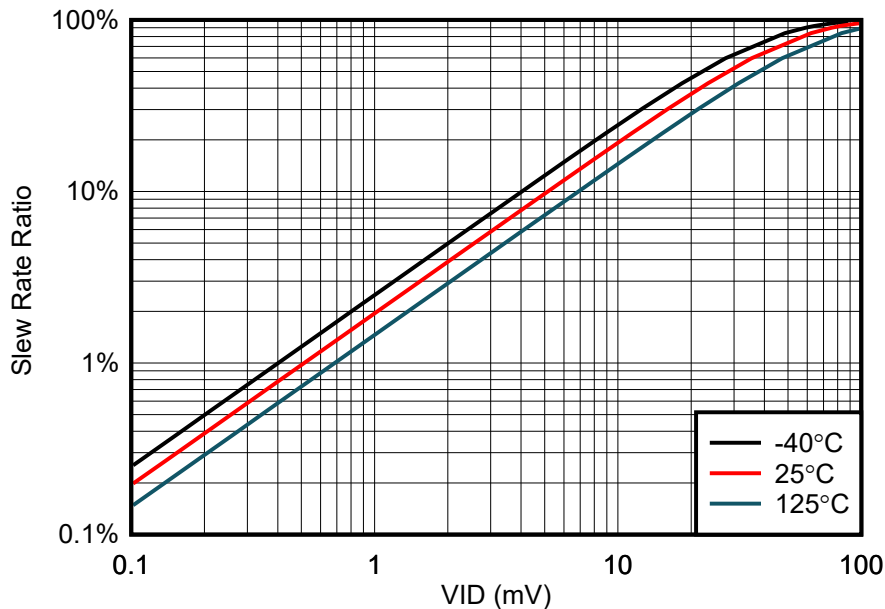
The output slew rate (SR) can be varied from  $-B/C_C$  to  $+B/C_C$ . The result of  $B/C_C$  is the slew rate that is specified on the data sheet. For some op amps, the positive and negative slew rate can be a little different; in this example the slower rate is recorded. The SR in the data sheet is always the magnitude of SR, ignoring polarity.

Current  $I$  and capacitance  $C_C$  are different for every bi-polar op amp. However, the relationship between  $V_{ID}$  and  $SR / \text{max } SR$  ratio is similar for most. This consistent relationship is based on two formulas, the first shown in Equation 1 where  $k$  = Boltzmann's constant,  $T$  = Temperature (Kelvin),  $q$  = Electron charge. The second formula, Equation 2, is the percentage of full slew rate.

$$V_{ID} = \frac{k \times T}{q} \times \ln\left(\frac{I_1}{I_2}\right) \tag{1}$$

$$SR/SR_{[MAX]} = \frac{|I_1 - I_2|}{(I_1 + I_2)} \tag{2}$$

Zero slew rate (0%) occurs when  $I_1=I_2$  at  $V_{ID}=0$  (more accurately stated as  $V_{ID} = -V_{OS}$ ). Maximum slew rate (100%) occurs when one of the currents [ $I_1$  and  $I_2$ ] are zero and the other is at full current. This requires  $|V_{ID}| \gg 100\text{mV}$ . Figure 2-2 shows the relationship between  $V_{ID}$  and slew rate relative to maximum slew rate for most bi-polar op amps.

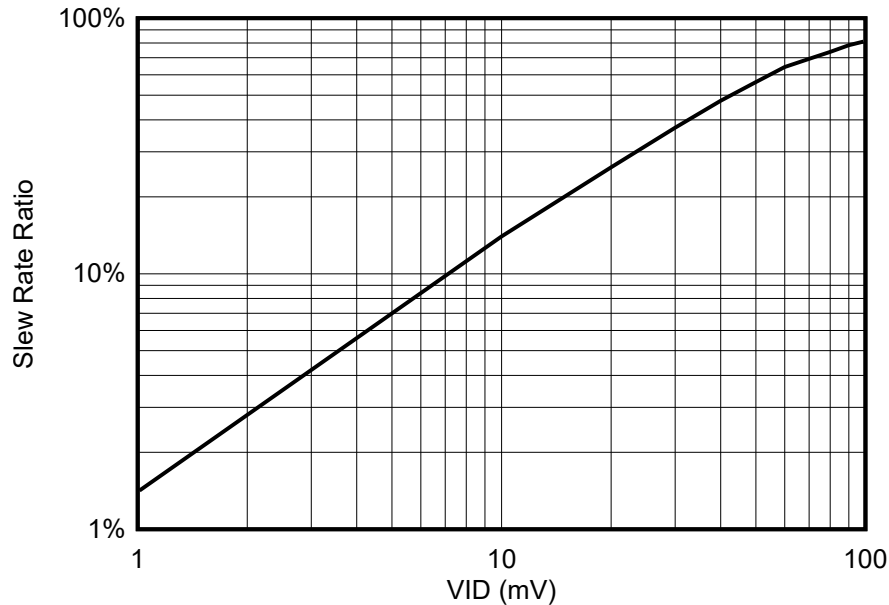


**Figure 2-2. Bipolar  $SR/SR_{[max]}$  Versus  $V_{ID}$**

Bipolar  $SR/SR_{[max]}$  versus  $V_{ID}$  chart also applies to Darlington bipolar input stages that have current sources on all emitters. There are a few Darlington op amps without a current source on the first emitter. TS321 is an example of a device that does not have a current source on the first emitter. For the TS321 op amp,  $V_{ID}$  needs to be double the chart value. For example, 2 mV ( $1 \text{ mV} \times 2$ ) gives 2% of the full slew rate. For JFET devices like the TL074, the  $V_{ID}$  needs to be eight times larger, as it takes 800 mV to get the full slew rate.

### 3 CMOS Op Amp Slew Rate Example

CMOS op amps replace NPN and PNP transistors with NMOS and PMOS transistors. The bias current split is based on voltage difference squared plus a linear factor. Therefore, expect some variation between different CMOS op amps. TLV9001 data is charted in [Figure 3-1](#) up to 100 mV. The curve in [Figure 3-1](#) looks similar to the bipolar example for  $V_{ID}$ . Most other CMOS amplifiers show similar behavior. [Figure 3-1](#) is referenced throughout this application note, see [Section 4](#) and [Section 5](#).



**Figure 3-1. CMOS  $SR/SR_{[max]}$  Versus  $V_{ID}$**

For the TLV9001, 100% of the maximum natural slew rate occurs with  $V_{ID} \gg 100$  mV. However, the internal bias current (B) and  $C_C$  capacitor give  $0.5$  V/ $\mu$ s slew rate, not the  $2$  V/ $\mu$ s stated in the data sheet. The TLV9001 employs a slew boost circuit to raise the slew rate to  $2$  V/ $\mu$ s. [Figure 3-1](#) is the natural slew rate based solely on bias current and compensation capacitance with the inactive boost circuit.

### 3.1 Slew Boost Example 1

The simplified CMOS slew boost schematic, Figure 3-2, includes an additional current source that increases the capacitor charge current beyond the bias current level when  $V_{ID}$  becomes large enough. The boost function has a dead band with zero output current while input  $V_{ID}$  is low. At some greater  $V_{ID}$ , the boost current ( $I_x$ ) rises with the  $V_{ID}$  input. This extra current increases the slew rate considerably. The boost circuit can provide positive and negative current flow to boost both positive and negative slew rates.

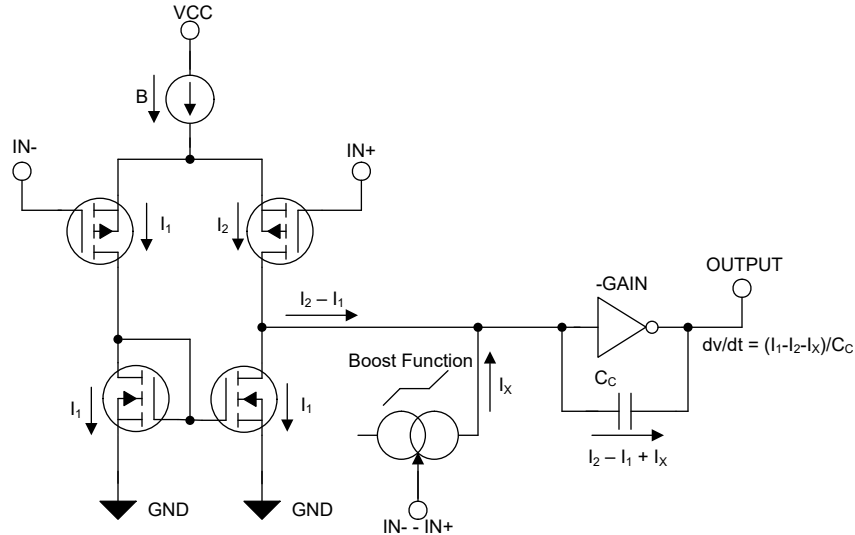


Figure 3-2. Simplified CMOS Slew Boost Schematic

The boost current ( $I_x$ ) versus  $V_{ID}$  can be proportionate or it can be stepped at a certain  $V_{ID}$  level. TLV9001 employs both methods, which is shown in Figure 3-3. Negative SR boost (red) increases proportionately starting near -140 mV. Positive slew rate boost (shown in black in Figure 3-3) increases suddenly near +270 mV, then raises proportionately. Regardless of the boost type, there is a limit to the boost current output. For very large  $V_{ID}$ , slew rate becomes a fixed value. In the TLV9001 example, the slower SR is about 2 V/ $\mu$ s, which matches the data sheet value.

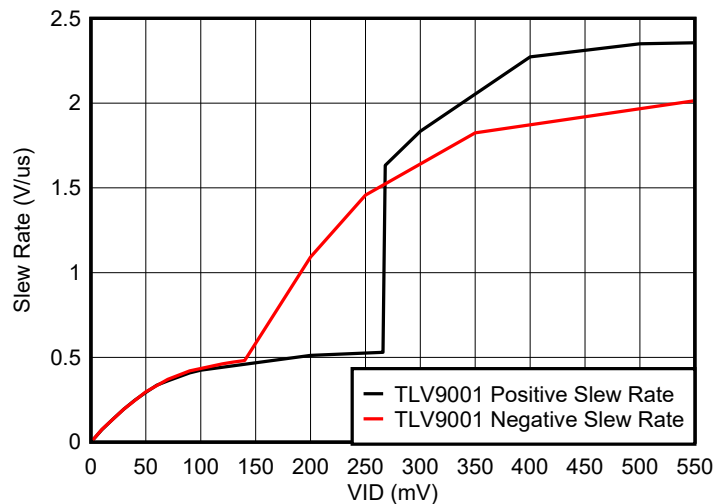


Figure 3-3. TLV9001 Slew Rate With Boost

### 3.2 Slew Boost Example 2

OPA2991 also has slew boost, but the slew boost occurs much earlier than TLV9001. Around 60 mV, the slew boost engages, starting with a lower initial slew rate. With further  $V_{ID}$ , the slew rate increases to 32 V/ $\mu$ s by  $V_{ID} = 800$  mV. Figure 3-4 and Figure 3-5 show two views, logarithmic and linear scales, for the OPA2991 slew rate versus  $V_{ID}$ .

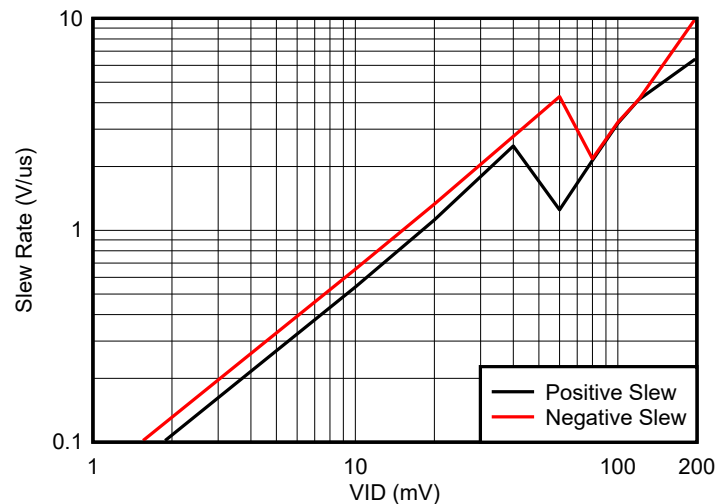


Figure 3-4. OPA2991 SR Versus VID Using Logarithmic Scale

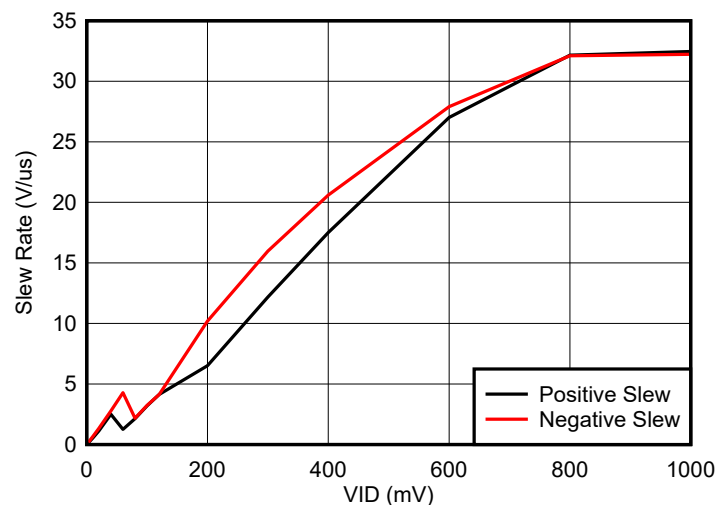


Figure 3-5. OPA2991 SR Versus VID Using Linear SR Scale

### 3.3 Slew Boost Summary

Most op amps do not have slew boost and slew rate. Whether an op amp has slew boost and slew rate requires assessing the listed data sheet value and the  $V_{ID}$  of the application. Boosted slew rate op amps have a more complex relationship between  $V_{ID}$  and SR. The data sheet does not always mention the presence of SR boost or the relationship with  $V_{ID}$ .

There are four methods to infer boost or no boost from a data sheet.

1. Comparing the slew rate versus the gain bandwidth
2. Comparing the quiescent current versus similar SR devices
3. Evaluate the large signal response
4. Evaluate the small signal response

Section 4 describes these four methods in depth, using the data sheets for the LMV831 and TLV9001 as examples.

## 4 Four Methods to Determine Boost or No Boost Using the Data Sheet

### Method 1: Compare Slew Rate Versus Gain Bandwidth

The first method is to compare the slew rate (SR) in V/ $\mu$ s to the gain bandwidth product (GBWP) in MHz. If the SR > GBWP, then slew boost is likely integrated in the device. If SR < GBWP, then boost is not as likely to be integrated into the device. TLV9001 has SR > GBWP, (2 V/ $\mu$ s > 1 MHz), which indicates that boost is likely integrated into the device. LMV831 has SR < GBWP, (2 V/ $\mu$ s < 3.3 MHz), which indicates that boost is not likely to be integrated in the device.

**Table 4-1. Device Parameters Used in Method 1 to Determine Presence of Boost**

Boost	No Boost
Device TLV9001	Device LMV831
Slew rate 2 V/ $\mu$ s	Slew rate 2 V/ $\mu$ s
Bandwidth 1 MHz	Bandwidth 3.3 MHz

### Method 2: Compare Quiescent Current Versus Similar SR Devices

The second method is to compare the quiescent current ( $I_Q$ ) per channel to other op amps that have similar supply voltage maximums and similar slew rates.  $I_Q$  and GBWP are proportionally related. If  $I_Q$  is very low or part of a lower bimodal distribution, then slew boost is expected. If  $I_Q$  is near the median or above the median value, then boost is not expected. TLV9001 has a very low  $I_Q$ , which makes boost very likely. LMV831 is lower than the median  $I_Q$  value, but much greater than the lowest  $I_Q$ , therefore, boost or no boost is inconclusive using this test.

**Table 4-2. Device Parameters Used in Method 2 to Determine Presence of Boost**

Part Number	$I_Q$ /CH (mA)	GBWP (MHz)	SR (V/ $\mu$ s)	Boost?
TLV9001	0.06	1	2	Likely
LMV831	0.25	3.3	2	Inconclusive
LMV821-N	0.30	5.6	2	Inconclusive
OPA377	0.76	5.5	2	No
OPA376	0.76	5.5	2	No
TLV376	0.82	5.5	2	No

### Method 3: Evaluate Large Signal Response

Use any large signal chart that has abrupt changes in rise and fall slopes, including charts called by another name, such as “Overload Recovery”. If a chart with these conditions can not be found, use the chart with the largest input signal. When looking at the transient response, select the slowest slew rate section that is more than 100 mV of  $V_{ID}$ . Taking into account the noise gain (NG) of the circuit, the slowest slew rate section for a NG of 11 is 1.1 V and for a NG of 1 the  $V_{ID}$  is 100 mV. As shown in Figure 4-1, the green ovals are the slowest slew rate with full  $V_{ID}$ . In both waveforms there is initially a faster slew rate. This initial increased slew rate can be caused by slew boost or internal parasitic capacitive feed-through. Typically, small rises come from capacitive feed-through and large rise come from slew boost. For the TLV9001 waveform, the selected area (SR) is 0.6 V/ $\mu$ s, which is less than half of the data sheet slew rate of 2 V/ $\mu$ s. Based on this information, slew boost is present in the TLV9001. For the LMV831 waveform, the selected area (SR) is 2.2 V/ $\mu$ s rising and 1.8 V/ $\mu$ s falling SR, which is close to the data sheet slew rate of 2 V/ $\mu$ s; therefore, so no boost is expected.

	Boost	No Boost
Device	TLV9001	LMV831
NG	11	1
$V_{IN}$	600 mV	500 mV
Selected SR	0.6 V/ $\mu$ s	+2.2, -1.8 V/ $\mu$ s
Data sheet SR	2 V/ $\mu$ s	2 V/ $\mu$ s

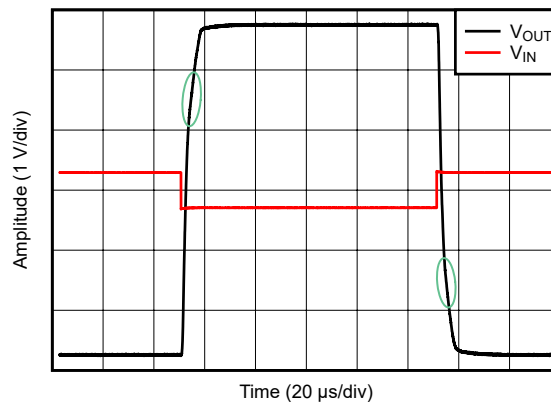


Figure 4-1. TLV9001 Overload Recovery

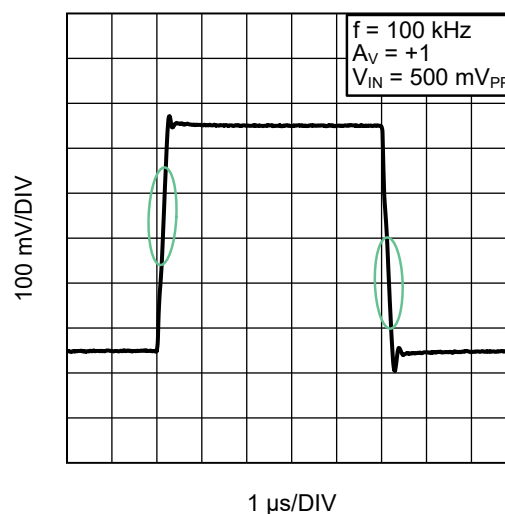


Figure 4-2. LMV831 Large Signal Step Response With Gain = 1



### Method 4: Evaluate Small Signal Response

The fourth method is to evaluate the SR in small input signal charts. Use the chart with the smallest input signal and highest noise gain. It can be necessary to zoom in to accurately measure the waveform relative to division scaling to get the initial slew rate after any internal capacitive-forward coupling. The time division of the TLV9001 waveform is too long, making the rise and fall appear to be vertical lines, so it is not possible to determine waveform SR with any accuracy. The TLV9001 waveform does not indicate boost or no boost. The LMV831 waveform is a great waveform to use as an indicator because the input is small, NG is high, and scaling makes rise and fall time measurable. The initial slew rate is consistent with the rest of the rising slew rate, so this section can be used for evaluation. Initial SR of the green oval area is 0.25 V/ $\mu$ s. The 10-mV  $V_{ID}$  translates to 14% SR[max] using Figure 3-1. The data sheet value (2 V/ $\mu$ s) scaled by 14% is 0.28 V/ $\mu$ s. The small signal slew rate of the waveform, 0.25 V/ $\mu$ s, closely matches the calculated slew rate, 0.28 V/ $\mu$ s. Based on these calculations, the LMV831 device does not have slew boost.

Result	Inconclusive	No Boost
Device	TLV9001	LMV831
NG	1	10
VIN	100 mV	10 mV
Initial SR	Unknown	0.25 V/ $\mu$ s
Data sheet SR $\times$ Figure 3-1 output	1.8 V/ $\mu$ s	0.28 V/ $\mu$ s

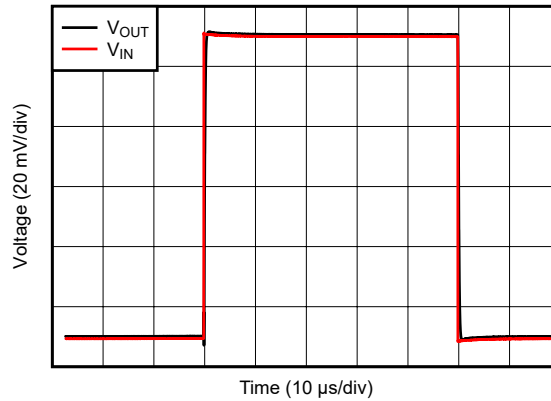


Figure 4-3. TLV9001 Small Signal Waveform

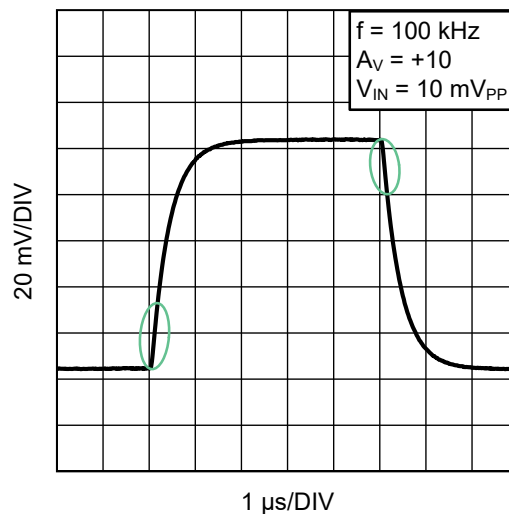


Figure 4-4. LMV831 Small Signal Waveform

## 5 Slew Rate Dependencies on Circuit Signal Levels and Op Amp Gain Set by Feedback Network

Figure 5-1 has two schematics that produce a 1-V output step. In the left circuit, the 1-V is amplified by a noise gain of 1. In the right circuit, 10 mV is amplified by a noise gain of 100. In these non-inverting circuits, signal gain and noise gain are equivalent.

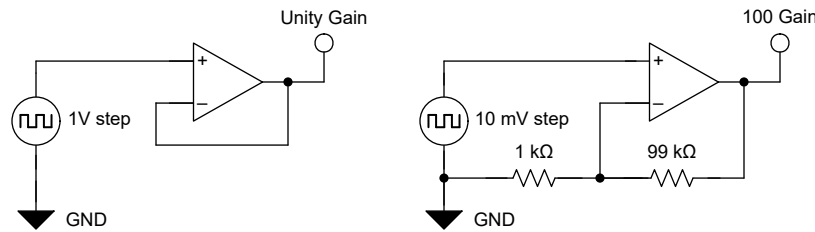


Figure 5-1. Two Schematics With The Same 1-V Output Step

Figure 5-1 is the resulting simulation waveform from the Figure 5-1 schematics. The unity gain (black curve) rises at  $2 \text{ V}/\mu\text{s}$ , which is the same as the data sheet specification. The 100 gain (red curve) has a slower slew rate that continues to decrease as the voltage rises. The initial slew rate for a 10-mV input step, following the Figure 3-1 output, is 14% of the natural slew maximum of  $0.5 \text{ V}/\mu\text{s}$ , which is  $70 \text{ mV}/\mu\text{s}$ . By the time the waveform rises half way, the  $V_{ID}$  has dropped to 5 mV. Now, the SR is the Figure 3-1 output 7% (of  $0.5 \text{ V}/\mu\text{s}$ ), which is  $35 \text{ mV}/\mu\text{s}$ .

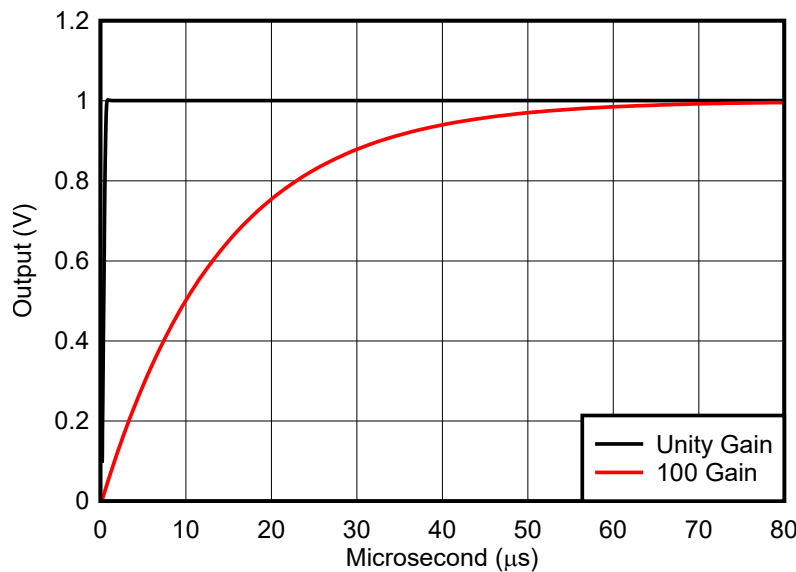


Figure 5-2. Two Waveforms With 1-V Step

Even if the TLV9002 device did not have slew boost, the unity gain slew rate ( $0.5 \text{ V}/\mu\text{s}$  natural) is much faster than a  $G=100$  curve. Slew boost or not, a smaller input signal with higher gain must always have a slower observed slew rate than a larger input signal with lower gain.

## 6 How Much Output Slew Rate is Needed to Support a Sine Wave or Other Non-step Inputs

The peak slew rate of an output sine wave of frequency ( $f$ ) and a peak-to-peak voltage ( $V_{PP}$ ) is shown in [Equation 3](#). If the op amp slew rate is not high enough, then the sine wave becomes triangular with a reduced amplitude. For any output waveform, the slew rate is simply the first derivative of the waveform. From these methods the required slew rate can be determined.

$$SR = V_{PP} \times \pi \times f \quad (3)$$

For signals other than a step input, also consider gain bandwidth product (GBWP). The absolute minimum GBWP needed for an application is shown in [Equation 4](#). For small signals on slew boost devices, it is recommended to use only GBWP for determining the sufficient op amp speed for a small input.

$$GBWP = f_{max} \times G_{noise} \quad (4)$$

With the required SR and GBWP determined, consider how much of the input signal can be used as  $V_{ID}$  to generate that slew rate and gain. Choosing an op amp with much greater SR and GBWP reduces the  $V_{ID}$  required and potentially reduces distortion. Higher SR and GBWP come with higher quiescent current. For low power applications there is a compromise between supply current and AC performance.

## 7 Stability Also Plays a Role in Observed Slew Rate

Very stable circuits with 90 degrees or more phase margins have longer rise times with slower observed SR because feedback is fully negative. The advantage of very stable circuits is the lack of overshoot. Critically stable and poor stability circuits with 45 degrees or less phase margin have a significant positive feedback effect that shortens edge times and increases observed SR at the expense of having overshoot, ringing, or possible oscillation.

## 8 Summary

The slew rate parameter in the data sheet is typically the quickest possible output rate change in  $V/\mu s$ . For low-power op amps, the units can be  $V/ms$ . Slew rate is reduced in applications with small inputs and high gains. Input difference voltage,  $V_{ID}$ , is needed to achieve an output slew rate. Achieving a faster SR requires a larger  $V_{ID}$ . However, a larger  $V_{ID}$  makes the virtual ground op amp concept less true, leading to a possible increase in signal distortion. Selecting an op amp with much higher slew rate and bandwidth than needed, to achieve lower signal distortion, is the best option.

## 9 References

1. Texas Instruments, [TI Precision Labs - Op Amp Slew Rate Introduction](#), video
2. Texas Instruments, [Understanding Operational Amplifier Specifications](#), application report
3. Texas Instruments, [TI Precision Labs - Op Amps Slew Rate - Lab](#), video

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