Noise, Slew Rate, and Unity Gain Stability Tradeoffs in High Speed Amplifiers

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Introduction

This paper examines the tradeoffs that are made between noise, bandwidth, and slew rate during the design of high-speed bipolar operational amplifiers. Because system applications of high-speed amplifiers impacts the device design, a brief analysis of noise performance in an analog-processing channel is given showing the key relationship between noise and gain. The tradeoff of noise, gain, slew rate, and stability is then examined from the perspective of the IC designer. Design techniques such as installing emitter degeneration resistors in the input stage are discussed. It is shown how adding such resistors helps to control stability, but at the expense of degrading the input voltage noise. Other compensation methods are also discussed with an eye on producing devices that are unity gain stable. Although unity gain stable devices are popular because of their ease of use, this paper shows that for best performance a unity gain stable amplifier is not necessarily the best choice.

System Noise Aspects

A typical analog-processing channel usually begins with a signal source followed by a string of amplifiers that provide gain, filtering, and/or other analog processing functions. Such an amplifier chain is shown in Figure 1. In this figure, v_s represents the signal source voltage and e_s represents the noise generated by the signal source. The amplifiers have gains G_1 and G_2, respectively. Noise generated by the amplifiers is represented by noise sources e_1 and e_2, respectively.

Because the noise sources are uncorrelated, multiple sources are combined by adding their mean square values. The noise at the output of the first amplifier, e_{out1}, is given by

$$e_{out1} = G_1\sqrt{(e_s^{\ 2} + e_1^{\ 2})}$$

This noise is then combined with the input noise source of the second amplifier, e_2, as a mean square value and multiplied by the gain, G_2. The result is the noise at the output of the second amplifier, e_{out2}.

$$e_{out2} = G_2\sqrt{e_2^{\ 2} + G_1^{\ 2}(e_s^{\ 2} + e_1^{\ 2})}$$

In a typical system application, it is often most useful to examine the noise in the system as an equivalent input noise where all noise has been reflected back to the input of the amplifier chain by dividing by the overall channel gain. This is done for convenience so that the noise in the channel that has been contributed by amplifiers and other sources is easily compared to the noise of the signal source

In the example circuit shown in Figure 1, the equivalent input noise is given by

$$e_{in} = \sqrt{e_s^{\,2} + e_1^{\,2} + \frac{e_2^{\,2}}{G_1^{\,2}}}$$

There are several important considerations regarding system noise performance that are indicated by the above equation.

- The noise of the first amplifier in the processing chain adds directly (as a mean square value) to the noise of the signal source.
- The noise of the second amplifier also adds to the signal source noise, but its contribution is reduced by the gain of the first stage.

It follows that for the best noise performing system the first amplifier in the chain should be the lowest noise amplifier with its noise well below that of the signal source. In addition, the gain of the first amplifier should be set as high as possible so as to minimize the effect of subsequent amplifiers in the processing chain.

In selecting operational amplifiers for use in a circuit design, many designers seem to look for unity gain stable amplifiers as a matter of course. This could be true for several reasons. First, they may find unity gain stable amplifiers easier to use simply because they don't have to worry as much about stability issues. Or, perhaps they choose unity gain stable amplifiers because there is a greater variety available from which to select. Some designers may even choose unity gain stable devices because it removes the future risk associated with the required system gain ever falling below the value at which a non-unity gain stable device could be used. Whatever the reason, many designers seem to go this route and it is not necessarily a correct one.

As will be shown in the following section, high-speed amplifiers that have been optimized for the lowest noise performance are usually not stable at unity gain. This should not present a problem, because as was shown above, best system performance is achieved with a low noise amplifier when it is used at gains higher than one. A circuit designer aware of this can then make a more educated selection of the proper amplifier.

The IC Designer's Care Abouts

In the design of high-speed amplifiers, there are many design tradeoffs made in arriving at the final device. However, several key parameters continually surface as the parameters that can have the most impact. These are usually bandwidth, slew rate, stability, and noise. Because these are all interrelated, it is important to consider the end use of the device when trading off these parameters. Following is a discussion of these parameters and their impact on producing high-speed amplifiers with low noise.

Basic High Speed Amplifier

Shown in Figure 2 is a simplified block diagram of a high-speed amplifier. It consists of an input stage with transconductance, g_m, a second stage of gain, and then the final output stage. The compensation capacitor is typically applied around the second stage causing the stage to act as an integrator.

Slew Rate

The slew rate performance of an amplifier is a large signal phenomenon. In the amplifier shown in Figure 2, the slew rate is limited by the available output current from the input stage, I_x, which charges the compensation point. This can be expressed as:

$$SlewRate = \frac{\Delta v_o}{\Delta t} = \frac{I_x}{C}$$

where I_x = the maximum current available to charge the Miller capacitance, and
C = the Miller compensation capacitance

Although the designer can change the current, I_x, it is basically a fixed value usually driven by the overall bias current desired. With power dissipation seemingly always a concern in most applications, rarely is the designer free to arbitrarily elevate this current to increase slew rate. That leaves the capacitor value as the only flexible variable for adjusting the slew rate.

For most high-speed applications, speed is almost always a critical factor, therefore, slew rate and bandwidth need to be maximized and settling time minimized. To do this the value of the compensation capacitor is set as low as possible. However, to provide for proper closed loop stability, the value of this capacitor needs to be increased until adequate phase margin is attained for the desired gain stability point.

Bandwidth and Stability

To determine the best value for the compensation capacitor, the amplifier frequency response is examined to see what compensation is required for stability. With several compensation options available to the IC designer, the final choice is made based on the desired amplifier performance and which performance parameters are of greatest importance. Shown in Figure 3 is a typical amplifier frequency response.

The uncompensated curve in Figure 3 shows that this amplifier is unstable with unity gain feedback and needs to be compensated. Three curves (Compensation A, Compensation B, and Compensation C) are shown that represents three different methods of compensation. Each of these methods produces an amplifier with different performance characteristics. The tradeoffs of each compensation method are described below.

Compensation A – This is a dominant pole method where the value of the Miller compensation capacitor, C, is selected to be high enough so that there is 45 degrees of phase margin at the unity gain crossover. This will produce an amplifier that is unity gain stable, but has reduced slew rate and increased settling time because the value of C is relatively large.

Compensation B – This method compensates the device by reducing the open loop gain and setting a dominant pole. The gain is typically reduced by installing emitter degeneration resistors in the emitters of the differential input stage. This reduces the g_m of the input stage, which then permits setting the dominant pole at a higher frequency than if the open loop gain were not reduced. Thus, the value of the compensation capacitor is less than in the previous compensation method so the slew rate of the device will be higher. However, using emitter resistors produces several drawbacks, the worse of which is that these resistors are a noise source and will increase the input noise of the device. If the goal of this device is to be low noise, then adding emitter degeneration resistors is not desirable.

Compensation C – This method is the same as Compensation A except the dominant pole is set at a higher frequency. The obvious advantage is that the value of the compensation capacitor is smaller than for the Compensation A case and, therefore, the high-speed performance will be better. Also, there are no emitter degeneration resistors used, so the input noise will be minimal. The disadvantage is that the device will not be unity gain stable but will be stable at some higher gain, such as 5 or 10, depending exactly on the final capacitor value used. However, as discussed in the previous section, a typical low noise analog channel should use a low noise amplifier at gains greater than one to maximize performance, therefore, having a low noise amplifier that is not unity gain stable is not really a disadvantage.

Summary

A simple analysis of an analog processing channel was presented showing that the optimum solution for low noise performance was for the first amplifier in the chain to be low noise and have its gain set as high as possible. The design tradeoffs within a high-speed amplifier were then presented. The results were that by using the proper method of compensation, a high-speed amplifier could be produced that matched the requirements of a low noise analog channel. Namely, that the best performing low noise amplifiers may be amplifiers that are not unity gain stable.