

Using a Decompensated Operational Amplifier for Improved Performance

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ABSTRACT

Decompensated operational amplifiers have improved noise, slew rate, harmonic distortion, etc., but required external compensation for stable operation. This report shows how to compensate such an amplifier and achieve the performance enhancement it provides in a unity-gain configuration.

The THS4011 and THS4021 operational amplifiers are used to illustrate the superior performance mentioned above. These operational amplifiers use the same basic structure. The THS4011 is internally compensated to be stable at unity gain without any need for external compensation, whereas the internal compensation of the THS4021 is relaxed, making external compensation necessary.

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1 Introduction

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

While writing this article, I talked with a colleague of mine about it, and his first response was *What do you mean by decompensated? I know what an uncompensated operational amplifier is, but I never heard of a decompensated operational amplifier.* With this in mind, I will start by explaining what I mean by a decompensated amplifier.

Uncompensated operational amplifiers have no internal compensation, and the parasitic elements that shape their higher frequency operation are left unchecked. This places the burden of compensation on the circuit designer.

The term *compensated amplifier* is used to describe an operational amplifier that is designed with internal compensation so that it is unity-gain stable ($G = +1$). Sometimes they are referred to as *unconditionally-stable* because unity gain requires the most compensation.

Decompensated lies somewhere between the uncompensated and compensated. Various IC manufacturers make decompensated operational amplifiers—especially in the high-speed amplifier market. External means are required for stable operation: gain compensation is the easiest and most straight forward. With enough close-loop gain, the inverse feedback factor intersects the open-loop gain curve at a frequency where the phase shift is less than 180° and the amplifier is stable. (The feedback factor is the transfer function from output to negative input, and is denoted by the Greek letter β .) For this reason, the manufacturer typically recommends a minimum amplifier gain for stable operation.

The THS4011 operational amplifier uses emitter-degeneration and dominant-pole compensation to internally compensate the amplifier 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.

The THS4021 does not use emitter degeneration in the input pair, and the dominant-pole capacitance is reduced. The THS4021 is termed a decompensated operational amplifier. Decompensation is a reduction in compensation, as opposed to uncompensation, where no compensation at all is used. The results are:

- Higher open-loop gain
- Increased slew rate
- Lower input-referred noise
- External compensation required 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 the two spots on the graph where:

- THS4011 – $|a(f)| = 0$ dB and $\angle a(f) \approx -105^\circ$
- THS4021 – $|a(f)| = 20$ dB and $\angle a(f) \approx -130^\circ$

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). Other means of compensation should be used when a lower gain is required.

One of the best reasons to use a decompensated amplifier is when there is a requirement for higher-gain circuits. The gain of the circuit is all that is required to compensate for stable operation.

Both amplifiers exhibit a constant-gain bandwidth product over most frequencies of operation, which is typical of voltage-feedback operational amplifiers. If your application requires a gain of 10 or more, using the THS4021 instead of the THS4011 results in over ten times more bandwidth. Other key performance enhancements of note in high bandwidth applications are noise reduction by a factor of 5, and slew rate increases by 1.5.

The case where a gain of 10 or more is required seems obvious; but if the gain required is less than 10, how do you use a decompensated operational amplifier and why would you want to? Examining these questions is the main purpose of this article. Methods that can be used to externally compensate the THS4021 for closed loop gains of +1 or –1 are examined. Performance of the externally compensated THS4021 is compared to the THS4011. A quick presentation of feedback is given, but it is assumed the reader is familiar with feedback theory, stability criteria, and compensation. If not, please refer to the application reports *Feedback Amplifier Analysis Tools*, literature number SLOA017 and *Stability Analysis of Voltage-Feedback Op Amps*, literature number SLOA020 from Texas Instruments.

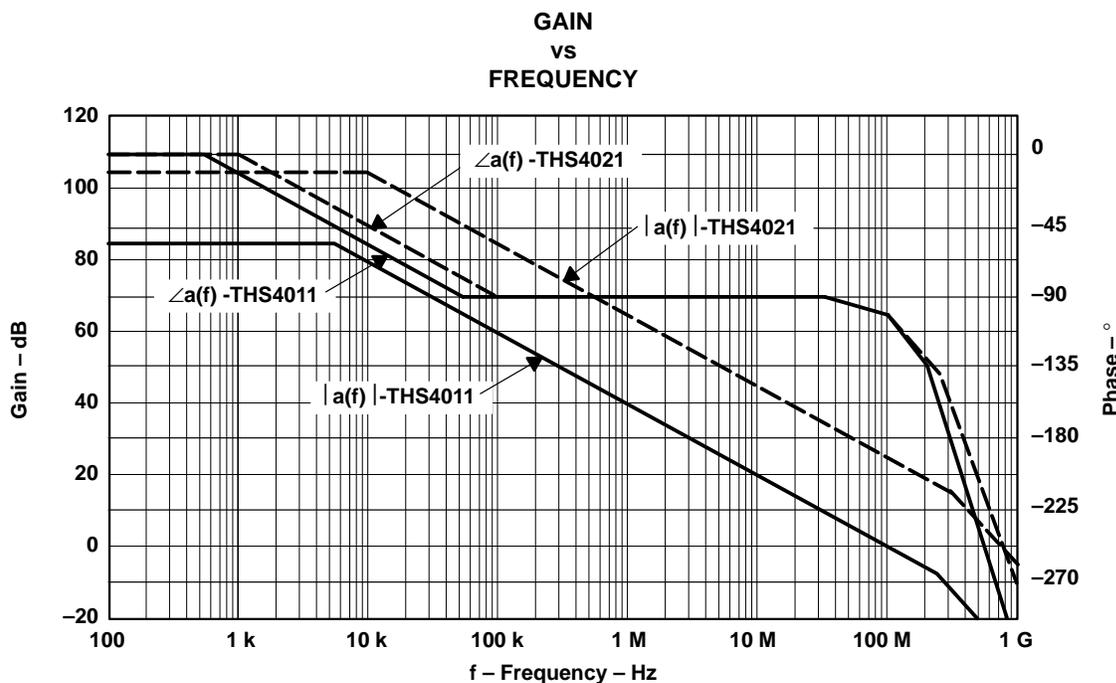


Figure 1. Open-Loop Gain and Phase – THS4011 and THS4021

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 operational amplifier with negative feedback. The input stage is A1, the intermediate stage is A2, the output stage is a x1 buffer, and β is the feedback factor. The open-loop gain is $a(f) = A1A2$, the loop gain is $a(f)\beta = A1A2\beta$, and $e1$, $e2$, and $e3$ are generalized-error sources within the operational amplifier. 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. When all other sources are set to 0:

With no feedback, $V_{out} = e1A1A2$,

but with feedback,

$$V_{OUT} = \frac{e1}{\beta + \frac{1}{A1A2}} \approx \frac{e1}{\beta} \text{ if } A1A2 \gg 1$$

$e2$ represents an error source at the intermediate stage. This error is amplified only by A2. Setting all other sources to 0:

With no feedback, $V_{out} = e2A2$,

but with feedback,

$$V_{OUT} = \frac{e2}{A1\beta + \frac{1}{A2}} \approx \frac{e2}{A1\beta} \text{ if } A2 \gg 1$$

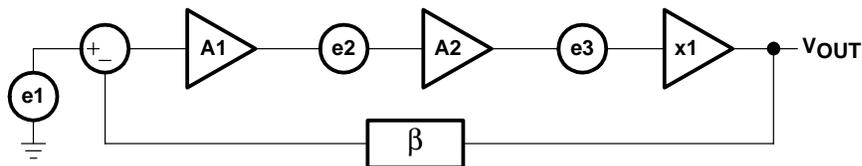
e_3 represents an error source at the output stage. It is buffered by a gain of +1 to the output. Setting all other sources to 0:

With no feedback, $V_{out} = e_3$,

but with feedback,

$$V_{OUT} = \frac{e_3}{1 + A_1A_2\beta} \approx 0 \text{ if } A_1A_2\beta \gg 1$$

Distortion is proportional to the amplitude of the signal, and is mainly attributed to the output stage. By taking advantage of the increased open-loop gain (or forward gain) of the THS4021, distortion should be reduced. On the other hand, noise is expected to remain unaffected by the increased gain since it is generally attributed to the input.



$$V_{OUT} = \frac{e_1A_1A_2}{1 + A_1A_2\beta} + \frac{e_2A_2}{1 + A_1A_2\beta} + \frac{e_3}{1 + A_1A_2\beta}$$

Figure 2. Model of Operational Amplifier With Negative Feedback

3 Test Circuits

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

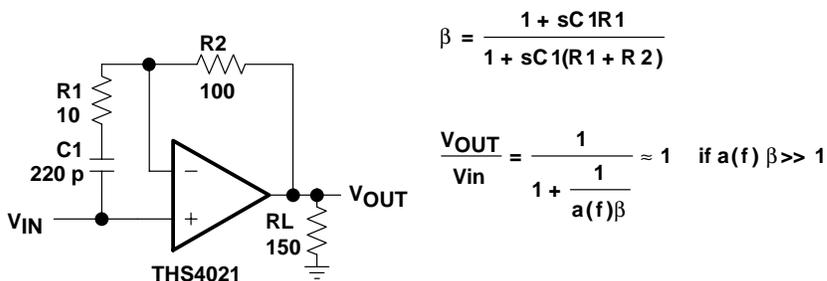


Figure 3. Circuit a: Externally-Compensated THS4021 – Noninverting Amplifier

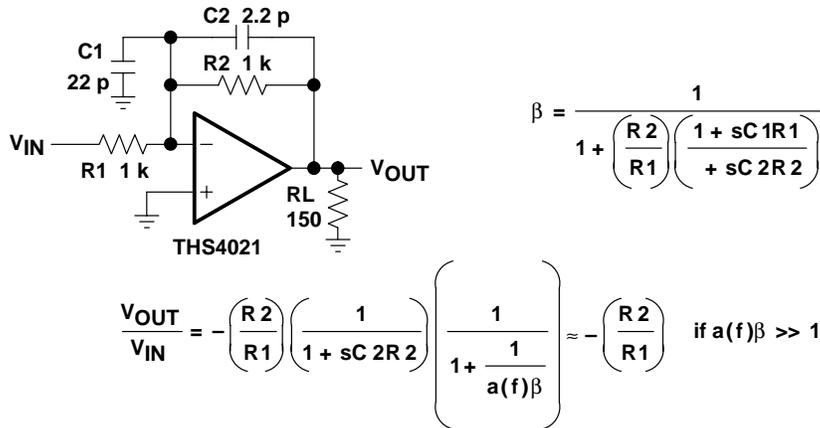


Figure 4. Circuit b: Two-Capacitor, Externally-Compensated, THS4021 – Inverting Amplifier

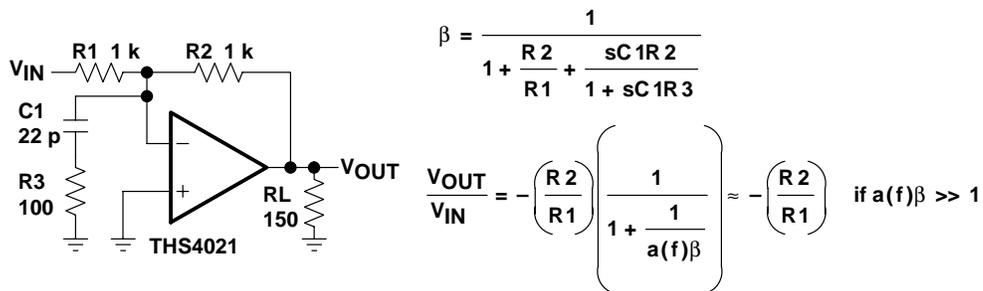


Figure 5. Circuit c: One-Capacitor, Externally-Compensated, THS4021 – Inverting Amplifier

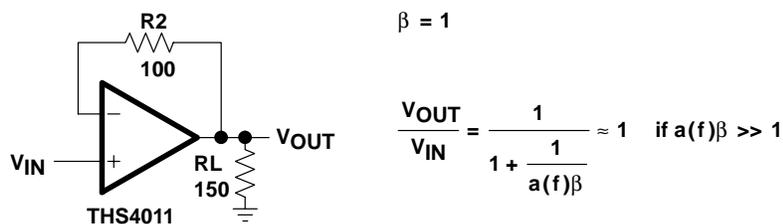


Figure 6. Circuit d: Internally-Compensated THS4011 – Noninverting Amplifier

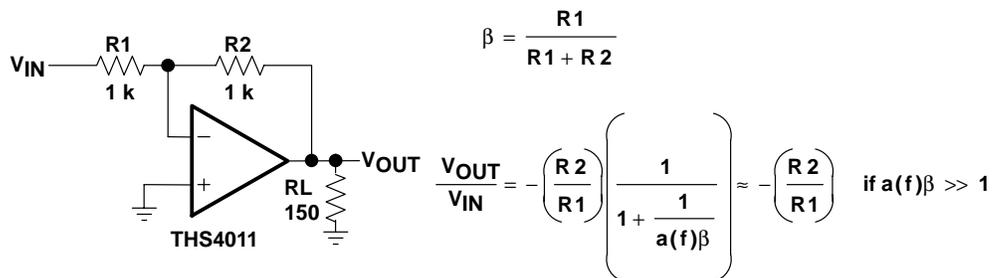


Figure 7. Circuit e: Internally-Compensated THS4011 – Inverting Amplifier

4 Analysis

In order to determine the stability of circuits a, b, and c, we should focus on the loop gain $a(f)\beta$ of the circuits. Figure 8 is a straight-line approximation of spice simulation of the open-loop gain magnitude $a(f)$ of the THS4021 operational amplifier and the inverse of the feedback factor, $\frac{1}{\beta}$.

$a(f)\beta$ can be seen graphically on the plot as the difference between the $a(f)$ and $\frac{1}{\beta}$ curves.

Stability is indicated by the rate of closure at the intersection of $a(f)$ and $\frac{1}{\beta}$.

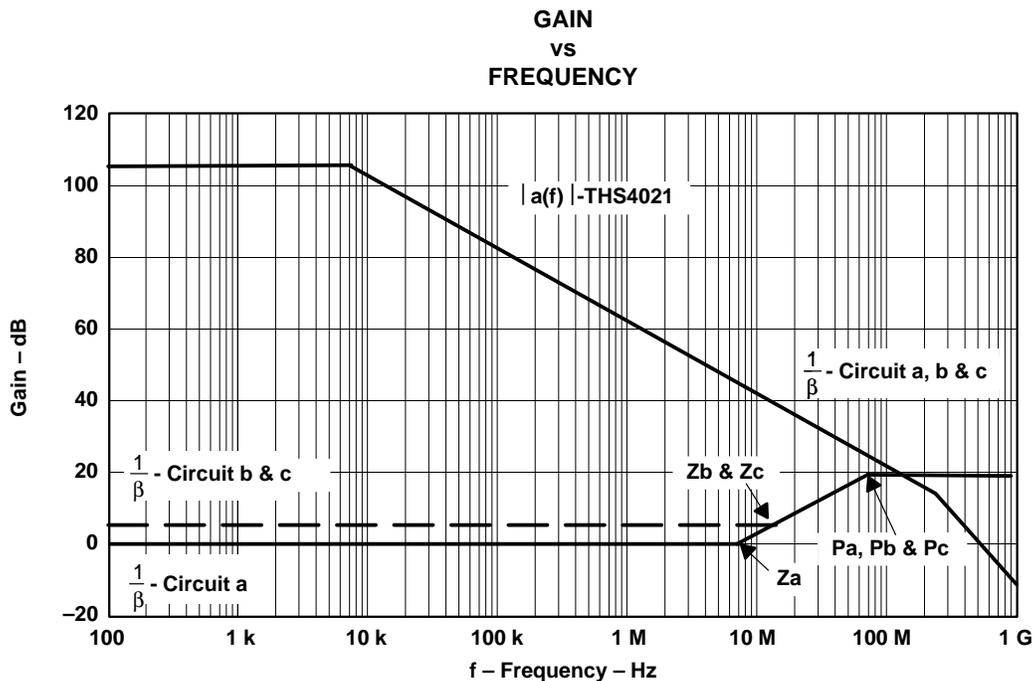


Figure 8. Plot of Open-Loop and Inverse-Feedback Factors of Test Circuits

Figure 9 shows the same information from a slightly different view—the magnitude and phase of $a(f)\beta$ (also a straight-line approximation of spice simulation). This makes it easier to determine phase margin—approximately 45° . Spice simulation is used because of the complex interaction of the high-frequency poles and zeroes.

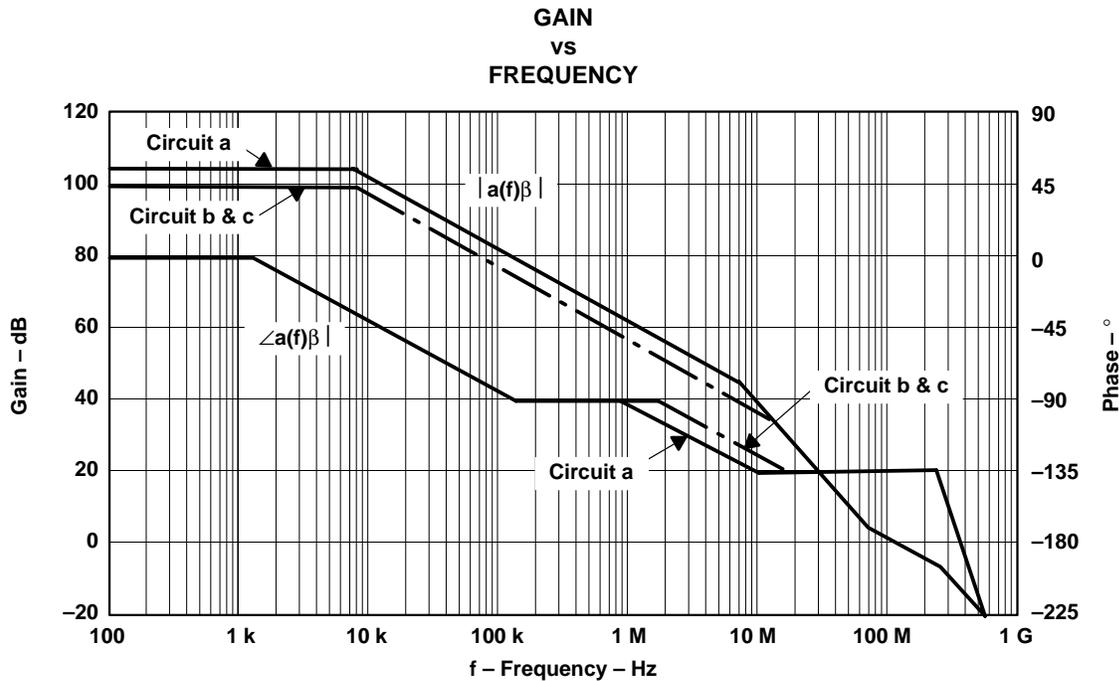


Figure 9. Plot of Magnitude and Phase of $|a(f)\beta|$ – Circuits a, b, and c

5 Design

The design is done by choosing the placement of the poles and zeroes in the feedback network. The following equations apply to the points noted on the Bode plot in Figure 8.

Circuit a:

$$Z_a = \frac{1}{2\pi C_1(R_1 + R_2)}, \text{ and } P_a = \frac{1}{2\pi C_1 R_1}$$

Circuit b:

$$Z_b = \frac{2}{2\pi C_1 R_1}, \text{ and } P_b = \frac{1}{2\pi C_2 R_2} \text{ (given } R_1 = R_2)$$

Circuit c:

$$Z_c = \frac{2}{2\pi C_1 R_2}, \text{ and } P_c = \frac{1}{2\pi C_1 R_3} \text{ (given } R_1 = R_2)$$

The poles and zeroes 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 frequencies in the externally-compensated circuits so that $\frac{1}{\beta} = 20$ dB at the point where it intersects $a(f)$. This satisfies the minimum-gain-of-10 requirement for stability of the THS4021. That is to say, the specification of a minimum gain of 10 implies that $\frac{1}{\beta} \geq 10$ (or 20 dB) at its intersection with $a(f)$.

Start the design by choosing the pole location, and be sure to allow a margin for process variations. In the examples shown here, the pole is chosen at about 1/2 the frequency at which a(f) is equal to the minimum gain specification of 20 dB. The component values are calculated, and convenient standard values are then selected.

Once the pole is located, the zero is found by dividing the pole frequency by the difference between the minimum-gain specification of the amplifier and $\frac{1}{\beta}$ at low frequency; that is,

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

Alternately, you can observe the circuits and arrive at the following relationships:

In circuit a, the high-frequency feedback factor is set by the ratio of R1 to R2. Therefore

$$R_1 = \frac{R_2}{10}.$$

In circuit b, the high-frequency feedback factor is set by the ratio of C1 to C2. Therefore $C_1 = C_2 \times 10$.

In circuit c, the high-frequency feedback factor is set by the ratio of R1 || R3 to R2. Therefore

$$R_3 = \frac{R_2}{10}.$$

So once the pole is located, the complete solution can be quickly found.

6 Component Selection

Selection of component values should be looked at with an eye to practicality. Since the amplifiers are high speed and capable of operating into the hundreds of megahertz, resistance values need to be kept low so that parasitic capacitors do not overly influence the results. Yet, care should be taken that resistor values are not too low that they may present excessive load to the amplifier. 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. 100 Ω resulted in diminished performance. Values above 1 kΩ resulted in capacitor values that were too small (less than 2.2 pF) and were not tested.

7 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 setup used to measure THD.

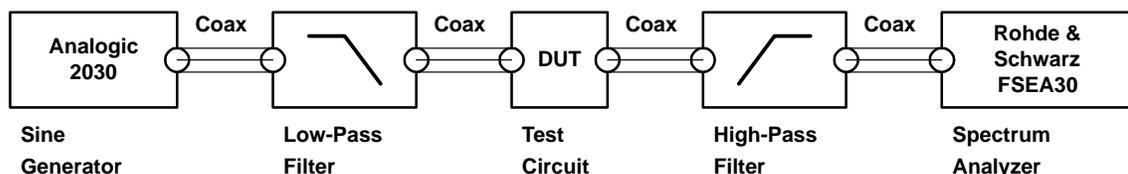


Figure 10. THD Test Setup

The filters that are used 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 used 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 the corner frequencies of the filters used:

Table 1. Filter Cutoff Frequencies

Fundamental (MHz)	LPF (MHz)	HPF (MHz)
1	1.1	1.9
2	2.2	3.8
4	4.4	7.6
8	8.8	15.2
16	17.6	30.4

Figure 11 shows the test results for the noninverting amplifiers. Circuit a has better distortion performance than circuit d at lower frequencies, but the advantage decreases at higher frequencies. Figure 12 shows the test results for the inverting amplifiers. Circuits b and c have better distortion performance across all the frequencies tested than circuit e.

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.

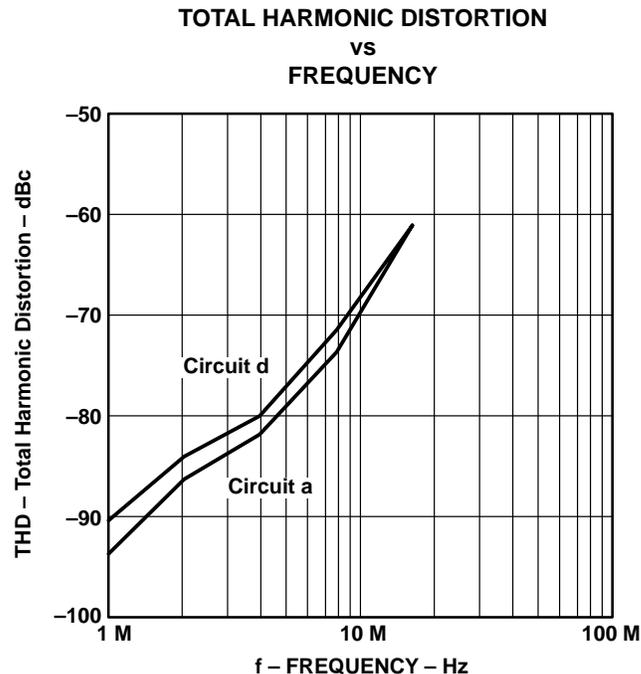


Figure 11. THD vs Frequency – Noninverting Amplifiers, $V_{OUT} = 2 V_{p-p}$

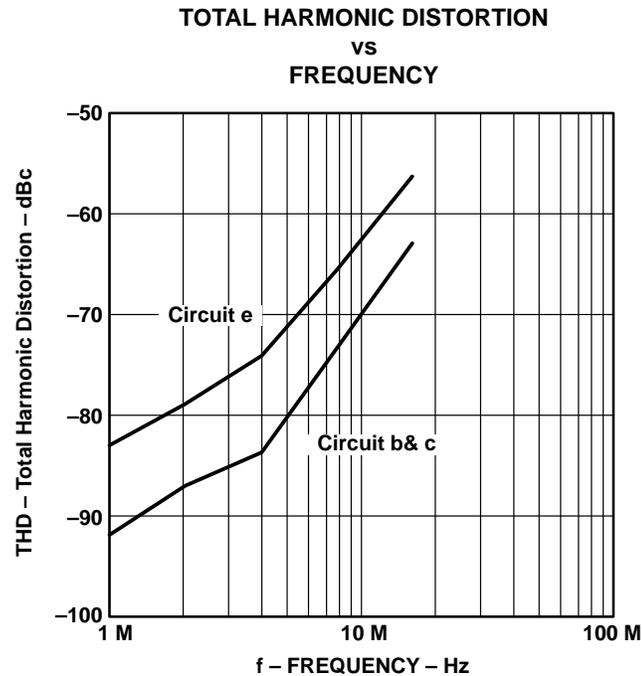


Figure 12. THD vs Frequency – Inverting Amplifiers, $V_{OUT} = 2\text{ Vp-p}$

8 Transient Response

Figures 13 and 14 show the transient response of circuits a, b, d, and e with an input-pulse signal ranging from -0 V to 2 V and 0.9-ns rise and fall times. Circuit c is not shown, but it 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 for both circuits appear to be comparable.

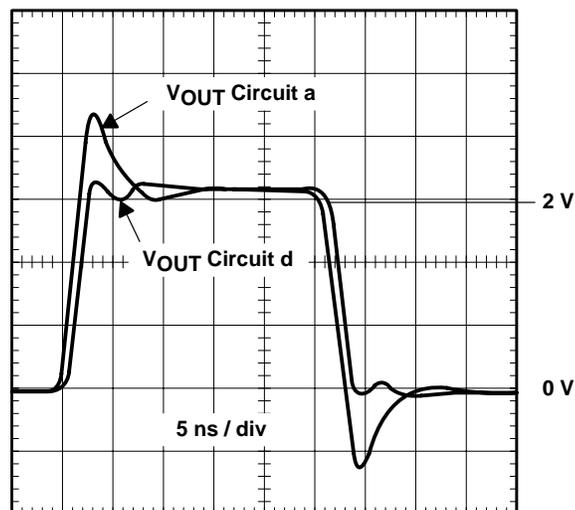


Figure 13. Transient Response – Noninverting Amplifiers

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

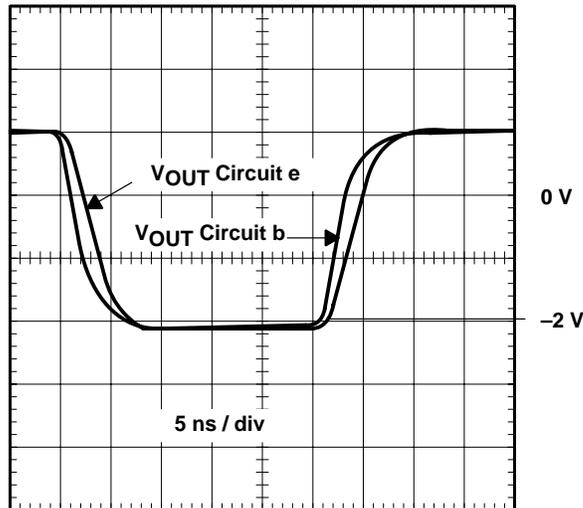


Figure 14. Transient Response – Inverting Amplifiers

9 Noise

The input-referenced white-noise specification for the operational amplifiers 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 five-times better for the externally-compensated circuits.

To directly measure the noise with unity gain is not very practical. For comparison purposes, noise is measured by configuring each operational amplifier with a noninverting gain of 1000 and measuring the output with a RMS voltmeter. Figure 15 shows the test setup.

The expected output noise is estimated by the formula: $E_n = e_n \times A \times \sqrt{\text{LPF}}$. E_n is the RMS output noise, e_n is the input-referenced white noise specification for the operational amplifier, A is the ideal closed-loop gain, and LPF is the corner frequency of the low-pass filter (137.5 kHz).

Using the THS4011 the noise is estimated to be 2.78 mV_(RMS), while the measured value is 2.47 mV_(RMS). Using the THS4021 the noise is estimated to be 0.56 mV_(RMS), while the measured value is 0.57 mV_(RMS). As expected, a ratio of about 5:1 is found.

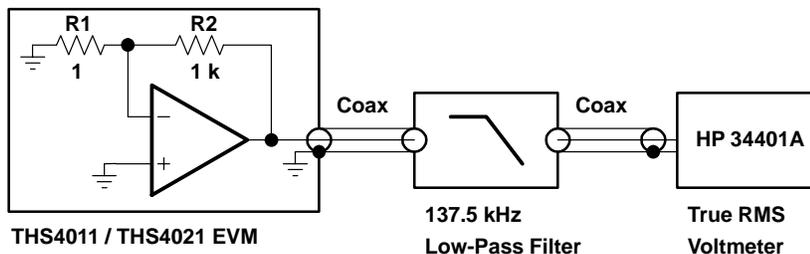


Figure 15. Noise Test Setup

This comparison of noise is valid for higher-gain circuits, but is not valid in the cases under consideration, where unity gain is desired. In the circuits shown in Figures 4, 5, and 6, the gain is unity at low frequency, but increases at high frequency. The gain breaks at 7 MHz from a gain of 1 or 2 to a gain of 10 at 70 MHz. Considering the noise over a 100-MHz bandwidth, the THS4011 circuit with gain of +1 will have about 1/2 the output noise as the other circuits.

10 Conclusion

The most obvious application to use a decompensated amplifier is in higher gain circuits. In applications with gains of 10 or more, using the THS4021 instead of the THS4011 results in over ten times more bandwidth, noise reduction by a factor of 5, and 1.5 times more slew rate.

To consider unity-gain performance, five different circuits have been tested for distortion, transient response, and noise performance. By comparing the noninverting amplifiers (circuit a versus circuit d) to the inverting amplifiers (circuits b and c versus circuit e), the following conclusions are drawn about using an externally-compensated THS4021 versus using the internally-compensated THS4011. A tabulated comparison is shown in Table 2.

In the inverting amplifiers (circuits b and c versus e), significant improvement in THD performance is seen across the frequencies tested. There was no significant difference between circuits b and c.

For the noninverting amplifiers (circuit a versus d), improvement in THD performance is also seen, but it diminishes with frequency, with no advantage seen at 16 MHz.

Transient performance shows mixed results. Slew rate and settling time are somewhat better when comparing the inverting topologies, but appears to be little change for the noninverting amplifier. The noninverting amplifier (circuit a) shows considerable overshoot, which may be undesirable.

If the noise is bandwidth limited, the THS4021 shows better noise performance; but little difference is expected if the full bandwidth of the parts is utilized.

Table 2. Comparison of Test Results

CIRCUIT	DESCRIPTION	TEST PARAMETER	COMMENTS
a	THS4021 noninverting 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	5 x improvement
b	THS4021 inverting amplifier with two-capacitor external compensation	Distortion	7–9-dB improvement at all frequencies tested
		Transient response	Faster initial response, slew rate, and settling time
		Noise	5 x improvement
c	THS4021 inverting amplifier with one-capacitor external compensation	Distortion	7–9-dB improvement at all frequencies tested
		Transient response	Faster initial response, slew rate, and settling time
		Noise	5 x improvement

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