Topics on Using the LM6181—A New Current Feedback Amplifier

Use your imagination . . . that's what jazz is all about. If you make a mistake, make it loud so you won't make it next time. — **Art Blakey**

Introduction

High-speed analog system design can often be a daunting task. Typically, after the initial system definition and the design approach is established, the task of component selection commences. Unfortunately, simple reliance on data sheet parameters provides only a partial feel for the device's actual operating nuances. This is unfortunately true no matter how complete a high-speed amplifier data sheet is written. Only by experimenting i.e., spending some time on the bench with the part, will the requisite experience be obtained for reliably using high-speed amplifiers. The high-speed demonstration board, described herein, can be effectively used to accelerate this process. In developing the LM6181 application program, the key focus areas for making high-speed design a little easier included:

- Designing a product that is more forgiving—for example it can directly drive backmatched cables (a heavy dc load), and significant capacitive loads (without oscillating).

- Developing a high-speed demonstration board that is easily reconfigurable for either inverting or non-inverting amplifier operation.

- Incorporate a highly accurate SPICE macromodel of the LM6181 into National's macromodeling library. This macromodel can be used in conjunction with bench results to more quickly converge on a reliable high-speed design.

Although it may seem that evaluation of high-speed circuit operation can be more quickly performed with computer simulation, full bench evaluation cannot be supplanted. By integrating *both* of these complementary tools, the cycle time from component selection to finalized design can be reduced.

Some Background Information on the LM6181

The LM6181 is a high-speed current feedback amplifier with typical slew rates of 2000 V/µs, settling time of 50 ns for 0.1%, and is fully specified and characterized for ±5V, and ±15V operation. Current feedback operational amplifiers, like the LM6181, offer two significant advantages over the more popular voltage feedback topology. These advantages include a bandwidth that is relatively independent of closed-loop gain (see *Figure 1*), and a large signal response that is closer to ideal. "Ideal" specifically means that the large signal response is not overtly dominated by non-linear slewing behavior (Ref. 1), as is typically found for voltage feedback amplifiers. An obvious consequence is dramatic improvement in distortion performance versus the signal amplitude, and settling time.

The high-speed demonstration board can be used to either examine the time domain, or frequency domain. However, the discussion will focus on using this board for the purpose of compensating the time domain response of the LM6181 for popular applications.

LM6181 Closed-Loop Frequency Response
$V_S = \pm 15V$; $R_f = 820\Omega$; $R_L = 1\ k\Omega$
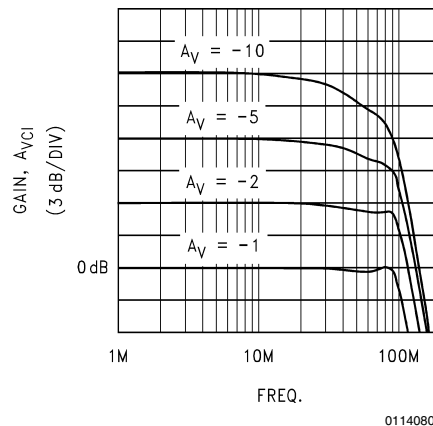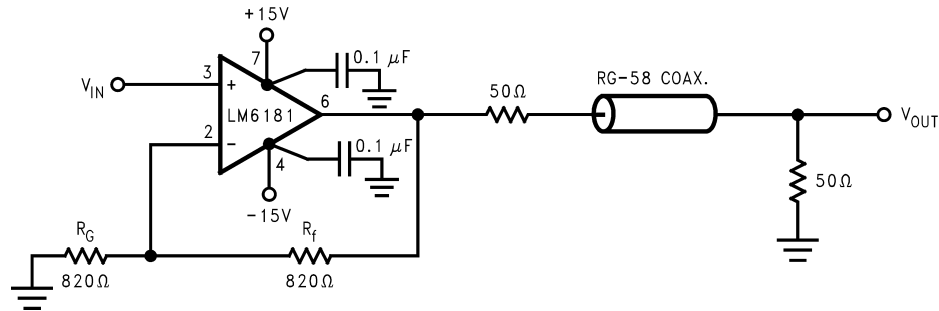

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FIGURE 1. Unlike voltage feedback amplifiers which directly trade bandwidth for gain, current feedback amplifiers provide consistently wideband performance regardless of moderate closed-loop gain levels.

Examples of this includes driving cables, dealing with capacitive loads, and generally obtaining a user specified fidelity to the pulse response. Essentially, the demonstration board simplifies the evaluation of high speed operational amplifiers in either the inverting, or the non-inverting circuit configurations. Appendix A includes the board schematic with the associated configuration options. Layout of the board included a host of mandatory high speed design considerations. These principles have been summarized in Appendix B (also see Ref. 2 to 4).

A popular application for high speed amplifiers includes driving backmatched cables as illustrated in *Figure 2*. Due to loading and typical bandwidth requirements this particular application places heavy demands on an amplifier. The LM6181 output stage incorporates a high-current-gain output stage that provides a lower output impedance into heavy loads, such as 100Ω and 15Ω. This enhances the amplifier's ability to drive backmatched cables (±10V, into 100Ω) since the internal current drive to the amplifiers output stage is used more efficiently. Additionally, the benefits of the current feedback topology of the LM6181 allows for wideband operation of 100 MHz, even when configured in closed-loop gain configuration of +2.

Some Background Information on the LM6181 (Continued)

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FIGURE 2. Backmatching of a cable is a clean way of terminating the source to the characteristic impedance. The LM6181 can deliver ±10V into the resulting dc load of 100Ω, at 100 MHz, typically.

Experimenting with the Time Domain

Some consideration needs to be addressed for the test signal chosen to evaluate the transient response of a linear system. By the properties of Laplace transforms, if a unit impulse input is used and the measured output response is integrated, the result of applying an inverse Laplace transform will yield the systems frequency response. This approach is not typically useful since pulse generators do not generate impulses and the integration becomes unduly complex. Additionally, this technique does not serve to establish an intuitive feel. Alternatively, if a slowly time-varying input signal is used as the test input, the high-frequency components in the system are not significantly excited. The step response often provides a meaningful evaluation of amplifier performance, and represents a more practical signal. Other advantages of using a step response is that it directly provides the dc gain, and the high-frequency nature of the step excites the high-frequency poles in the amplifier's system transfer function.

When evaluating step response performance of wideband amplifiers it is important to use a pulse generator that provides a sufficiently fast risetime. A step response, in relation to the system that is being evaluated, must have a risetime relationship of:

$$t_{risetime} < \frac{0.35}{(\text{Bandwidth of Amplifier})}$$

Therefore, evaluating the step response of the LM6181 amplifier, where the typical bandwidth for gains of +2 is 100 MHz, will require a step input signal with a maximum risetime of 3.5 ns. Since there will always be a certain amount of risetime degradation due to the oscilloscope probe and the oscilloscope, use the same measurement equipment for evaluating both the integrity of the input signal and for measuring the output response of the system. *Figure 3* illustrates a satisfactory input pulse for evaluating the LM6181.
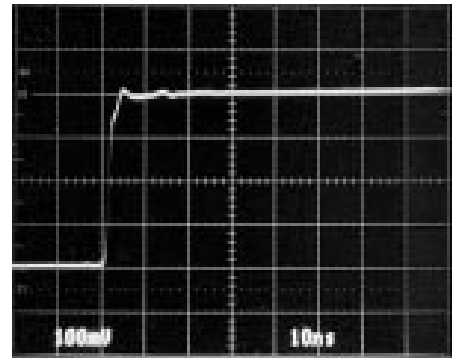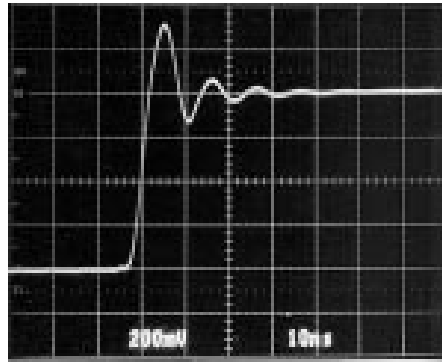

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FIGURE 3. Always start the dynamic characterization of high-speed amplifiers with an input signal that maintains adequate speed, with little aberration. Measuring the input signal, from a fast pulse generator, (a Hewlett-Packard 8082A pulse generator was used), also provides a check of correct terminations of the probe—oscilloscope combination.

Probably the largest area of difficulty in high-speed design is when amplifiers drive capacitive loads. Unfortunately, many amplifiers on the marketplace are specified to handle a maximum of a meager 20 pF of capacitive load before oscillation occurs. This maximum limitation equivalently implies that the amplifiers pulse response will be sensitive to typical oscilloscope capacitance—the probe becomes an integral part of the overall circuit, which makes meaningful judgements on measurements very difficult.

Although direct capacitive loading should typically be minimized in general practice, *Figure 4* illustrates that for moderate values of capacitive load, due to the oscilloscope probe, the LM6181 is still very well behaved. *Figure 5* illustrates the simulation using SPICE and the LM6181 macro-model. The LM6181 SPICE macromodel has superb ac and transient response characteristics. For availability information concerning the complete macromodeling library, including the LM6181, along with an outline of the model's capabilities, refer to Appendix C.

Experimenting with the Time Domain   (Continued)

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FIGURE 4. Output response of a real LM6181, A_V = +2, R_f = R_G = 820Ω. Output load is oscilloscope probe, Tektronix P6106A, 10 MΩ, 8.7 pF.
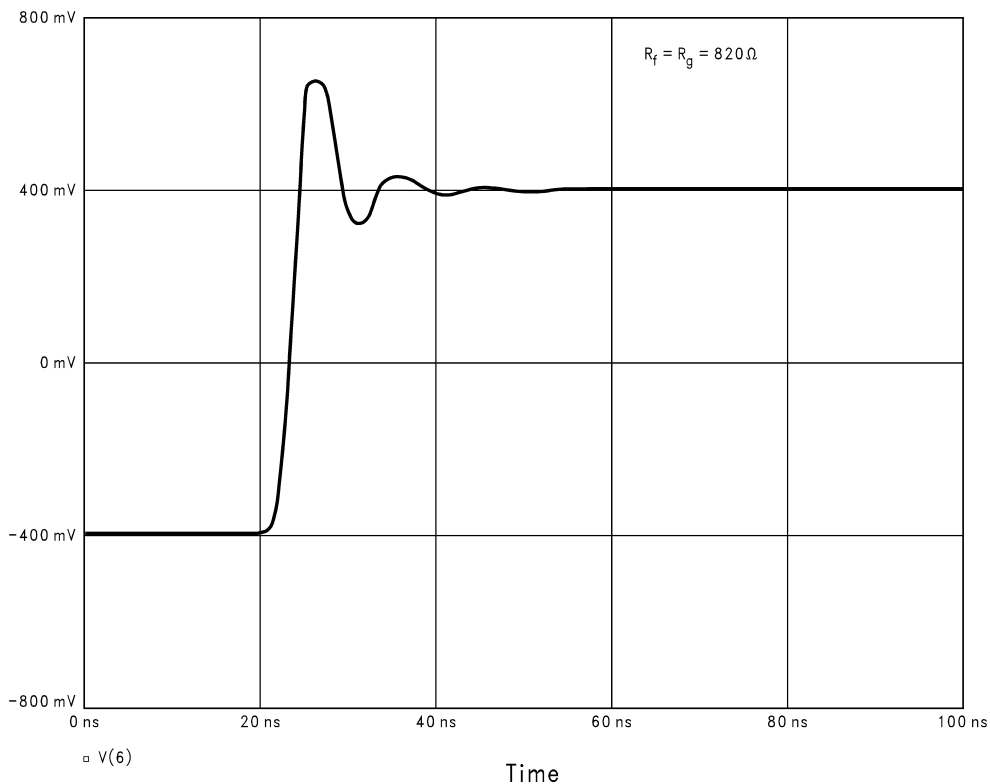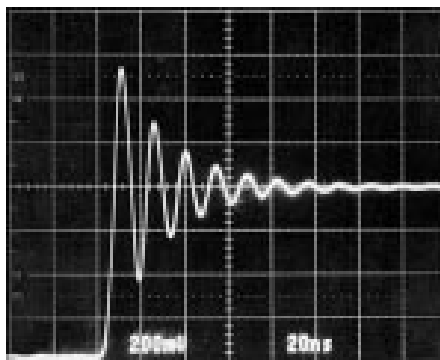

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FIGURE 5. Simulated output response of the circuit in *Figure 3* using the LM6181 macromodel. See Appendix C for more information regarding the LM6181 macromodel and National's Macromodel library.

Compensating the Pulse Response

Degradation in the phase margin, due to direct capacitive loading of high-speed amplifiers can potentially induce oscillation. The output impedance of the amplifier, coupled with the load capacitance, forms a lag network in the loop transmission of the amplifier. Since this network delays the feedback, phase margin is reduced such that even when a system is not oscillating excessive ringing can occur, as illustrated in *Figure 6* where the capacitive load is 48 pF.

A direct solution to reducing the ringing for driving capacitive loads is to indirectly drive the load i.e., isolate the load with a real impedance, such as a moderately small value of resistance. In *Figure 7* a 47Ω resistor was used to isolate the capacitor's complex impedance from the amplifier's output, thereby preserving the amplifier's phase margin. An obvious trade-off exists between taming the time domain response, and maintaining the amplifier's bandwidth, since this form of compensation directly slows down the amplifier's response.

## Compensating the Pulse Response (Continued)

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FIGURE 6. Direct capacitive loading will reduce the phase margin and resulting pulse fidelity of any amplifier. A pole is created by the combination of the op amp's output impedance and the capacitive load. This results in delaying the feedback or loop transmission. In this example the LM6181 is directly driving a 48 pF load. High-speed current-feedback amplifiers can handle capacitive loads, and maintain pulse fidelity, by indirectly driving them. This is illustrated in *Figure 7*.
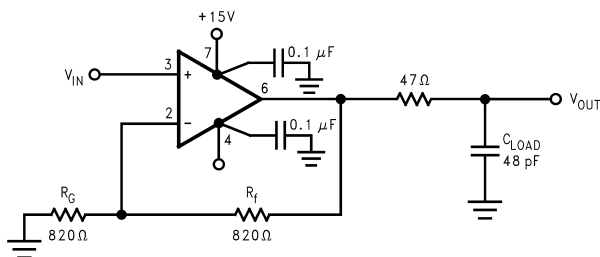
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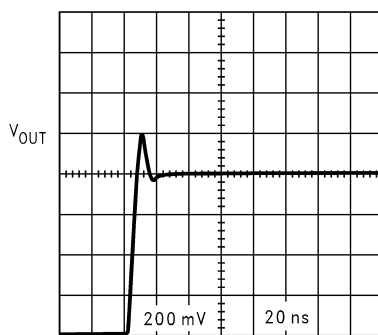
FIGURE 7. A small resistor can be used, such as 47Ω, at the output of the amplifier to indirectly drive capacitive loads.

For general applications of the LM6181, the suggested feedback resistance, R_f, is 820Ω. However, a characteristic unique to current-feedback amplifiers is that they will have different bandwidths depending on the feedback resistor R_f. This results in current-feedback amplifiers maintaining a net closed-loop bandwidth that remains (this is of course an approximation; second order effects do take their toll, of course) the same for moderate variations of closed-loop gain. This feature of current feedback amplifiers actually makes them relatively easy to compensate. By simply scaling the gain setting and the feedback impedance, the appropriate bandwidth can be obtained at the desired value of closed-loop gain. *Figure 8* was cut from the LM6181 data sheet, and describes this relationship.

Compensating the Pulse Response (Continued)
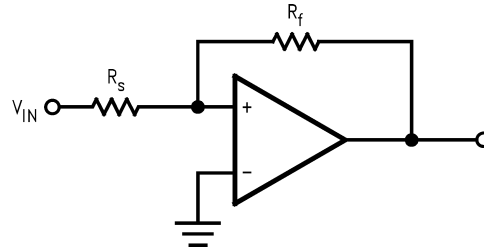
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Bandwidth vs R_F and R_S
**$A_V = -1$, $R_L = 1$ kΩ**
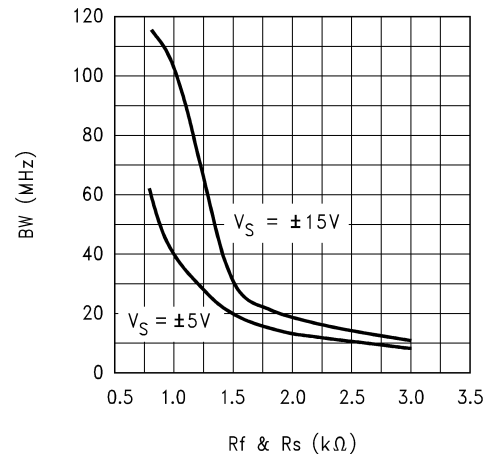
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FIGURE 8. By scaling both R_F and R_S the closed-loop gain stays constant but the bandwidth changes.

A practical application of using altered feedback values for compensating the LM6181 when driving a 100 pF capacitive load is illustrated in *Figure 9*. By reducing the open-loop bandwidth of the amplifier, the resulting degradation of phase margin is reduced, thereby improving the pulse response fidelity.

Compensating the Pulse Response (Continued)

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200 mV   20 ns
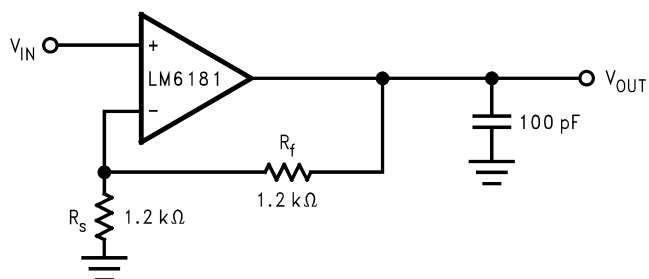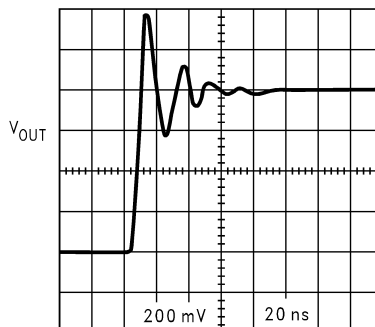
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FIGURE 9. Normally, if $R_F = R_S = 820\Omega$, the LM6181 would oscillate with 100 pF of capacitive load. In this example the feedback, R_F and R_S values are scaled to 1.2 kΩ so that the closed-loop gain is A_V = +2, but the open-loop band width decreases, maintaining adequate phase margin.

An often overlooked factor in dynamically understanding high-speed amplifiers is the effect that dc loading has on amplifier speed. When driving backmatched cables, for example, the Thevenin equivalent load is usually either 100Ω, or 150Ω. *Figure 10* (from the LM6181 data sheet) provides bandwidth versus dc load information. *Figure 11* illustrates the step response for the LM6181 in a gain of +2, with a dc equivalent load of 100Ω. When the step response is compared against *Figure 4* it is obvious that dc loading will affect amplifier bandwidth. Additionally, since amplifier dynamics is also affected by supply voltage, the LM6181 is fully characterized for both ±5V and ±15V operation.

Compensating the Pulse Response

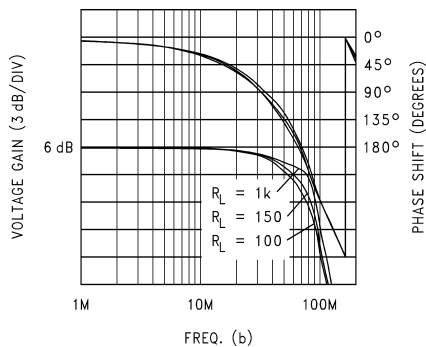(Continued)

Inverting Gain Frequency Response
$V_S = \pm15V$; $A_V = -1$; $R_F = 820\Omega$
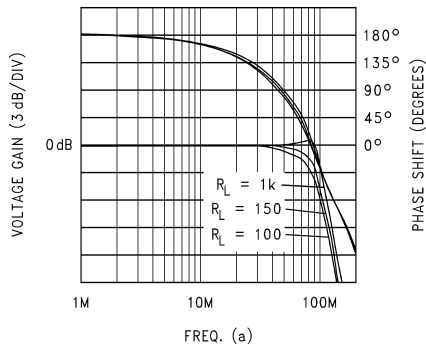
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Non-Inverting Gain Frequency Response
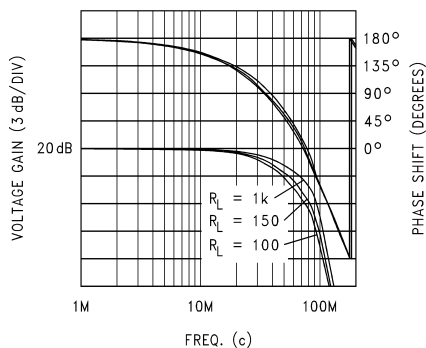$V_S = \pm15V$; $A_V = +2$; $R_f = 820\Omega$
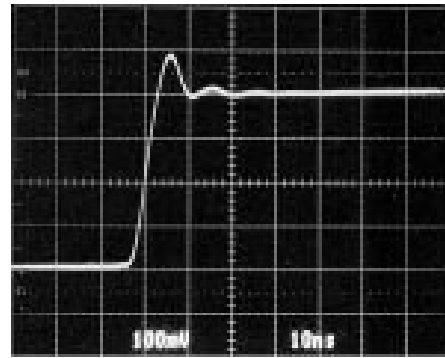

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Inverting Gain Frequency Response
$V_S = \pm15V$; $A_V = -10$; $R_F = 820\Omega$

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FIGURE 10. DC loading of a high-speed amplifier will affect bandwidth. (Refer to the LM6181 data sheet for ±5V bandwidth vs loading characteristic curves.)
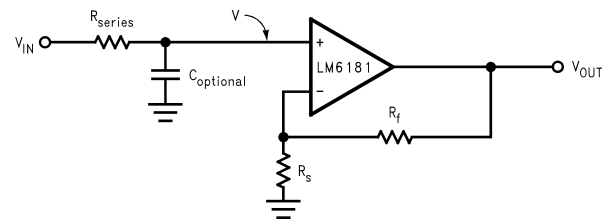

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FIGURE 11. Output step response of LM6181 when driving backmatched cables. Comparing this step response to *Figure 4* illustrates the bandwidth reduction due to the 100Ω resistive load.

Compensating Non-Inverting CF Amplifiers

Often, for the inverting amplifier configuration, simply scaling the feedback and gain setting resistor is the easiest way of compensating for peaking and overshoot in the step response. The non-inverting configuration, however, can alternatively be compensated by adding a series input resistor, as shown in *Figure 12*. This resistor, in combination with the input and stray input capacitances of the amplifier bandwidth limit the input step response, and accordingly reduce peaking in the output response. This effect is equivalent to increasing the risetime of the leading edge of the input pulse (some pulse generators have this adjustment).

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$$f_{-3\,dB} \text{ of } V \cong \frac{1}{2\pi(C_{optional} + 3\,pF) \cdot R_{series}}$$

FIGURE 12. Peaking and ringing for non-inverting amplifier configurations can be reduced by adding a series input resistor, R_{series}. This resistor interacts with the amplifiers input capacitance to provide a low pass bandwidth limit for the input pulse. If more bandwidth reduction is required $C_{optional}$ can be used.

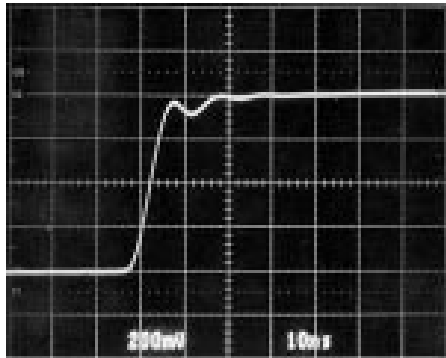## Compensating Non-Inverting CF Amplifiers (Continued)

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FIGURE 13. Resulting pulse response for LM6181 using R$_{series}$ = 680Ω, A$_V$ = +2, R$_S$ = R$_F$ = 820Ω, C$_{LOAD}$ ≈ 8.7 pF. Compare this response with *Figure 4*, overshoot and ringing has been dramatically reduced.

Snake Oil and Spice Macromodels Cure All Evils

Not all amplifier macromodels are created equal. For example, driving capacitive loads with high-speed amplifiers is a good way of evaluating and comparing op-amp macromodels. Capacitive loading directly affects the loop dynamics of a closed-loop amplifier system. And since this capacitive load interacts with the output impedance of the amplifier to delay the feedback (or loop transmission), the phase margin is reduced, as stated earlier.

Simulating high-speed systems when driving capacitive loads places a demand on the amplifier's macromodel. Constructing an accurate macromodel is not simple. Unfortunately, parameterized models (an efficient method of using a computer to generate many inaccurate models per a typical workday) lack the extensive software testing and bench measurement analysis required for sophisticated simulation work. The amplifier's output stage, the frequency response, and the input parasitic structures need to be carefully measured on the bench, then accurately mimicked in the macromodel. The moral is to be aware, and:

ALWAYS TEST YOUR MACROMODEL!

Compare the similarity between results in *Figure 14* with the bench results of *Figure 6*. Increased confidence in using a specific high-speed amplifier macromodel can be obtained by corresponding bench results of driving capacitive loads with simulation results.

Driving reactive loads, such as capacitive loads, can be used not only to indicate limitations for the associated SPICE macromodel, but also to reveal some of the amplifier's high-speed personality. Never assume that a macromodel of an operational amplifier includes characteristics that are germane to your particular simulation.

Summing Things Up

The focus has been on high-speed analog design methodology, as opposed to generating a plethora of varied application circuits. By establishing a foundation—understanding the amplifier, referring to the typical characterization curves, using correct high-speed layout techniques, knowing the SPICE macromodels limitations, and adopting some basic compensation techniques, a large fraction of everyday high-speed design challenges can be addressed confidently.
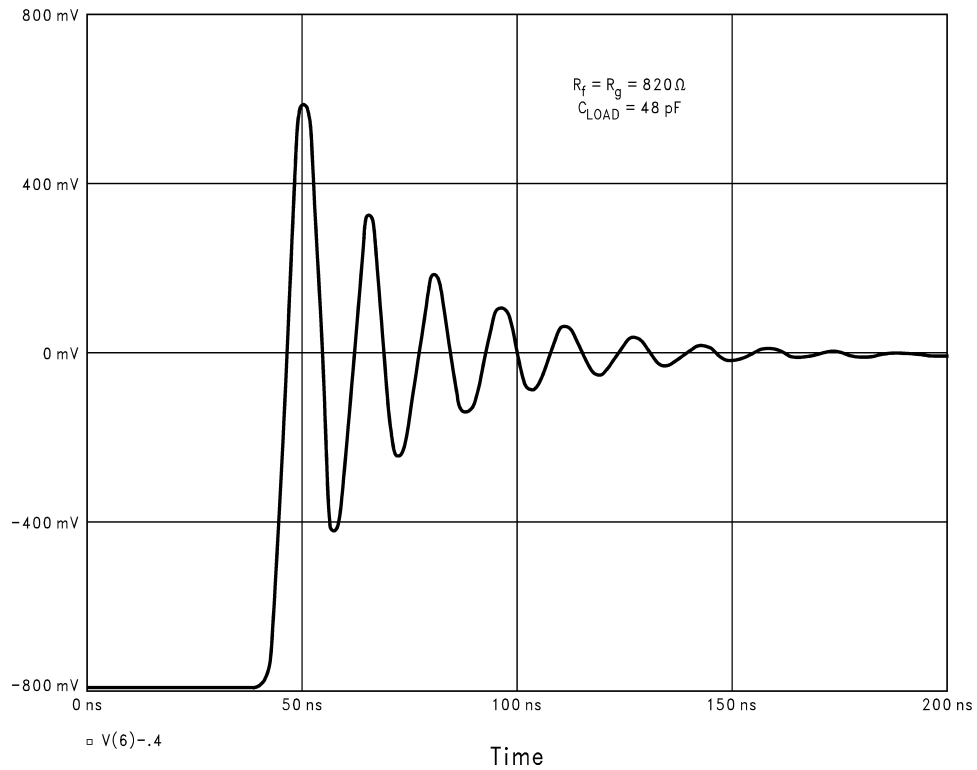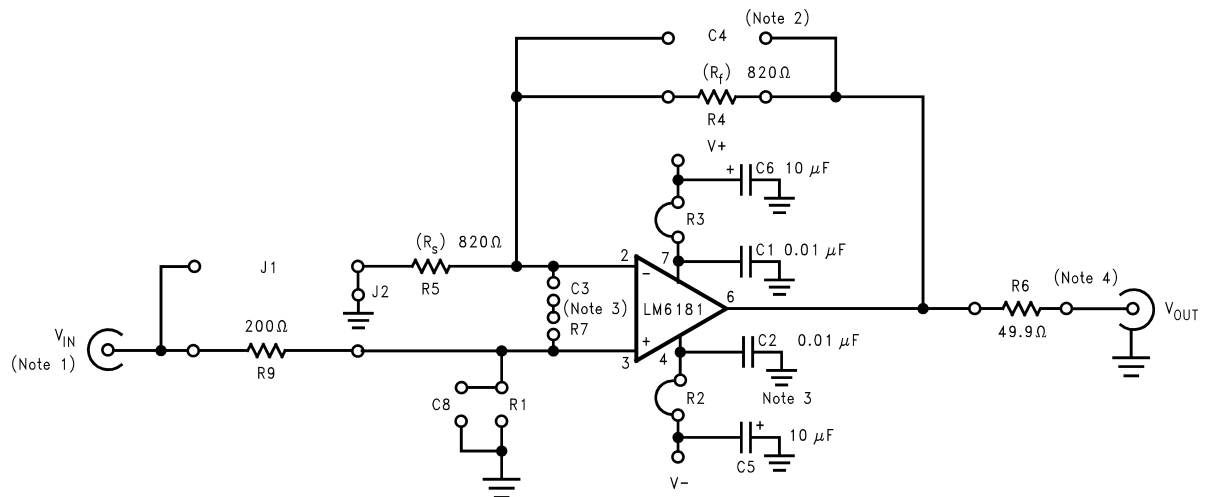
Summing Things Up (Continued)

□ V(6)−.4

Time

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FIGURE 14. Simulation of LM6181 step response with A$_V$ = +2, R$_F$ = R$_S$ = 820Ω, and C$_{load}$ = 48 pF.

APPENDIX A

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The LM6181 high speed demonstration board can be configured for either inverting or non-inverting amplifier configurations. This board was intentionally embellished with options so that it can be used as a general-purpose 8-pin op-amp evaluation board.

Note 1: Terminate this BNC connection with the appropriate connector. Otherwise ringing due to high-frequency reflections will occur.

Note 2: Do not lead compensate current feedback amplifiers—oscillation will result. Lead compensation uses a feedback capacitor, C_4.

Note 3: C3 and R7 are optional lag-compensation network points.

Note 4: R6 is for back matched driving of cables.

APPENDIX B: High Speed Board Design Caveats

1. Good high frequency termination is always required for the input signal. It is important, for evaluating any amplifier, to check the integrity of the input signal.

2. RF quality, ceramic capacitors are used for bypassing and are placed close to the amplifiers supply pins.

3. The feedback network is placed in close proximity to the amplifier.

4. The entire top side of the board is ground planed. This lowers the high-frequency impedance for ground return signals.

5. The amplifier inputs have ground plane voids since these amplifier nodes are sensitive to parasitic stray capacitance. This is specifically a key issue for the non-inverting amplifier configuration.

6. All leads are kept as short as possible, using the most direct point-point wiring techniques.

APPENDIX C: Features Modeled For LM6181 Macromodel

Supply-Voltage-Dependent Input Offset Voltage (V_{OS})

Temperature-Dependent Input Offset Voltage (TCV_{OS})

Supply-Voltage-Dependent Input Bias Current (I_{b+} & I_{b-} PSR)

Temperature-Dependent Input Bias Current (TCI_{B+} & TCI_{B-})

Input-Voltage-Dependent Input Bias Current (I_{b-} CMRR)

Non-Inverting Input Resistance

Asymmetrical Output Swing

Output Short Circuit Current (I_{SC})

Supply-Voltage-Dependent Supply Current

Quiescent and Dynamic Supply Current

Input-Voltage-Dependent Input Slew Rate

Input-Voltage-Dependent Output Slew Rate

Multiple Poles and Zeroes in Open-Loop Transimpedance (Z_t)

Supply-Voltage-Dependent Input Buffer Impedance

Supply-Voltage-Dependent Open-Loop Voltage Gain (A_{VOL})

Feedback-Resistance-Dependent Bandwidth

Accurate Small-Signal Pulse Response

Large-Signal Pulse Response

DC and AC Common Mode Rejection Ratio (CMRR)

DC and AC Power Supply Rejection Ratio (PSRR)

White and 1/f Voltage Noise (e_n)

White and 1/f Current Noise (i_n)

For information related to obtaining National's SPICE macromodeling library, including the LM6181, call a National sales office.

References

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