Selecting High-Speed Operational Amplifiers Made Easy

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ABSTRACT

High-speed op amps come in current- and voltage-feedback versions. Voltage-feedback amplifiers are sometimes de-compensated to allow greater speed, but this technique has been superceded by current-feedback amplifiers. Differential-output op amps are gaining popularity for transformerless A/D interfaces.

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1 Introduction

The availability of high-speed operational amplifiers (op amps) is relatively recent. Most designers are either unaware of the differences between high- and low-speed op amps, or are intimidated by them. This note is written to make the basic concepts of high-speed op amps easy to understand. It is intended as a guide for designers who must specify and use a high-speed op amp.

2 Voltage Feedback and Current Feedback

There are two basic types of high-speed op amp[1], voltage and current feedback. A brief review of these types of op amps follows.

2.1 Voltage-Feedback Op Amps

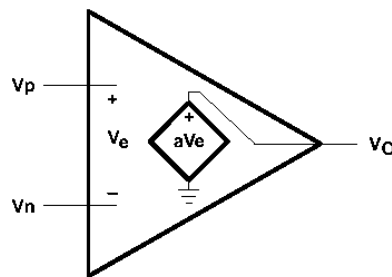The voltage-feedback op amp is familiar to designers. Its ideal form is shown in Figure 1.

Figure 1.   Ideal Voltage-Feedback Op Amp

The gain of an ideal voltage-feedback op amp is given by:

$$V_O = a \times V_e$$

where V_O is the output voltage, a is the open-loop voltage gain, and V_e (= Vp – Vn) is the error voltage.

Although no op amp is ideal, modern processing techniques yield devices that come close, at least in some parameters. This is by design. In fact, different op amps are optimized to be close to ideal for some parameters, while other parameters for the same op amp may be quite ordinary. It is a trade-off. Some parameters can be improved, but only at the expense of others. It is the designer's function to select the op amp that is closest to ideal in ways that matter to the application, and to know which parameters can be discounted or ignored.

When dealing with high-speed op amps, the parameters that are of most interest to the designer are bandwidth and slew rate. In voltage-feedback amplifiers, bandwidth is inversely related to gain over the normal operating range of the op amp. This linear relationship is a –20 dB/dec roll-off caused by an internal compensation capacitor. This capacitor was introduced to solve a problem that has plagued voltage-feedback op amps from the time they were first introduced, namely, instability (i.e., the tendency to oscillate). The technique works well, and it has allowed the production of many varieties of voltage-feedback op amps over the years. Unfortunately, the compensation capacitor also limits the response of the op amp at high frequencies.

2.2 Current-Feedback Op Amps

There is much confusion amongst designers as to exactly what a current-feedback op amp is. The term *current feedback* refers to the internal construction of the op amp, not to something external to it. The ideal current-feedback op amp is shown in Figure 2.
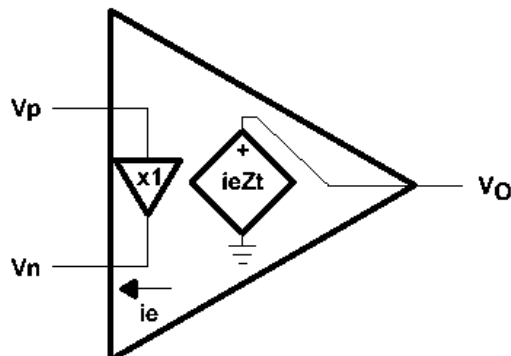

Figure 2.   Ideal Current-Feedback Op Amp

The gain of an ideal current-feedback op amp is given by:

$$V_O = i_e Z_t$$

where V_O is output voltage, i_e is the error current, and Z_t is the open-loop transimpedance gain.

It can be seen in Table 1 that the slew rate of a current feedback op amp is more than an order of magnitude greater than that of a voltage feedback op amp.

**Table 1.   Voltage- and Current-Feedback Characteristics**

CHARACTERISTIC	VOLTAGE FEEDBACK	CURRENT FEEDBACK
Part number	THS4001	THS3001
Bandwidth (MHz)	300	420
Slew rate (V/μs)	400	6500
Settling time (ns)	30	40
I/O (mA)	100	100

Op amp design is a series of trade-offs and an improvement in one parameter is always accompanied by degradation of others. This is certainly the case with current-feedback amplifiers where, to a degree, dc performance has been sacrificed to gain speed.

2.3 Applying Current-Feedback Op Amps

It is important to resolve misconceptions about how to use current-feedback amplifiers. The average designer does not know how to build a gain stage with a current-feedback op amp. Usually there is the assumption that something esoteric is done with the traditional, familiar, gain topologies. This is not true. In fact, as shown in Figure 3, *there is no difference*!

INVERTING GAIN

VOLTAGE FEEDBACK   CURRENT FEEDBACK

NONINVERTING GAIN
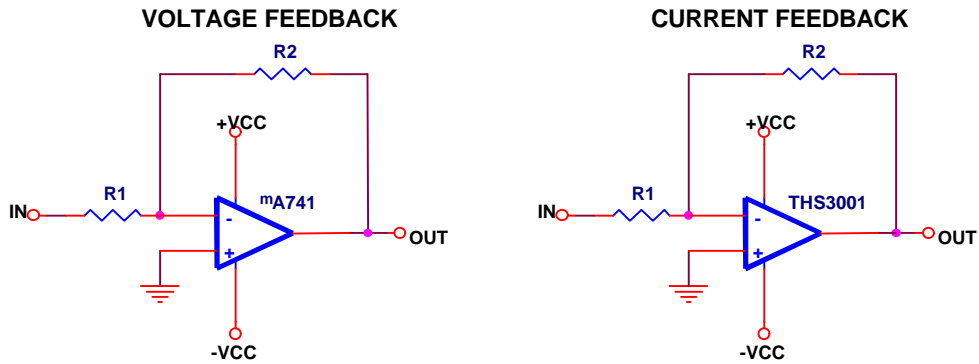
VOLTAGE FEEDBACK   CURRENT FEEDBACK
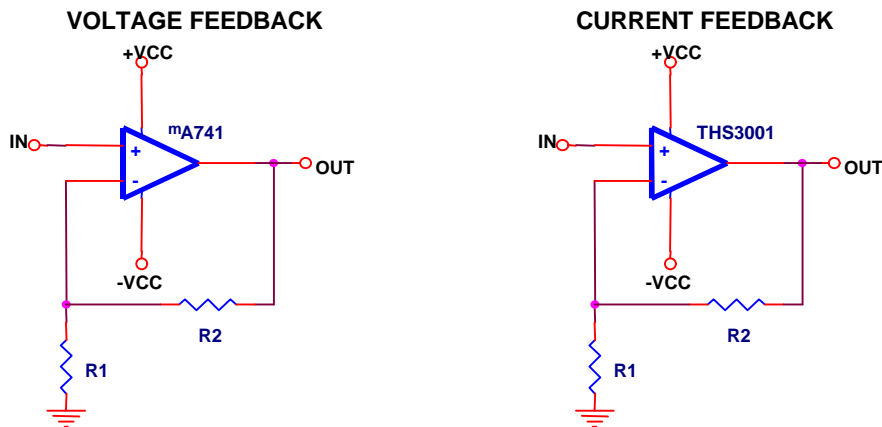
Figure 3.   Gain Stage Topology for Voltage and Current-Feedback Op Amps

There are several do's and do not's for current-feedback op amps: first, the do not's:

- Do *not* use a current-feedback op amp as a traditionally configured unity gain buffer (output connected directly to inverting input)! Correct and incorrect unity gain buffers are shown in Figure 4:

NO!!!   YES

Figure 4.   Use of a Current-Feedback Op Amp as a Unity Gain Buffer

- Do *not* connect a capacitor from the output of a current-feedback op amp to the noninverting input. Designers will often do this when trying to implement a low-pa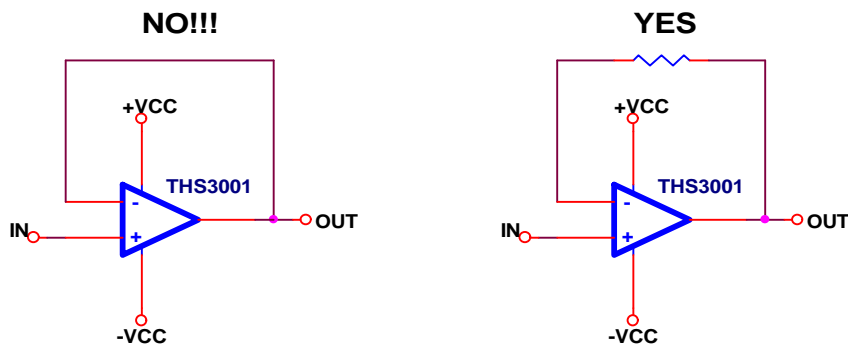ss filter. Correct and incorrect ways to implement a low-pass filter with a current-feedback op amp are shown in Figure 5.

NO!!!   **YES**
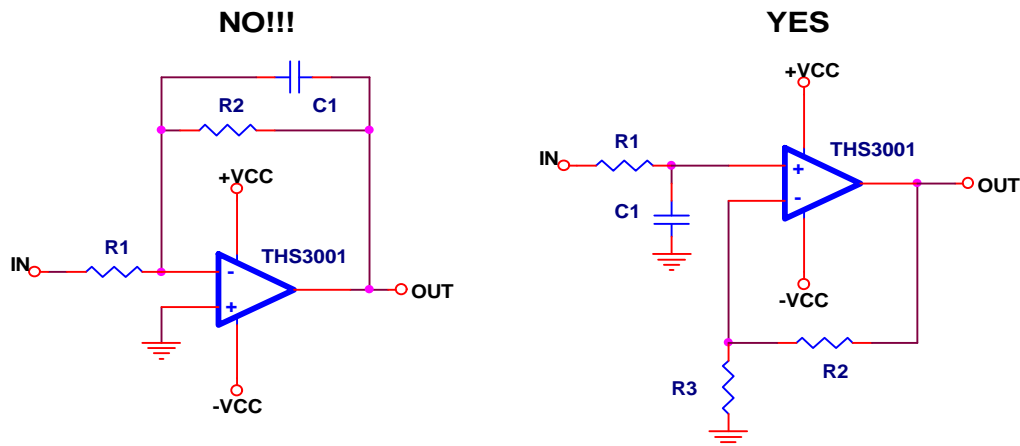
Figure 5.   Low Pass Filter With a Current Feedback Op Amp

The correct way to implement a two-pole filter is to use the Sallen Key topology, as shown in Figure 6, adding the recommended feedback resistor for the current feedback amplifier.

Figure 6.   Two-Pole Low Pass Filter With Current Feedback Op Amps

Along with the do not's, there are some do's:

- Do watch the trace length on the inverting input. Capacitance on this input, formed by parasitic capacitance with other layers and traces, will reduce the phase margin (see Figure 7).

Figure 7.   Effect of Capacitance at the Inverting Input

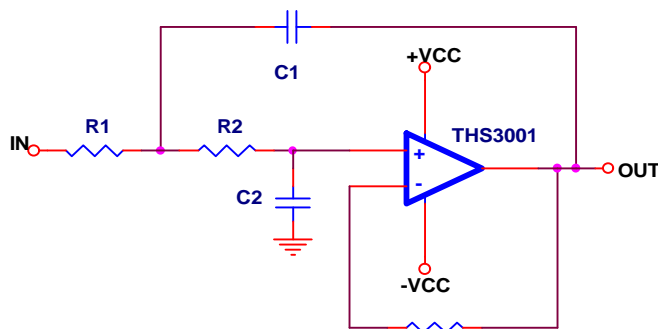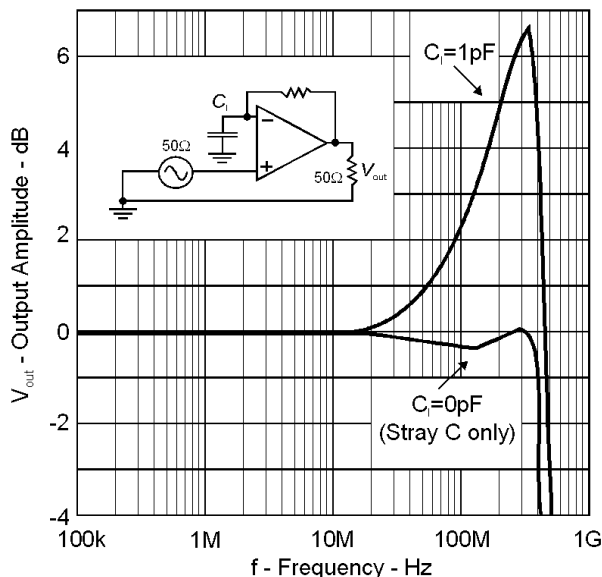Parasitic capacitance comes primarily from PCB traces. Long or wide traces create capacitance with ground planes and adjacent traces. Keep the inverting input trace short.

- The current-feedback op amp must have a resistor in the feedback loop. This resistor is usually specified in the data sheet for the device. It is chosen to limit overshoot or undershoot in the output amplitude near the maximum operating frequency.

- To change the gain of a current-feedback op-amp circuit, change the input gain resistor, not the feedback resistor.

- Do use correct PCB techniques, including a separate analog ground plane for high-speed op amps.

- Do use correct decoupling techniques. This includes placing a 10 nF or 100 nF ceramic capacitor less than 0.1" from the power supply pin.

3   Compensated vs Uncompensated Op Amps

It is possible to make a high-speed voltage-feedback op amp without a compensation capacitor. Doing so allows the op-amp gain to be semi-independent of bandwidth, but the designer is responsible for externally compensating the op amp.

At present, there are very few uncompensated op amps on the market. Many so-called uncompensated op amps actually have compensation capacitors that are smaller than usual, and thus are decompensated partially, albeit not completely. The user must supply additional compensation, trading bandwidth for stability.

Decompensated op amps have not been widely successful in the market. The newer, current-feedback amplifiers achieve high speeds without sacrificing stability. Voltage-feedback amplifiers with compensation have also become faster than those decompensated devices that are on the market. Consequently, this note covers decompensated op amps in only general terms. In the event that a decompensated op amp is needed, exact component values can be found in the data book[4] and techniques to derive such values have been discussed by Mancini[2].

All voltage-feedback amplifiers can be made unstable under the right conditions. The techniques described here can usually solve stability problems.

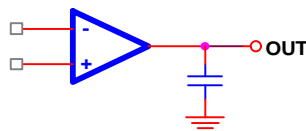The worst enemy of stability is load capacitance (Figure 8).

Figure 8.   Load Capacitance Causes Instability

Load capacitance is most commonly encountered when interfacing an op amp to a data converter, which can have relatively large variable capacitance at its input. The problem is especially severe in uncompensated (or decompensated) op amps.
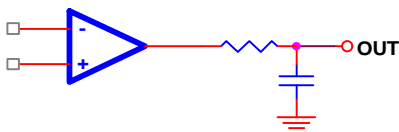

Figure 9.   Load Capacitance Can Be Isolated With a Resistor

The usual method of isolating load capacitance is with a small series resistor (Figure 13). However, this also forms an RC low-pass filter with the cutoff frequency of $f_O = 1/(2pRC)$ and, as a consequence, it will limit the frequency response of the circuit and load the amplifier at frequencies above $1/(2pRC)$. Many times, the A/D manufacturer will specify the component values for this RC circuit. Follow the manufacturer's recommendations.

Unless connection points are supplied to the internal op-amp compensation points, there are very few places at which the designer can apply compensation. The output terminal, as shown in Figure 9, is one such place. Another way to compensate an unstable voltage-feedback op amp is through lead compensation, as shown in Figure 10.
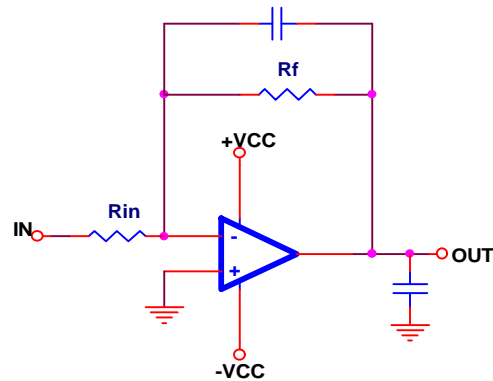
Figure 10.   Lead Compensation for Load Capacitance

The concept is to balance the phase lag caused by the load capacitance with a phase lead from the feedback capacitance so that the two capacitors effectively cancel each other. Frequency response can actually *increase* with the correct value of the feedback capacitor. Direct calculation is beyond the scope of this note and, indeed, laboratory experimentation may produce the quickest results. Note that the lead capacitor also works in a noninverting gain circuit.

Inverting-input capacitance can cause instability in both voltage- and current-feedback op amps. The problem is especially severe in op-amp circuits with gains of less than one (inverting attenuator circuits). The lead-capacitor technique can also be used to compensate for input capacitance on the inverting input, as shown in Figure 11.
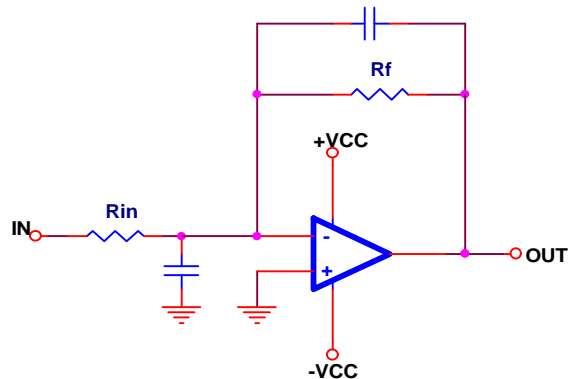

Figure 11.   Lead Compensation for Inverting-Input Capacitance

Both load and inverting-input capacitance can contribute to instability, so the lead capacitor should be selected to compensate for both.

Note that current-feedback amplifiers are much less tolerant of capacitors in the feedback loop. Place a resistor in series with the feedback capacitor.

4   Differential vs Single-Ended Op Amps

Differential op amps have been increasing in popularity in recent years. Differential-output op amps actually revive a design concept almost 50 years old. The original vacuum-tube-based op amp, the K2-W, was a differential-output device. The primary application for differential-output op amps is interfacing to differential-input A/D converters.
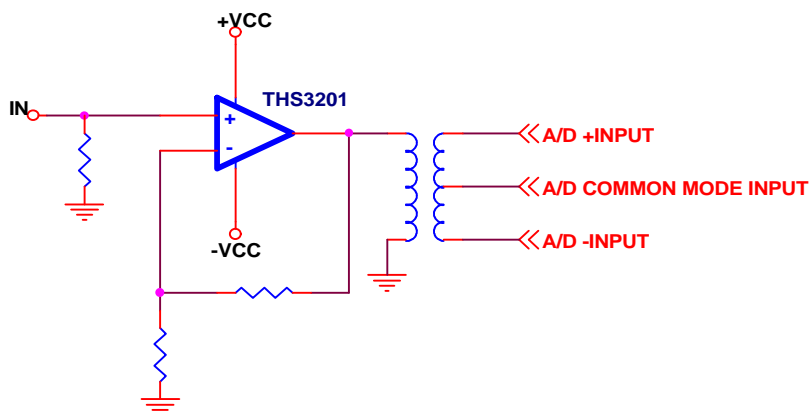
Figure 12.   Traditional Method of Interfacing to Differential-Input A/D Converters

Figure 12 shows how differential A/D converters have been interfaced in the past. The differential inputs of the A/D converter are connected through a transformer to a single-ended op amp. There is nothing inherently wrong with this approach, but it does have some disadvantages:

- It does not take advantage of the noise rejection possible with differential circuitry.

- The circuit does not include dc in the frequency response. By definition, transformer T1 isolates dc and limits the ac response of the circuit.

Figure 13.   Improved Differential A/D Interface
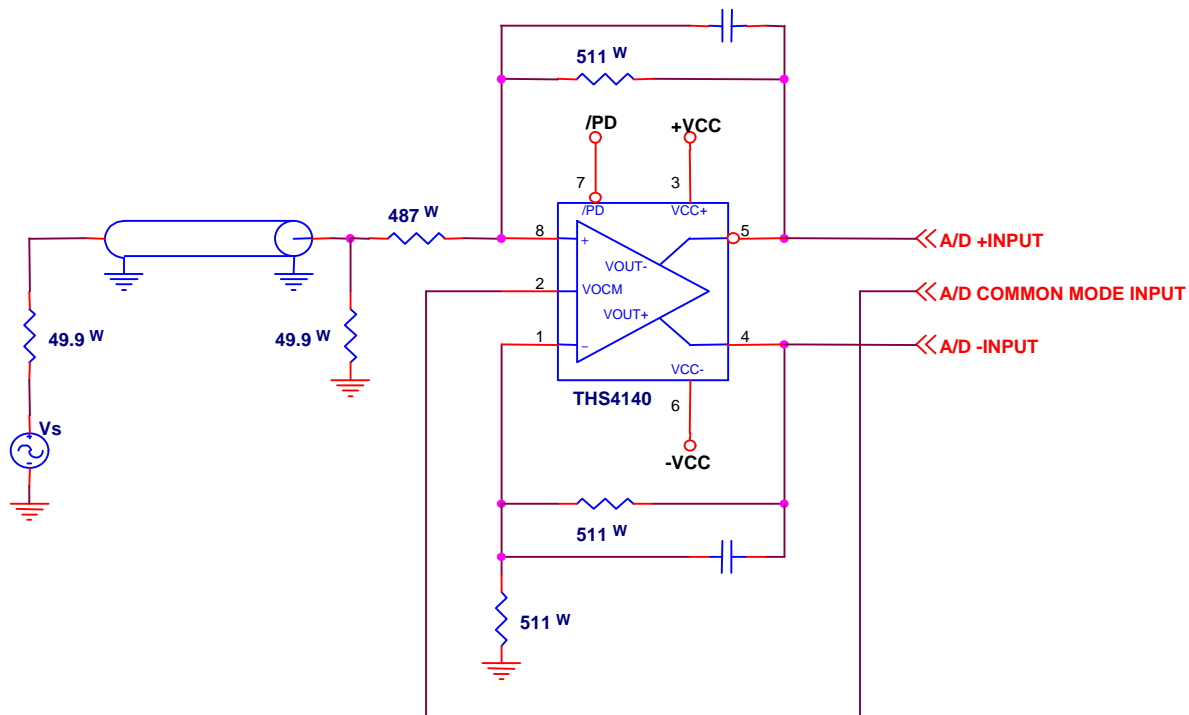
Figure 13 shows an improved A/D Interface. A differential-output op amp, the THS 4140, has been substituted for the single-ended op amp. This allows the transformer to be eliminated. The main advantage of this circuit is that it includes dc in the frequency range; in other words, it is dc accurate.

5   Putting It All Together: Selecting the Right High-Speed Op Amp

With this background, a designer now should be in a better position to make a good decision about which high-speed op amp is right for a given application. In this section, some suggestions are made about which particular op amp to select. The selections are not intended to be exclusive because (a) any application may contain additional constraints that would lead to a better choice, and (b) new devices will become available after publication of this note.

5.1   Any Differential Load

For differential loads, use THS413X, THS414X, or THS415X.

5.2   High Speed

Table 2 is a guide for the application of high-speed op amps. The best parameters are in bold face type. If your application needs:

- A current-feedback op amp: Use 3001

- A dual op amp: All op amps except for the 3001 and 4001 are available in dual packages.

- Offset trimming: The op amps listed that are available as single devices have nulling inputs, except the THS3001.

- To operate from a single 5-V supply: Use 4001.

- To drive capacitive loads: Use the 404X. Any op amp can do this if compensated correctly, however.

- For video applications: Use 4011.

- Low noise: Use 3001, 402X, or 403X.

- Fast settling time: Use 4011.

- Low THD: Use 3001.

- High load drive: Use 6002, 6012, 6022, or 6032.

- Low quiescent power consumption: Use 408X.

Parameter	THS3001	THS4001	THS4011/2	THS4021/2	THS4031/2	THS4041/2	THS4051/2	THS4061/2	THS4081/2
Speed (MHz)	420	270	290	350	100	165	70	180	175
Slew rate V/μs	6500	400	310	470	100	400	240	400	230
Settling time (ns)	40	40	37	40	60	120	60	40	43
Differential gain (%)	0.01	0.04	0.006	0.02	0.02	0.01	0.01	0.02	0.01
Differential phase angle (Deg.)	0.02	0.15	0.01	0.08	0.03	0.01	0.01	0.02	0.05
Output drive (mA)	100	100	110	100	90	100	100	115	85
Distortion dBc 1 MHz, 150	−96	−72	−80	−68	−72	−75	−82	−72	−64
Noise nV/rtHz	1.6	12.5	7.5	1.5	1.6	14	14	14.5	10
Quiescent Current per amplifier (mA)	6.6	7.8	7.8	7.8	8.5	8	8.5	7.8	3.4

Table 2.   High-Speed Op Amp Parameters

References:

1. *Voltage Feedback vs Current Feedback Op Amps*, James Karki, Texas Instruments, Literature Number SLVA051.

2. *Stability Analysis of Voltage-Feedback Op Amps Including Compensation Techniques*, Ron Mancini, Texas Instruments, Literature Number SLOA020.

3. *THS1050/1060 EVM User's Guide*, Texas Instruments Literature Number SLAU044A.

4. *High-Speed Amplifier Data Book*, Texas Instruments Literature Number SLOD005.

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