

# Easily improve the performance of analog circuits with decompensated amplifiers

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## Introduction

A decompensated amplifier is an amplifier, usually an operational amplifier (op amp), that has had its stability reduced in order to improve its performance. A decompensated amplifier can obtain a higher gain bandwidth product, lower noise, a higher slew rate and better loop gain while using less current than a compensated equivalent that is unity-gain stable. However, because they are less stable than other amplifiers, circuit designers often shy away from choosing decompensated amplifiers because they think they are challenging to configure or that they will cause oscillations. However, with only a little bit of knowledge, a decompensated amplifier can easily and effectively improve circuit performance in many applications.

## How do decompensated amplifiers work?

The easiest way to understand how a decompensated amplifier differs from a typical op amp is to use Bode plots to compare amplifier frequency responses in terms of the open-loop gain and the noise gain of the two architectures.

In standard first-order op-amp models, designers typically assume that the amplifier's open-loop frequency response is flat from DC to some corner frequency, and then continues to decrease at  $-20$  dB per decade after the corner frequency until infinitely high frequencies. In terms of the transfer function, the rolloff would be caused by a single pole in the function. However, a single pole response is not the case even for the simplest of amplifiers. In reality, the amplifier's response will at least have a second pole frequency where the slope increases from  $-20$  dB per decade to  $-40$  dB per decade. Figure 1 compares a first-order amplifier to a more realistic second-order amplifier response. The dotted portion of the blue line represents the second pole where the response deviates from ideal.

Many designers ignore the second pole of the amplifier's response because it typically

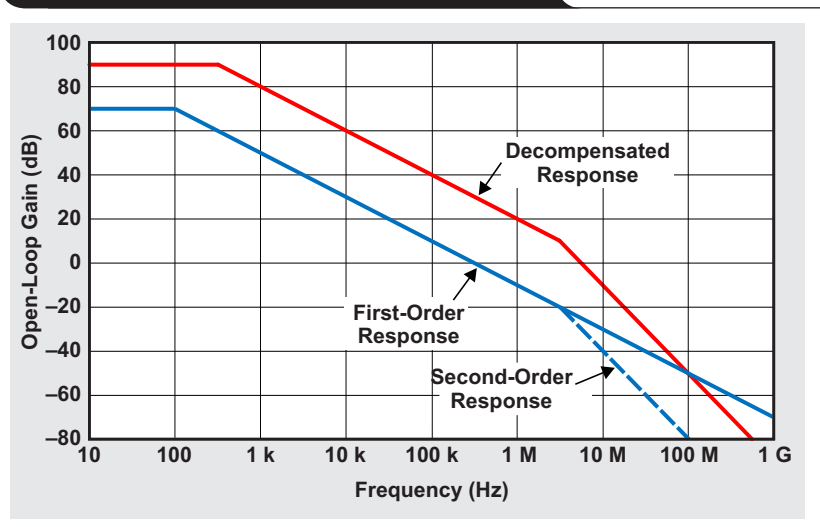
occurs much higher in frequency than the amplifier's unity-gain point, and therefore does not typically have much effect on the amplifier in standard configurations. However, it is important to be aware of this pole to understand the response of decompensated amplifiers.

## Decompensated amplifiers

The simplest definition of a decompensated amplifier is an amplifier that has had its internal compensation reduced to the point that it is no longer stable at unity gain. This means that the second pole in the amplifier's response now lies at a frequency that is above 0 dB. Because the amplifier is no longer stable in a unity-gain configuration, the data sheet will generally specify a minimum stable gain that is specific to the amplifier.

The exact value of this minimum gain depends on how much the amplifier was decompensated, with common values around 5 V/V to 10 V/V. The reason a decompensated amplifier becomes unstable at lower gains is because the second pole in the response adds additional phase shift in the feedback loop before the loop gain reduces to zero, resulting in a phase margin lower than the commonly suggested 45 degrees of margin. However, it is very easy to keep a decompensated amplifier stable by using it with a gain at or greater than its minimum stable value. The red line in Figure 1 shows the frequency response of a decompensated amplifier compared to a unity-gain-stable amplifier.

Figure 1. Amplifier open-loop responses



Although they are inherently less stable, decompensating an amplifier can improve its gain bandwidth and noise for the same amount of quiescent current, or it can decrease the required quiescent current while maintaining the same noise and gain-bandwidth performance. The bandwidth improvement is evident when comparing the frequency response of unity-gain-stable and decompensated versions of an amplifier. In Figure 2, the unity-gain-stable and decompensated responses show a simple illustration of decompensating an amplifier by shifting the amplifier's frequency response. It is easy to see how that for a given gain, the decompensated response will yield a higher bandwidth than the unity-gain-stable version. In addition, the noise is typically reduced in a decompensated amplifier because the degeneration resistors used for the input differential pair can be reduced in value.

Figure 3 shows a simplified version of a PNP bipolar transistor-based differential pair that would be common as the input for a voltage-feedback amplifier. Using degeneration resistors on the emitters of the two PNP devices helps stabilize the amplifier; however, these resistors add noise to the circuit and also lower the DC open-loop gain. When decompensating the amplifier, these resistors can be either lowered or removed, which lowers the total input noise and improves the DC open-loop gain.

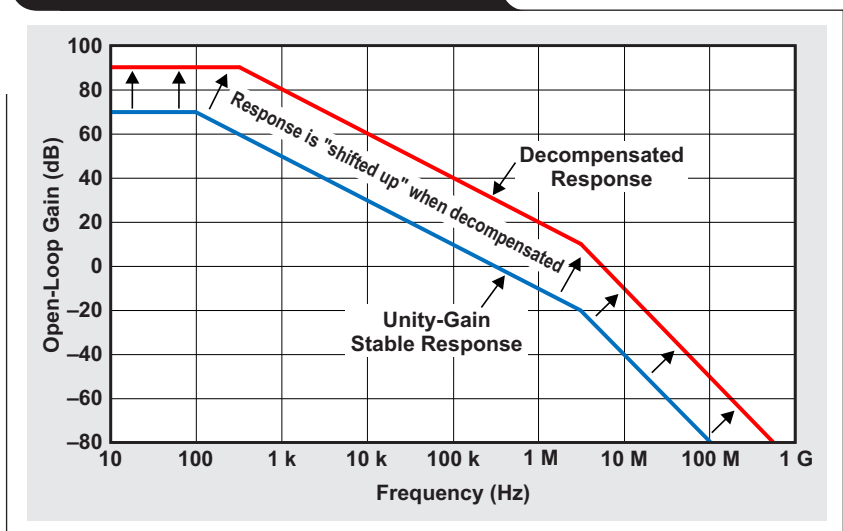
The OPA858 and OPA859 operational amplifiers are examples of how decompensation can improve amplifier bandwidth and noise. They both share the same amplifier core, but the OPA858 has been decompensated to improve the bandwidth and noise performance while maintaining the same amount of quiescent current consumption. Table 1 compares the OPA858 and OPA859 amplifier specifications, where the OPA858 was able to achieve over six times the gain bandwidth and a noise reduction of 24% by decompensating the amplifier.

**Table 1. OPA858 and OPA859 comparison**

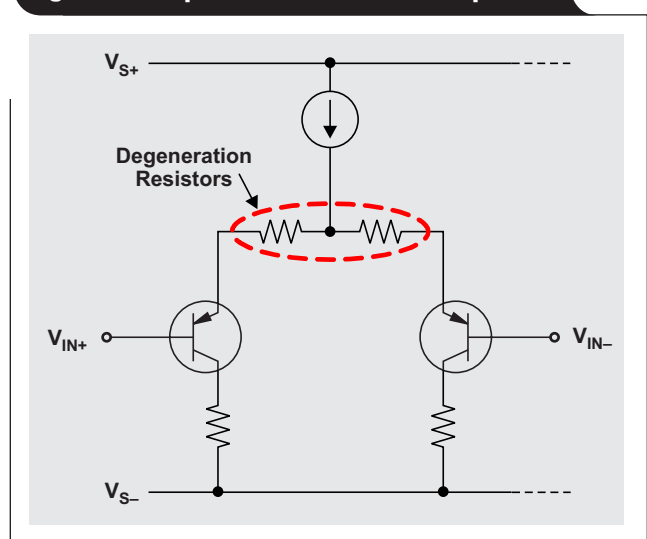
Amplifier	Gain Bandwidth	Noise	Quiescent Current
OPA858 (decompensated)	5,500 MHz	2.5 nV	20.5 mA
OPA859	900 MHz	3.3 nV	20.5 mA

In addition to gain bandwidth and noise, decompensating an amplifier also improves the loop gain across frequency. This means that the amplifier is going to maintain higher values of loop gain at any given frequency, which will additionally improve its linearity performance. Better linearity means that the amplifier will comparatively have improved harmonic distortion, power-supply rejection ratio, intermodulation distortion and other linearity specifications.

**Figure 2. Decompensated responses**



**Figure 3. Simplified PNP differential pair**



### Using decompensated amplifiers as voltage amplifiers

The simplest way to use a decompensated amplifier is as a standard inverting or non-inverting voltage amplifier. The design criteria are exactly the same as using a compensated device, except that the noise gain (equal to the non-inverting gain irrespective of an inverting or non-inverting amplifier configuration) must be kept above the minimum stable value for the chosen device. As long as the minimum stable gain requirement is met, the amplifier will perform without issue and will have all of the benefits of higher bandwidth and lower noise.

### Using decompensated amplifiers as transimpedance amplifiers

Though it is not initially apparent, one of the most natural fits for a decompensated amplifier is as a transimpedance amplifier. When looking at the typical transimpedance circuit shown in Figure 4, it is easy to see that at DC, the circuit appears to have a noise gain of 1, which would not make it a good fit for a decompensated device. However, take note of the two effective capacitances present in the circuit: the feedback capacitor and the equivalent input capacitance caused by the sum of the diode, circuit board, and amplifier capacitances. These two capacitances affect the gain as frequency increases and form a high-frequency gain equivalent to  $1 + C_{EQ}/C_F$ .

Because the stability point of the amplifier is ultimately determined when the noise gain crosses the amplifier's open-loop response, the capacitors form an effectively higher gain that keeps a decompensated amplifier stable. Figure 5 illustrates how a transimpedance amplifier's noise gain changes over frequency, and how it crosses a decompensated amplifier's open-loop gain above the minimum required gain for stability.

For an example of a decompensated amplifier used in transimpedance applications, the OPA858 is an excellent choice. Figure 6 shows the OPA858's transimpedance bandwidth compared to the unity-gain-stable OPA859 in similar configurations. From the plot in Figure 6, it is easy to see the benefit of the decompensated OPA858, which obtains significantly more bandwidth compared to the OPA859. Section 10.1.1 in the OPA858 data sheet<sup>[1]</sup> provides a detailed description of how to use this amplifier for transimpedance applications and includes additional performance measurements.

Because the input sources for transimpedance applications can vary significantly, so will the total input capacitance to the circuit and the required feedback capacitance. To help calculate the values for a transimpedance design, Texas Instruments has provided a high-speed amplifier calculator.<sup>[2]</sup> The application report, *Transimpedance Considerations for High-Speed Amplifiers*,<sup>[3]</sup> provides additional details on the theory of transimpedance amplifier circuits, including detailed stability and noise analysis.

Figure 4. Transimpedance amplifier circuit

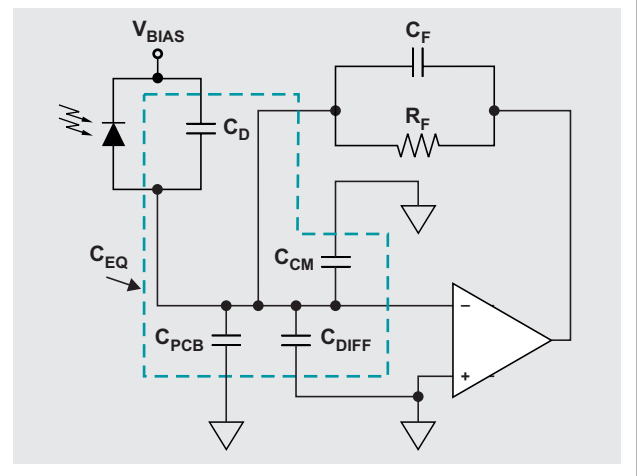


Figure 5. Transimpedance amplifier response

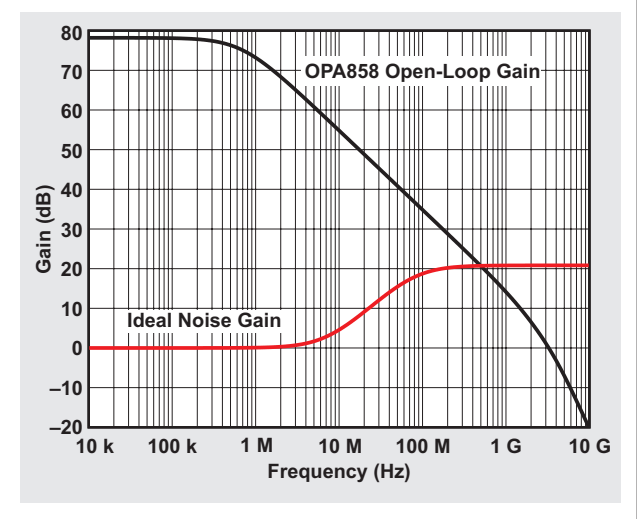


Figure 6. OPA858 bandwidth and noise performance as a transimpedance amplifier

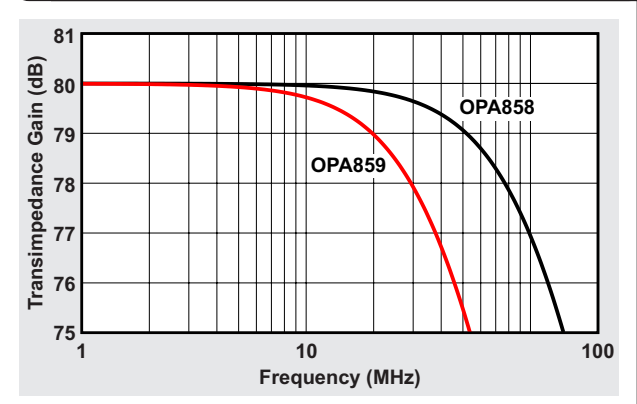
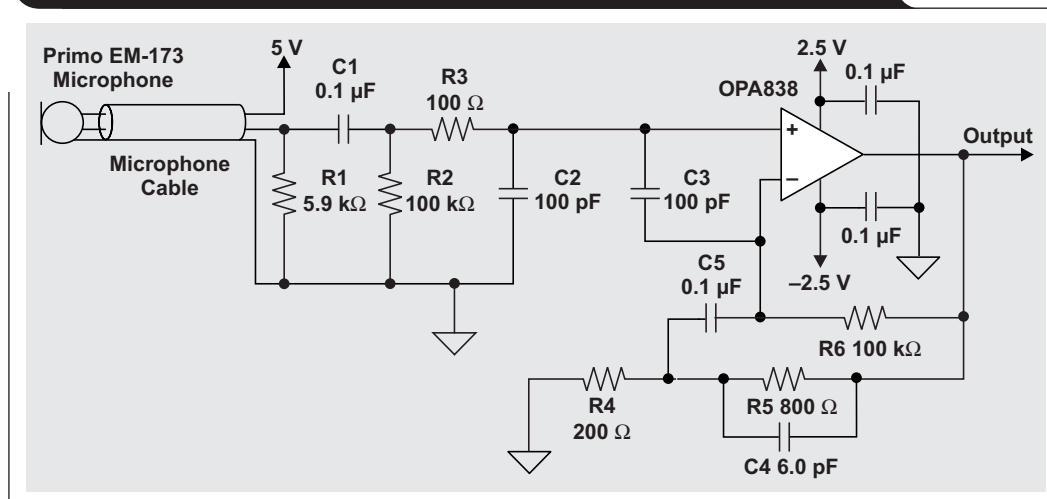


Figure 7. OPA838 pre-amplifier for a three-wire electret microphone



### Using decompensated amplifiers at gains lower than minimum

The minimum gain of a decompensated amplifier is the value required to keep the device stable. However, as described in the transimpedance amplifier section, the minimum-gain value is actually only critical at the point where the amplifier's open-loop gain and circuit-noise gain intersect. With this knowledge, it's possible to design application circuits that use decompensated amplifiers where the gain is kept lower than the minimum at the application's frequencies of interest, and then increased at the critical point of stability. The easiest way to implement a frequency-based noise-gain shift is to use an input and feedback capacitor, much like in the transimpedance amplifier circuit.

Figure 7 shows an example of using a decompensated amplifier in an application below its minimum stable gain. The circuit is a low-noise preamplifier with a non-inverting gain of 5 V/V for high-fidelity three-wire electret microphones using the OPA838 decompensated amplifier. The OPA838 is a 300-MHz gain-bandwidth amplifier, which means that the open-loop gain and noise-gain intersection point will fall much higher in frequency than the audio band of interest for the circuit, so the components added for stability will not affect performance. Because it is a decompensated amplifier, the OPA838 has extremely low noise (1.8 nV/√Hz), second-order distortion of -130 dBc at 10 kHz, and third-order distortion of -140 dBc at 10 kHz, while consuming just under 1 mA of quiescent current. These specifications make it a good candidate for a high-fidelity audio application and show the advantages of a decompensated device.

In Figure 7, adding feedback capacitor C4 and input capacitor C3 increases the high-frequency noise gain and stabilizes the amplifier. Without the stabilizing capacitors, the circuit would have a phase margin of 35 degrees and also have frequency-response peaking along with potential

instability. However, with the additional two capacitors, the phase margin increases to a stable 50 degrees. And because the capacitors are small in value, they only add an effect at high frequencies, which are filtered out well beyond the audio band of interest in this application.

### Conclusion

Decompensated amplifiers are often the best devices to maximize a circuit's performance and power. They are naturally suited to a wide variety of applications such as high-gain circuits and transimpedance amplifiers. With a basic understanding of open-loop response and noise gain, they are very easy to stabilize and use effectively. While they are not a good fit for all applications, there are many common and uncommon circuits that can benefit from the use of decompensated amplifiers.

### References

1. OPA858 data sheet, Texas Instruments.
2. Samir Cherian, "High-speed Amplifier Calculators," TI E2E™ Community, Apr 25, 2016.
3. Xavier Ramus, "Transimpedance Considerations for High-Speed Amplifiers," Texas Instruments Application Report (SBOA122), November 2009.
4. Theory of decompensated amplifiers and stabilization techniques, "AN-1604 Decompensated Operational Amplifiers," Texas Instruments Application Report (SNOA486B), May 2013.

### Related Web sites

Videos and information on many amplifier topics:

**TI Precision Labs Op Amps portal**

Product information:

**OPA858, OPA859, OPA838**

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