Using a decompensated op amp for improved performance

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Introduction

If your application requires optimum noise, slew rate, and distortion performance, you may want to use a decompensated or uncompensated op amp.

The THS4011 op amp uses emitter degeneration and dominant pole compensation to compensate the amplifier internally so that external compensation is not required. Placing resistors in the emitter leads of a differential amplifier pair results in negative feedback, which reduces the gain of the stage. This is referred to as emitter degeneration. A capacitor placed in the intermediate stage of the amplifier provides dominant pole compensation.

Figure 1. Open-loop gain and phase—THS4011 and THS4021

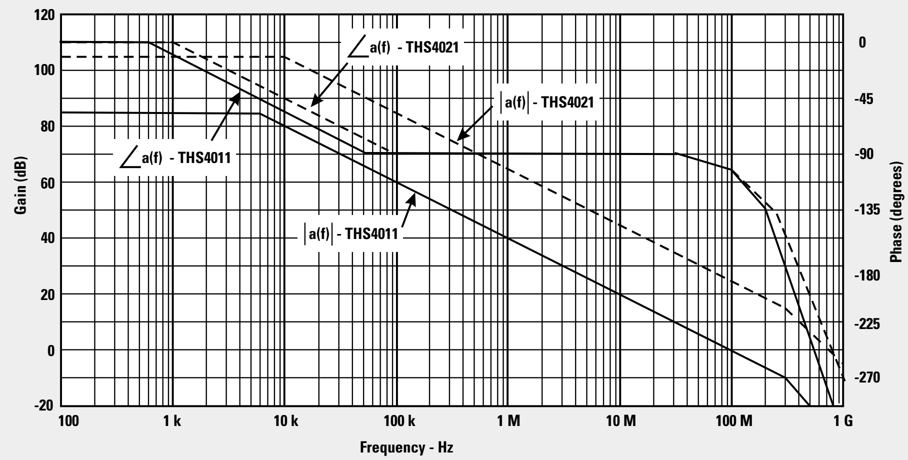
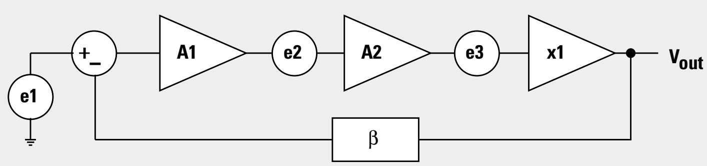


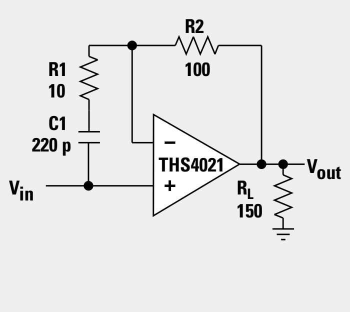
Figure 2. Model of op amp with negative feedback



$$V_{out} = \frac{e1\,A1\,A2}{1 + A1\,A2\,\beta} + \frac{e2\,A2}{1 + A1\,A2\,\beta} + \frac{e3}{1 + A1\,A2\,\beta}$$

Figure 3. Externally compensated THS4021—non-inverting amplifier

Circuit a



$$\beta = \frac{1 + sC1R1}{1 + sC1(R1 + R2)}$$

$$\frac{V_{out}}{V_{in}} = \frac{1}{1 + \frac{1}{a(f)\beta}} = 1 \text{ if } a(f)\beta >> 1$$

The THS4021 does not use emitter degeneration in the input pair, and the dominant pole capacitance is reduced. The THS4021 is termed a decompensated op amp. Decompensation means the compensation is reduced, as opposed to uncompensated, where no compensation at all is used. The result is:

- higher open-loop gain,
- increased slew rate,
- lower input referred noise, and
- required external compensation for unity gain stability.

Figure 1 shows the open-loop gain, magnitude $|a(f)|$ and phase $\angle a(f)$, of the THS4011 and THS4021. Note that $|a(f)|$ is about 20 dB higher for the THS4021; and note the two spots on the graph where, for THS4011,

$|a(f)| = 0$ dB and $\angle a(f) \approx -105°$

and, for THS4021,

$|a(f)| = 20$ dB and $\angle a(f) \approx -130°$

So the THS4011 has 75° of phase margin at a closed-loop gain of +1 and requires no external compensation. The THS4021 has 50° of phase margin when compensated by giving it a closed-loop gain of +10 (or –9). If a gain lower than this is required, another means of compensation is used.

This article shows how to compensate the THS4021 externally for stable operation while maintaining a closed-loop gain of +1 or –1. To compare distortion, transient response, and noise performance, the THS4011 and THS4021, with external compensation, are tested. Also, practical component selection is considered. A quick presentation about feedback is given, but it is assumed that the reader is familiar with feedback theory, stability criteria, and compensation. If not, please see References 1 and 2.

Feedback and errors

Feedback theory predicts that error sources within an amplifier are reduced if the loop gain is increased.

Figure 2 shows a model of an op amp with negative feedback. The input stage is A1, the intermediate stage is A2, the output stage is the x1 buffer, and β is the feedback factor. The open-loop gain is a(f) = A1A2, and the loop gain is a(f)β = A1A2β. e1, e2, and e3 are generalized error sources within the op amp. The following discussion analyzes the output response due to the individual error sources.

e1 represents an error source at the input. It is amplified by the full open-loop gain of the amplifier. Setting all other sources to 0, if there were no feedback, V_{out} = e1A1A2, but with feedback,

$$V_{out} = \frac{e1}{\beta + \frac{1}{A1A2}} \approx \frac{e1}{\beta} \quad \text{if } A1A2 >> 1$$

e2 represents an error source at the intermediate stage. It is amplified only by A2. Setting all other sources to 0, if there were no feedback, V_{out} = e2A2, but with feedback,

$$V_{out} = \frac{e2}{A1\beta + \frac{1}{A2}} \approx \frac{e2}{A1\beta} \quad \text{if } A2 >> 1$$

e3 represents an error source at the output stage. It is buffered by a gain of +1 to the output. Setting all other sources to 0, if there is no feedback, V_{out} = e3, but with feedback,

$$V_{out} = \frac{e3}{1 + A1A2\beta} \approx 0 \quad \text{if } A1A2\beta >> 1$$

In general, feedback has no effect on reducing errors generated at the input, but it becomes effective with errors generated within the amplifier and is most effective in reducing errors at the output. By taking advantage of the increased open-loop gain of the THS4021, one can expect to reduce distortion products generated in the intermediate and output stages of the op amp.

Test circuits

Figures 3–7 show the test circuits. Circuits a, b, and c show the THS4021 with external

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Figure 4. Two-capacitor, externally compensated THS4021—inverting amplifier

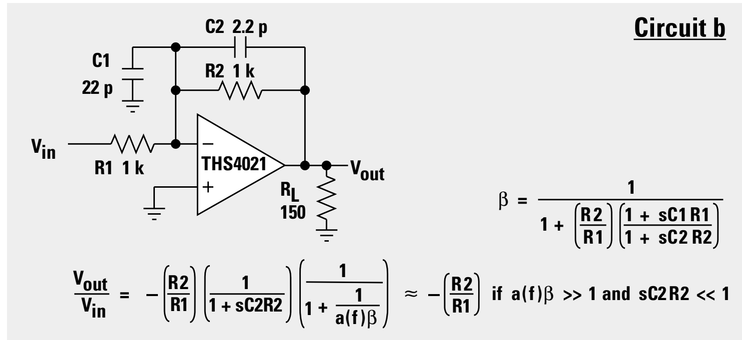


Figure 5. One-capacitor, externally compensated THS4021—inverting amplifier

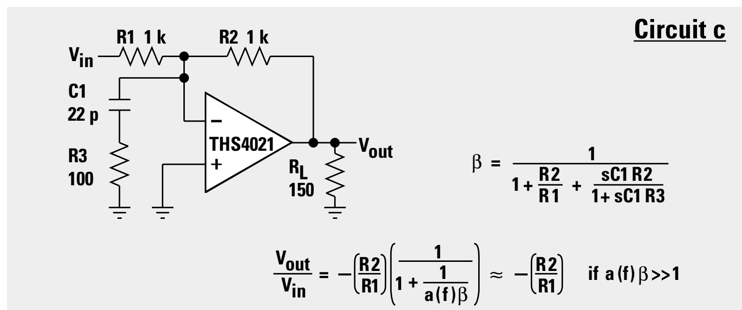


Figure 6. Internally compensated THS4011—non-inverting amplifier

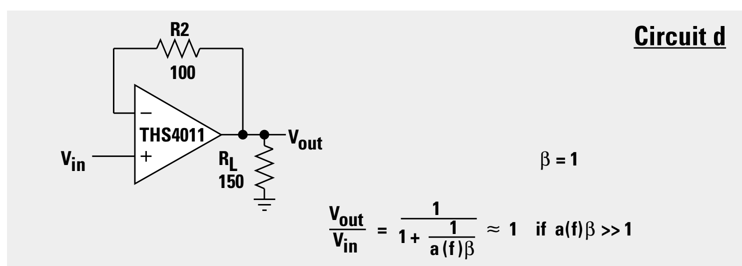
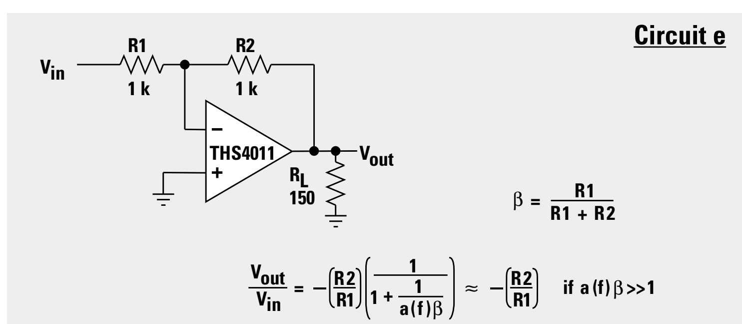


Figure 7. Internally compensated THS4011—inverting amplifier



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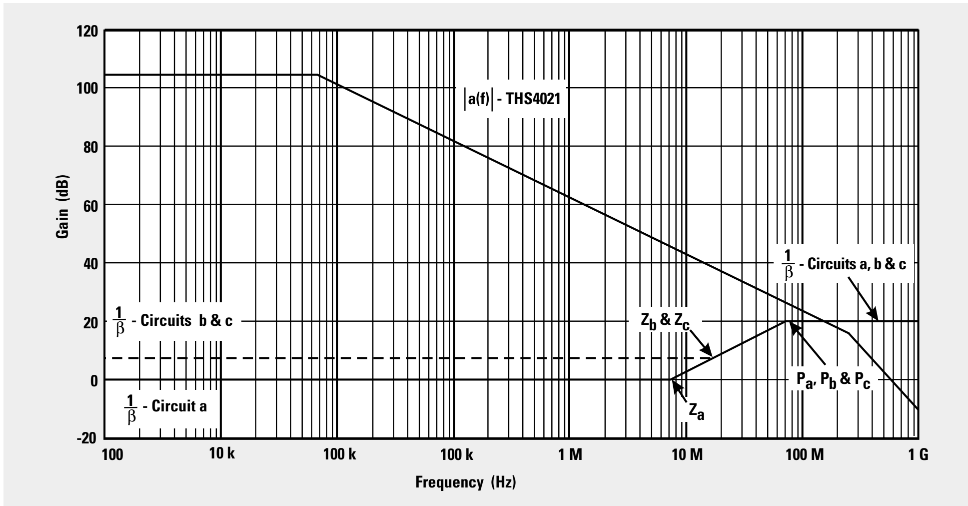
compensation. Circuits d and e show the THS4011. All circuits have ideal gains of either +1 or –1. The test data presented later is based on testing these circuits with the component values shown.

Figure 8. Bode plot of open-loop and inverse feedback factors of test circuits



Analysis

In order to determine stability of circuits a, b, and c, we are interested in the loop gain, a(f)β, of the circuits. Figure 8 shows a Bode plot of the open-loop gain, a(f), of the THS4021 op amp and the inverse of the feedback factor, 1/β.

a(f)β can be seen graphically on the Bode plot as the difference between the a(f) and 1/β curves. Stability is indicated by the rate of closure at the intersection of a(f) and 1/β.

Figure 9 shows the same information from a slightly different view, with magnitude and phase of a(f)β. This makes it easier to determine phase margin—approximately 45°.

Design

Design means choosing the placement of the poles and zeros in the feedback network. The following equations apply to the points noted on the Bode plot in Figure 8.

Circuit a: $Z_a = \dfrac{1}{2\pi C1(R1+R2)}$ and $P_a = \dfrac{1}{2\pi C1R1}$

Circuit b: $Z_b = \dfrac{2}{2\pi C1R1}$ and $P_b = \dfrac{1}{2\pi C2R2}$

(given R1 = R2)

Circuit c: $Z_c = \dfrac{2}{2\pi C1R2}$ and $P_c = \dfrac{1}{2\pi C1R3}$

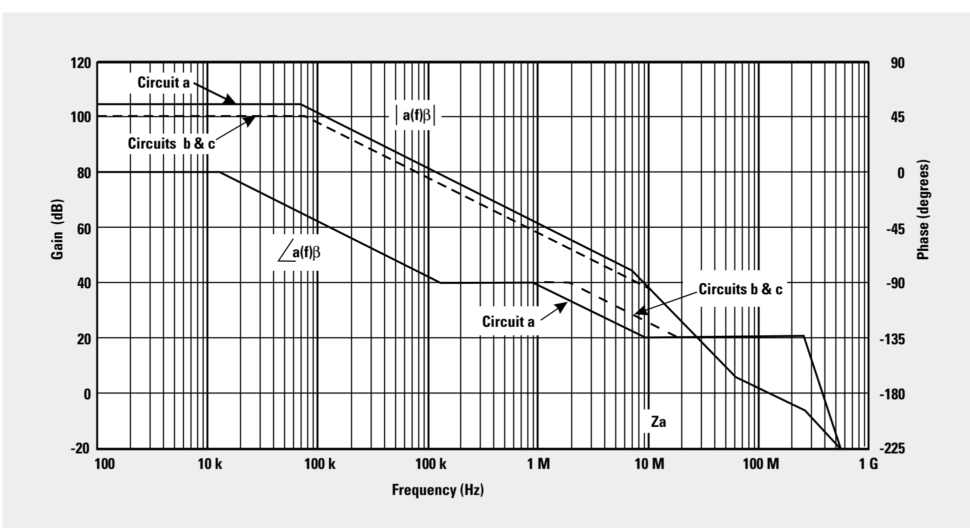
(given R1 = R2)

The poles and zeros are chosen to obtain the largest possible excess loop gain over the maximum frequency range and still maintain stability. The feedback must be reduced at high frequency in the externally compensated circuits so that 1/β = 20 dB at the point where it intersects a(f). This satisfies the minimum gain of 10 requirement for stability for the THS4021. That is to say, what is really meant by specifying a minimum gain of 10 is that 1/β ≥ 10 (or 20 dB) at its intersection with a(f).

Start the design by choosing the pole location and be sure to give a margin for process variations. In the examples shown here, the pole is chosen at about half the frequency at which a(f) equals the minimum gain specification (20 dB). The component values are calculated, and then convenient standard values are selected.

Once the pole is located, the zero is found by dividing the pole frequency by the difference between minimum gain specification of the amplifier and 1/β at low frequency—i.e.,

Figure 9. Bode plot of magnitude and phase of a(f)β—Circuits a, b, and c



$$Z_a = \frac{P_a}{10^{\frac{20}{20}}},\ Z_b = \frac{P_b}{10^{\frac{14}{20}}},\ \text{and}\ Z_c = \frac{P_c}{10^{\frac{14}{20}}}$$

Alternately, you can look at the circuits with a little intuition and arrive at the following relationships: In Circuit a, the high-frequency feedback factor is set by the ratio of R1 to R2. Therefore R1 = R2/10. In Circuit b, the high-frequency feedback factor is set by the ratio of C1 to C2. Therefore C1 = C2 x 10. In Circuit c, the high-frequency feedback factor is set by the ratio of R1 || R3 to R2. Therefore R3 = R2/10. So once the pole is located, the complete solution is quickly found.

Component selection

Selection of component values should be looked at with an eye to practicality. Since the amplifiers are high-speed, capable of operation into the hundreds of MHz, resistance values need to be kept low so that parasitic capacitors do not overly influence results. The designer should be careful about resistor values that are too low, which will load the amplifier too much. The following comments are based on observations made while testing the circuits.

- In Circuit a, feedback resistor values in the range of 100 Ω to 500 Ω provided the best results. Values of 49.9 Ω and 1 kΩ resulted in diminished performance.
- In Circuits b and c, feedback resistor values in the range of 200 Ω to 1 kΩ provided the best results. A value of 100 Ω resulted in diminished performance. Values above 1 kΩ result in capacitor values that are too small (less than 2.2 pF*) and were not tested.

*Approximately 0.6-pF parasitic is measured across the feedback so that parasitic capacitance on the EVM becomes a significant percent when low-value capacitors are used.

THD

The next question to answer is what actually happens when the circuits are tested in the lab. The circuits are built and tested using the THS4011 and THS4021 EVMs, available from Texas Instruments. Figure 10 shows the basic test set-up used to measure THD.

The filters are sixth-order elliptic filters that have approximately 80-dB out-of-band rejection. The purpose of the low-pass filter, LPF, between the generator and the test circuit is to reject harmonics coming from the sine generator. The high-pass filter, HPF, between the test circuit and the spectrum analyzer is there to reject the high-amplitude fundamental and to prevent generation of harmonics in the input circuitry of the spectrum analyzer. Table 1 shows the fundamental frequencies and corner frequencies of the filters used.

Table 1. Filter cut-off frequencies

FUNDAMENTAL (Hz)	LPF (Hz)	HPF (Hz)
1 M	1.1 M	1.9 M
2 M	2.2 M	3.8 M
4 M	4.4 M	7.6 M
8 M	8.8 M	15.2 M
16 M	17.6 M	30.4 M

Figure 11 shows the test results for the non-inverting amplifiers. Circuit a has better distortion performance than Circuit d at lower frequencies, but the advantage

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Figure 10. THD test set-up

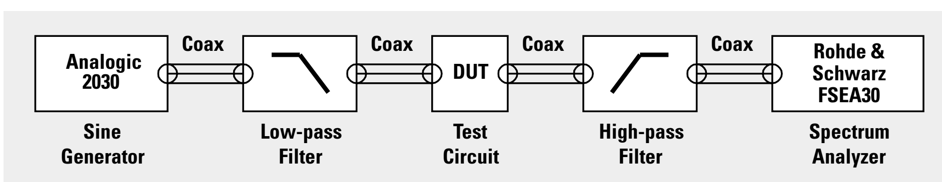
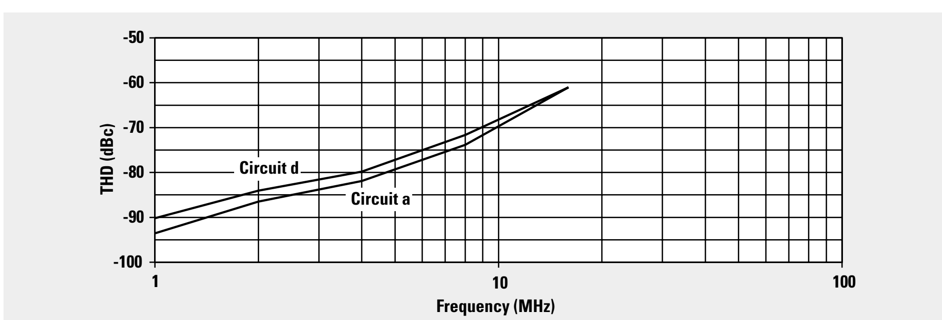


Figure 11. THD vs. frequency—non-inverting amplifiers, $V_{out} = 2V_{p-p}$



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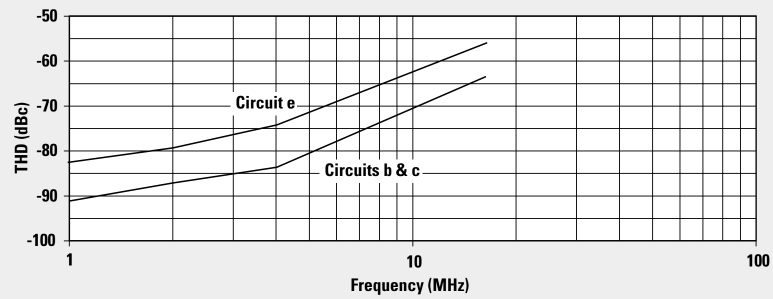
decreases at higher frequencies. Figure 12 shows the test results for the inverting amplifiers. Circuits b and c have better distortion performance than Circuit e across all the frequencies tested.

In general, the externally compensated THS4021 circuits have better distortion performance due to their increased loop gain compared to the circuits using the internally compensated THS4011.

Figure 12. THD vs. frequency—inverting amplifiers, V_{out} = $2V_{p-p}$



Transient response

Figures 13 and 14 show the transient response of Circuits a, b, d, and e resulting from a positive 2-V input pulse with 0.9-ns rise and fall times. Circuit c is not shown but is very similar to Circuit b.

Circuits a and d appear to have similar slew rates, but Circuit a responds more quickly to the input pulse. Circuit a exhibits about 30% overshoot, but settling times appear to be about the same.

Circuit b reacts more quickly to the input pulse and has approximately twice the slew rate of Circuit e. It appears to settle slightly faster as well.

Noise

The input-referenced white noise specification for the op amps is

$$\frac{1.5\,\text{nV}}{\sqrt{\text{Hz}}}$$

for the THS4021 and

$$\frac{7.5\,\text{nV}}{\sqrt{\text{Hz}}}$$

for the THS4011. Given that the circuits have essentially the same noise gain over most of the frequencies of operation and that the resistor noise is about the same, the noise performance should be 5 times better for the externally compensated circuits.

To measure the noise directly with unity gain is not very practical. For comparison purposes, noise is measured by configuring each op amp in non-inverting gain of 1000 and measuring the output with an RMS voltmeter. Figure 15 shows the test set-up.

The expected output noise is estimated by the formula:

$$\text{En} = \text{en} \times \text{A} \times \sqrt{\text{LPF}}$$

En is the RMS output noise, en is the input-referenced white noise specification for the op amp, A is the ideal closed-loop gain, and LPF is the corner frequency of the low-pass filter (137.5 kHz).

Estimated noise using the THS4011 is 2.78-mV RMS, and 2.47 mV is measured. Estimated noise using the THS4021 is 0.56-mV RMS, and 0.57 mV is measured. As expected, about a 5:1 ratio is seen.

Figure 13. Transient response—non-inverting amplifiers

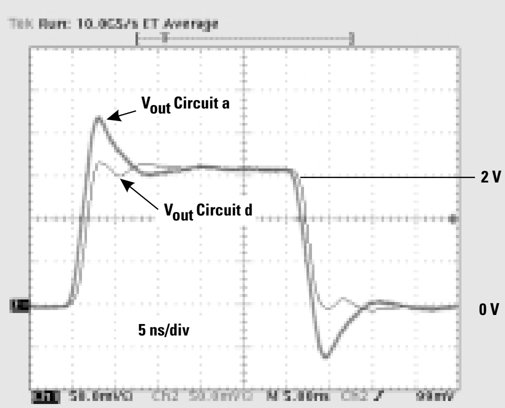
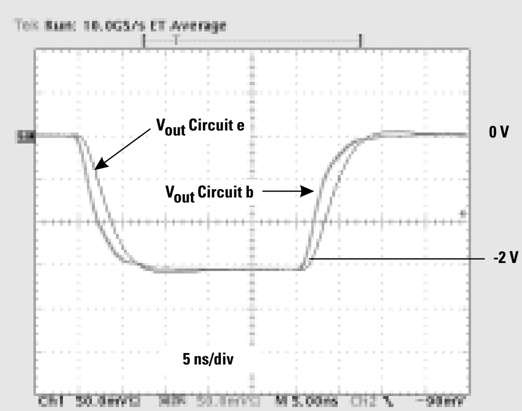


Figure 14. Transient response—inverting amplifiers



Conclusion

Five different circuits have been tested for distortion, transient response, and noise performance. By comparison of the non-inverting amplifiers, Circuit a vs. Circuit d, and inverting amplifiers, Circuits b and c vs. Circuit e, the following conclusions about using an externally compensated THS4021 vs. using the internally compensated THS4011 have been drawn (see Table 2).

In the inverting amplifiers, Circuits b and c vs. Circuit e, significant improvement in THD performance was seen across the frequencies tested. There was no significant difference between Circuits b and c.

For the non-inverting amplifiers, Circuit a vs. Circuit d, improvement in THD performance was also seen but diminished with frequency, with no advantage seen at 16 MHz.

Transient performance showed mixed results. Slew rate and settling time were somewhat better when comparing the inverting topologies but appeared to be little changed for the non-inverting amplifier. The non-inverting amplifier, Circuit a, showed considerable overshoot, which may be undesirable.

Given that the circuits have essentially the same noise gain over most of the frequencies of operation and that the resistor noise is about the same, the noise performance should be better for the externally compensated circuits. Lab data shows about a 5:1 ratio—in line with the difference in the noise specification of the op amps.

Figure 15. Noise test set-up

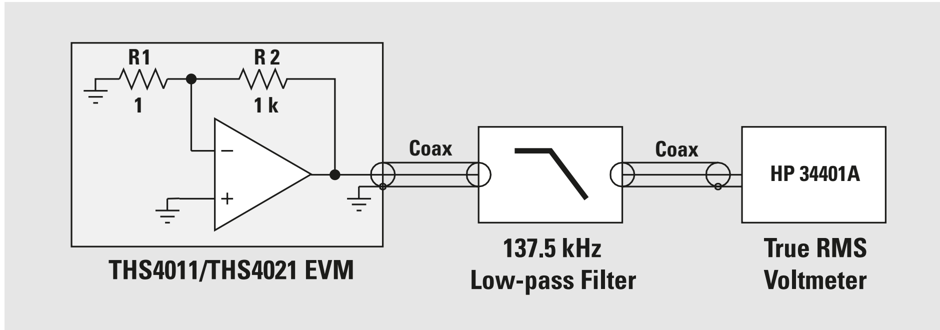


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Table 2. Comparison of test results

CIRCUIT	DESCRIPTION	TEST PARAMETER	COMMENTS
a	THS4021 non-inverting amplifier with external compensation	Distortion	4-dB improvement seen at 1 MHz with decreased improvement at higher frequencies
		Transient response	Faster initial response, but comparable slew rate and settling time
		Noise	5x improvement
b	THS4021 inverting amplifier with two-capacitor external compensation	Distortion	7- to 9-dB improvement at all frequencies tested
		Transient response	Faster initial response, slew rate, and settling time
		Noise	5x improvement
c	THS4021 inverting amplifier with one-capacitor external compensation	Distortion	7- to 9-dB improvement at all frequencies tested
		Transient response	Faster initial response, slew rate, and settling time
		Noise	5x improvement

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