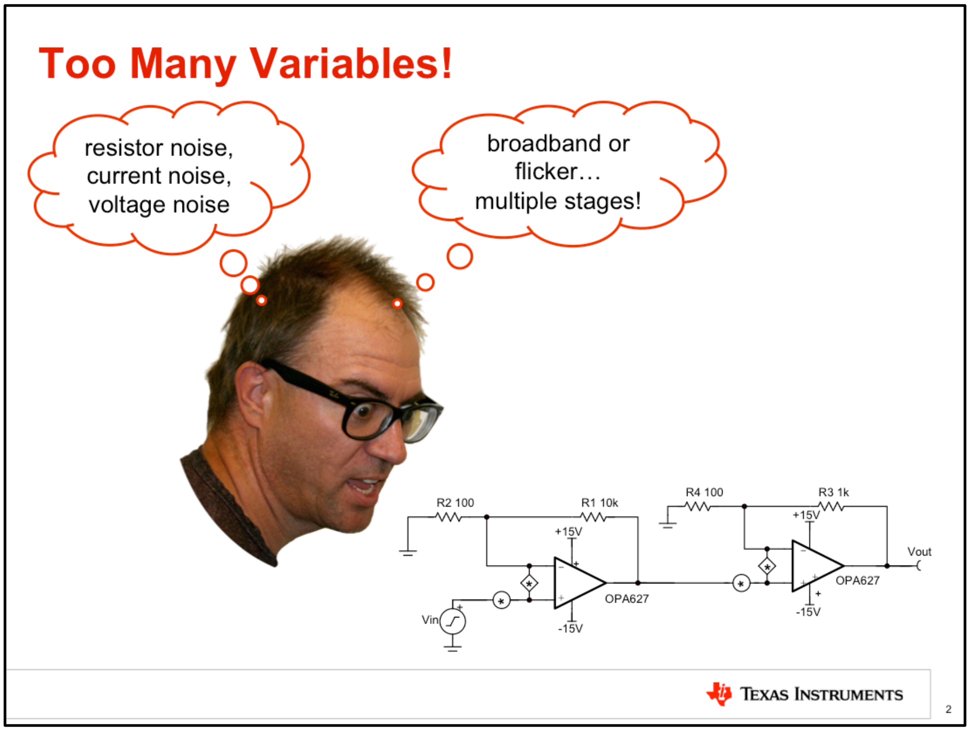
Hello, and welcome to the TI Precision Lab discussing intrinsic op amp noise, part 4.

In the last video we did a comprehensive noise hand calculation for a very simple op amp circuit. In a real-world circuit, these hand calculations can be long and complex. In this video we will provide several rules of thumb which can be used to simplify noise calculations by identifying the dominant source of noise and ignoring noise sources that do not make a significant contribution. Identifying the dominant source of noise will give you insight into how you can quickly and effectively improve your system's noise performance.

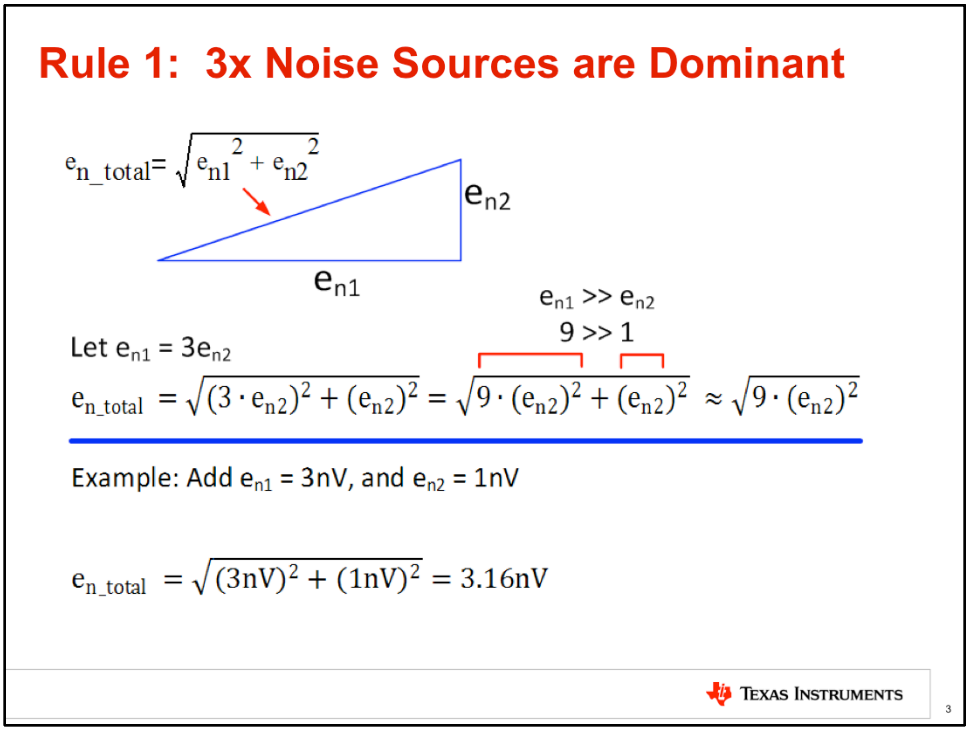


Noise analysis can seem overwhelming to new engineers. Generally, the complete noise calculation for a simple circuit will take more than 10 steps. On more complex circuits, it can be even longer! It is also difficult to get an intuitive feel for a circuit's noise performance by doing the full calculation.

Thankfully, there is good news. In most cases it is possible to simplify the calculation by focusing on the dominant noise source or sources, and ignoring the insignificant noise sources. The trick lies in identifying what is significant and what can be ignored. This presentation covers several rules that will help you to determine if the noise source is significant or can be ignored. Knowing the dominant noise source not only simplifies your calculation, but also will highlight the factor that you need to focus on to reduce the overall noise level. For example, if current noise is the dominant factor, you may need to change from a bipolar amplifier to a CMOS amplifier. On the other hand, if resistor noise is dominant, you might want to reduce the resistor values in your circuit.

It is important to note that you cannot get much insight into what are the dominant noise sources through simulation. For example, the simulation will not let you know if resistor noise or current noise is dominant. For this reason, simulation should be used to confirm your hand calculations rather than as the only tool for noise analysis.

Now, let's look at the rules for simplification of noise analysis.

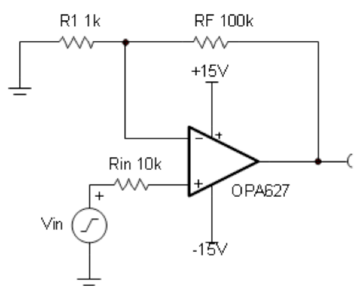


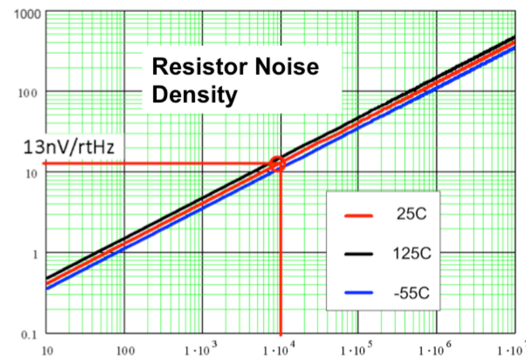
You have probably heard the engineering rule explaining that when adding two numbers together, the smaller of the two numbers can be ignored if there is a factor of ten difference between the two values. For example, when adding 10 and 1, you can ignore the smaller of the two values and introduce a relatively small error. In this case the error would be 10%. Of course, the estimate is even better if you use a factor of 100 or 1,000. This allows the math for complex engineering problems to be greatly simplified.

The first rule of noise analysis is based on the same idea. However, remember that random uncorrelated noise sources add as the square root of the sum of the squares. So, for noise, we no longer need a factor of 10 difference between the two numbers to do the simplification. In the case of noise, a factor of 3 difference between the two terms is effectively the same as a factor of 9 because the terms are squared. For example, if a 1nV noise source is added with a 3nV noise source, the total noise is 3.16nV. In this example, ignoring the 1nV noise source only introduces a 5% error.

As before, increasing the factor of difference between the two terms will further improve the estimate. However, for noise analysis, a small increase in the factor will have a dramatic improvement on the accuracy of the estimate because the terms are squared. The other rules that we will discuss will compare different noise sources to determine the dominant source. Rule 1 is used as the basis for making this comparison. Let's now cover the other rules.

Rule 2: Minimize Resistor Noise





OPA627 Data Sheet				
Parameter	Min	Typ	Max	Units
Noise Density (1kHz)		4.5		nV/rtHz

Resistor e_{nr} > Op-Amp e_n
13nV/rtHz > 4.5nV/rtHz

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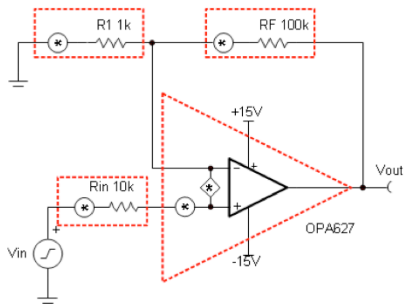
In the first noise video we learned that resistors generate noise. The second rule of a low noise system design is to keep the resistor noise much lower than the intrinsic op-amp noise. The reason is that low noise amplifiers are expensive! It doesn't make sense to use an expensive low noise amplifier with large-value resistors that dominate the noise performance. It is normally a simple design change to scale the resistors to lower values in order to reduce the overall noise response. The only real concern when reducing the resistor values is that power consumption will increase. It can be challenging to develop a low noise solution that is also low power.

Rule 3: Focus on Voltage Noise or Current Noise



from Rin

$$e_{ni} = i_n \cdot R_{in}$$

$$e_{in} = \left(2.5 \frac{fA}{\sqrt{Hz}}\right) \cdot (10k\Omega) = 25 \frac{pV}{\sqrt{Hz}}$$

from Req

$$e_{ni} = i_n \cdot R_{eq}$$

$$e_{in} = \left(2.5 \frac{fA}{\sqrt{Hz}}\right) \cdot (1k\Omega) = 2.5 \frac{pV}{\sqrt{Hz}}$$

Voltage Noise e_{nv} > Current Noise as Voltage e_{ni}
4.5nV/rtHz > 0.025nV/rtHz

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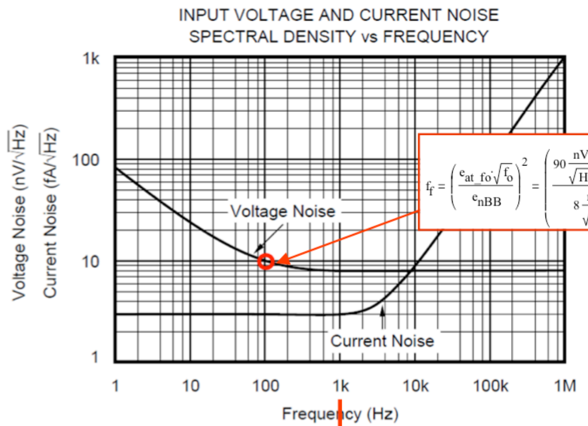
The third rule of low noise design is to determine whether current noise or voltage noise is the dominant source of noise. In most cases, current noise is **not** significant on CMOS and JFET amplifiers. Most CMOS amplifiers have current noise in the fA/√Hz range, and bipolar amplifiers have current noise in the pA/√Hz range.

Current noise can be a concern if large input resistors or feedback elements are used. For resistances of 100kΩ or greater, you may need to use a CMOS or JFET amplifier. On the other hand, current noise is usually not a concern when small resistors are used. For resistances less then 1kΩ, the current noise can generally be neglected even when bipolar devices are used.

The easiest way to determine if the current noise is significant is to convert current noise spectral density to voltage noise spectral density and directly compare the two quantities. Always look at both the source resistance as well as the equivalent parallel combination of the feedback elements when doing the calculation. In this example, the input resistance is 10kΩ, and the noise current density is 2.5fA/√Hz. Just multiply the input resistance by the noise current density to calculate the equivalent voltage nosie density, which turns out to be 25pV/√Hz. This is very small compared to the 4.5nV/rtHz noise voltage for the OPA627.

One objective of this step is to make sure that you are using the right type of device. Once again, you may consider a CMOS or JFET device if the feedback or source resistance is large.

Rule 4: Focus on Broadband or 1/f Noise



$$f_f = \left(\frac{e_{at\_fo} \cdot \sqrt{f_o}}{e_{nBB}}\right)^2 = \left(\frac{90\frac{nV}{\sqrt{Hz}} \cdot \sqrt{1Hz}}{8\frac{nV}{\sqrt{Hz}}}\right)^2 = 100Hz$$

f_f is the corner frequency. Where the 1/f noise is equal to broadband noise.

Rule of Thumb: Broadband noise dominates if BW > 10 x f_f

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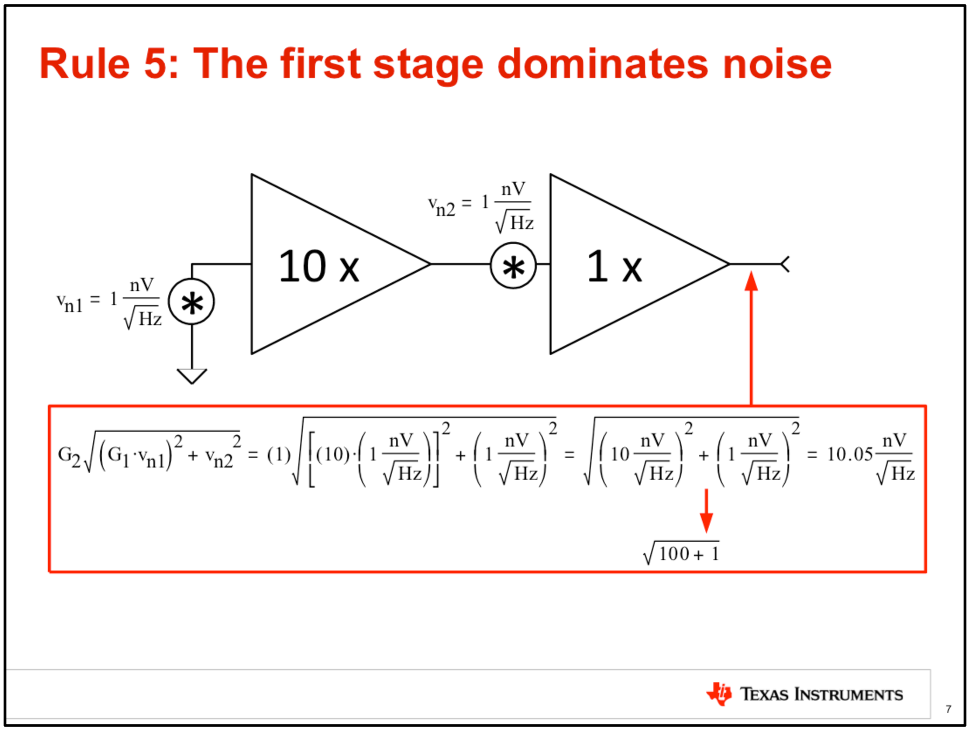
Many engineers new to noise analysis focus a lot of time and effort looking at plots of 0.1Hz to 10Hz noise or 1/f noise. Often times, however, the system bandwidth is wide and this low frequency noise is insignificant. You should consider the bandwidth of your system relative to the 1/f noise corner of the op amp. The 1/f noise corner is the point at which the 1/f noise is equal to the broadband noise. This slide shows an equation for the precise calculation of this point. However, for the purpose of this rule it is sufficient to graphically estimate the point by looking at the bend in the noise curve.

Rule 4 states that the contribution of 1/f noise can be can be ignored if the system bandwidth is 10 times greater than the 1/f noise corner frequency. For most precision amplifiers, the noise corner is between 1Hz and 1kHz. Thus, for systems with bandwidth greater than 10kHz you rarely need to consider 1/f noise.



The last rule that can be used to simplify noise calculations relates to multiple stage amplifiers. It is common in analog systems to use several amplifier stages cascaded in series to achieve optimal performance. In general, it is advised to use the highest gain in the first stage. Doing this will make the error sources in the first stage dominant so that errors in subsequent stages can be safely ignored. In many cases, an expensive high precision amplifier is used in the first stage and a lower cost less precise device is used in subsequent stages to achieve excellent overall precision at a lower cost.

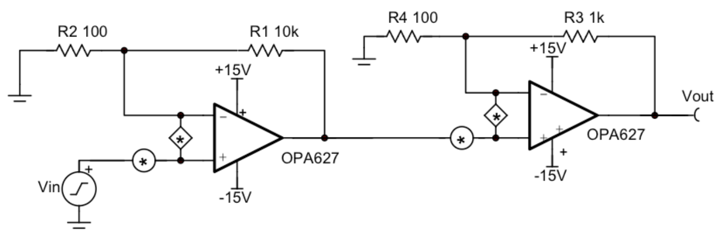
This example illustrates why the first stage is normally the dominant source of noise. The key to understanding this is to remember that the input noise of the first stage is multiplied by the gain of the first stage and added with the input noise of the second stage. In this example, the input referred noise for each amplifier is 1nV/√Hz, but the first op amp is in a gain of 10 while the second op amp is in a gain of 1. The output noise of the first stage is calculated by multiplying the first stage noise by the first stage gain, for a total of 10nV/√Hz. Comparing the 10nV/√Hz output noise from the first stage to the 1nV/√Hz input noise from the second stage, you can easily see that the first stage is dominant and you can ignore noise from the second stage. Take care to make sure that the first stage gain is large enough to ensure that the output noise from the first stage is at least three times greater than the input of the second stage.

Rule 2: Voltage Noise vs. Resistor Noise

$$e_{nr} = \sqrt{4k_n \cdot T_n \cdot R_{eq}} = \sqrt{4\left(1.38 \cdot 10^{-23}\right) \cdot (298) \cdot (100)} = 1.3 \frac{nV}{\sqrt{Hz}}$$

$$e_{nv} = 4.5 \frac{nV}{\sqrt{Hz}}$$ from data sheet

Note $e_{nv} > 3 \cdot e_{nr}$ so ignore resistor noise



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Let's take a look at a few real world examples that illustrate the Rules of Thumb.

Let's start with Rule 2: minimize resistor noise. We can calculate the precise resistor noise of this circuit from the equivalent feedback resistors, or we can use the graph. Generally, I just use the graph because it's easy and we only need an approximate value for the noise. Compare the resistor noise to the op amp voltage noise from the data sheet. In this example, the resistor noise is 1.3nV/√Hz and the op amp voltage noise is 4.5nV/√Hz. Therefore, the op amp noise is about 3.5 times larger than the resistor thermal noise. This is good, because we normally want the op amp noise to be dominant. We could further reduce the thermal noise by decreasing the feedback resistors, but it would have little effect on the overall noise. Also, reducing the feedback resistors will increase the systems power dissipation.

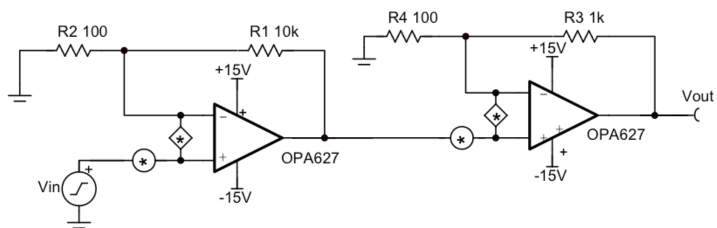
Remember, one of the main goals of this rule is to simplify the final noise calculation. In this case we do not need to consider the resistor noise, because the amplifier noise is dominant.

Rule 3: Voltage Noise vs. Current Noise

$$e_{ni} = i_{bn} \cdot R_{eq} = 1.6 \frac{fA}{\sqrt{Hz}} \cdot 100\Omega = 0.16 \frac{pV}{\sqrt{Hz}}$$

$$e_{nv} = 4.5 \frac{nV}{\sqrt{Hz}}$$ from data sheet

Note $e_{nv} > 3 \cdot e_{ni}$ so ignore current noise



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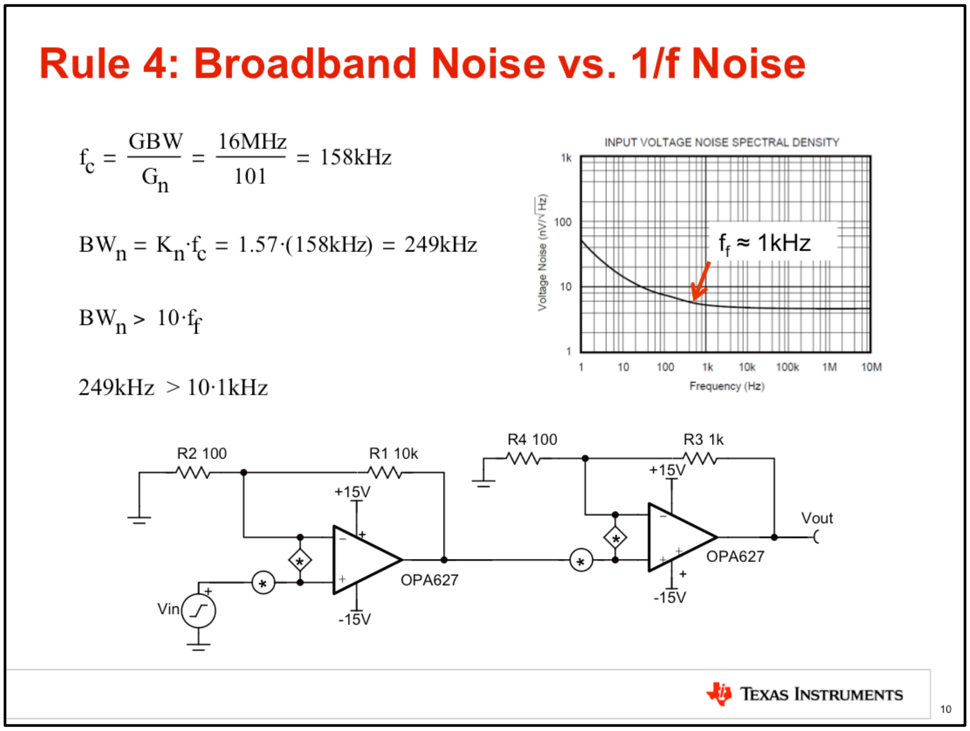
Rule 3 enables us to check if op amp voltage noise or current noise is dominant.

The check is done by simply multiplying the current noise by the equivalent feedback resistance. In this example, the device has a JFET input so the current noise is very low at 1.6fA/√Hz. In general, for current noise in this low range it is very unlikely that current noise will be a significant contributor. However, in this example we do the calculation for completeness. The current noise multiplied by the equivalent resistance translates to an equivalent 0.16pV/√Hz of voltage noise. This is significantly smaller than the 4.5nV/√Hz of amplifier voltage noise, so the current noise can be ignored. This test is much more important if bipolar amplifiers are used or if very large feedback or source resistance is used.



Now let's see if we can ignore the 1/f noise. In this example, the 1/f noise corner can be graphically estimated to be about 1kHz. Of course, you could use the equation given earlier to find the precise location of the noise corner but the estimate is sufficient when using Rule 4. After finding the noise corner, we need to know the noise bandwidth. Using the gain bandwidth product and the noise gain, we find that the bandwidth is 160kHz. The noise bandwidth is then calculated with the factor of 1.57 for a first order brick wall filter correction, as discussed in a previous video.

The noise bandwidth comes out to 249kHz, which is **much** higher than the noise corner at 1kHz. Thus, for this example we can ignore the 1/f noise. Besides simplifying the calculation, this rule keeps you focused on what is important. For example, the 0.1Hz to 10Hz noise waveform is really just a way of looking at the 1/f noise. This curve is not relevant if the broadband noise is dominant.

Rule 5: Is the First Stage Dominant?

$e_{n1} := 4.5 \frac{nV}{\sqrt{Hz}}$ $e_{n2} := 4.5 \frac{nV}{\sqrt{Hz}}$

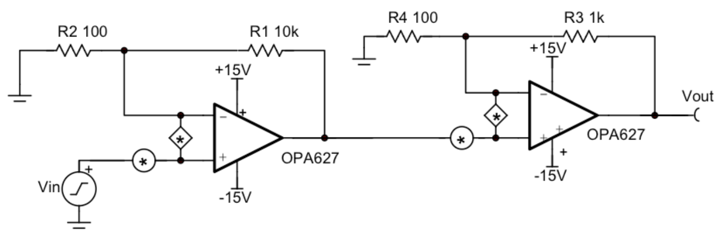
$G_{n1} = 101$ $G_{n2} = 11$

Output noise of first stage

$$e_{n1} \cdot G_{n1} = \left(4.5 \frac{nV}{\sqrt{Hz}}\right) \cdot (101) = 455 \frac{nV}{\sqrt{Hz}}$$

Comparing output noise from first stage
to input noise of second stage.

$$455 \frac{nV}{\sqrt{Hz}} >> 4.5 \frac{nV}{\sqrt{Hz}}$$



The fifth rule tells us that the first stage noise is normally dominant. Normally this will be the case, but it is always best to check if the first stage gain is low or if the following stages use amplifiers with higher noise.

In this case the first stage's noise gain is 101 and a low noise amplifier is being used for both stages. So, it is likely that the input stage noise will be dominant. Let's compare the first stage output noise with the second stage input noise. In this case, you can see that the output noise from the first stage is 101 times greater then the input noise to the second stage. Thus, you can safely ignore the noise from the second stage to simplify your calculations.

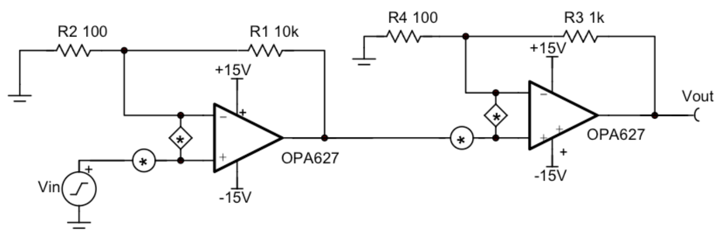
Simple Hand Calculation – Total Noise

$$f_c = \frac{GBW}{G_n} = \frac{16MHz}{101} = 158kHz$$

$$BW_n = K_n \cdot f_c = 1.57 \cdot (158kHz) = 249kHz$$

$$E_{n\_in\_simple} = e_n \cdot \sqrt{BW_n} = \left(4.5 \frac{nV}{\sqrt{Hz}}\right) \cdot \sqrt{249kHz} = 2.245\mu Vrms$$

$$E_{n\_out\_simple} = G_{n1} \cdot G_{n2} \cdot E_{n\_in\_simple} = (11) \cdot (101) \cdot (2.245\mu Vrms) = 2.5 \cdot mVrms$$



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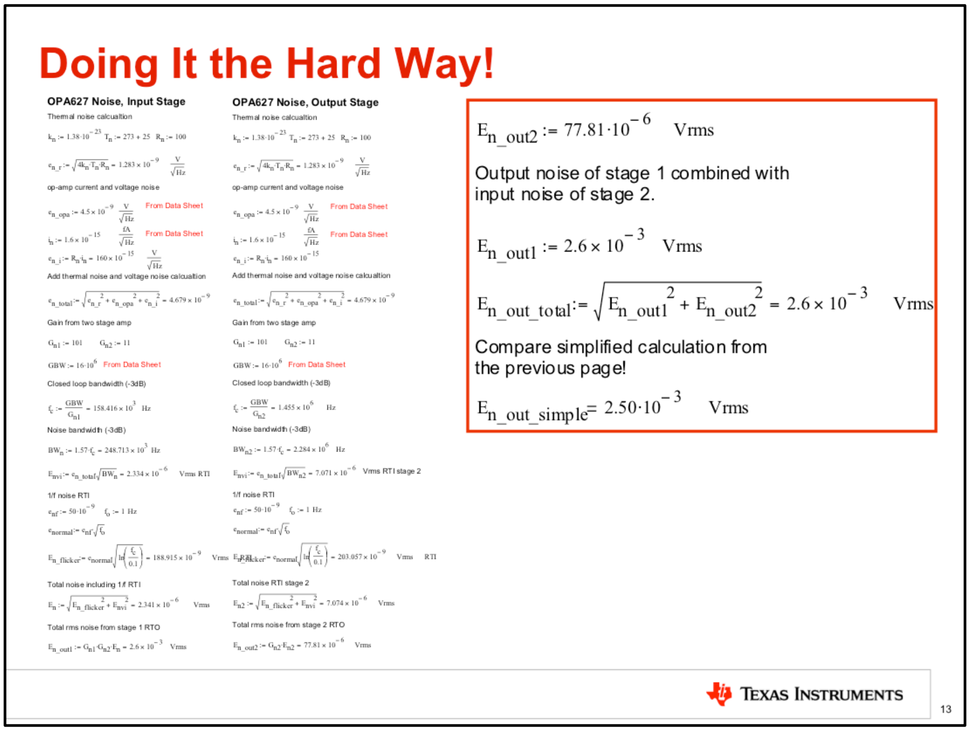
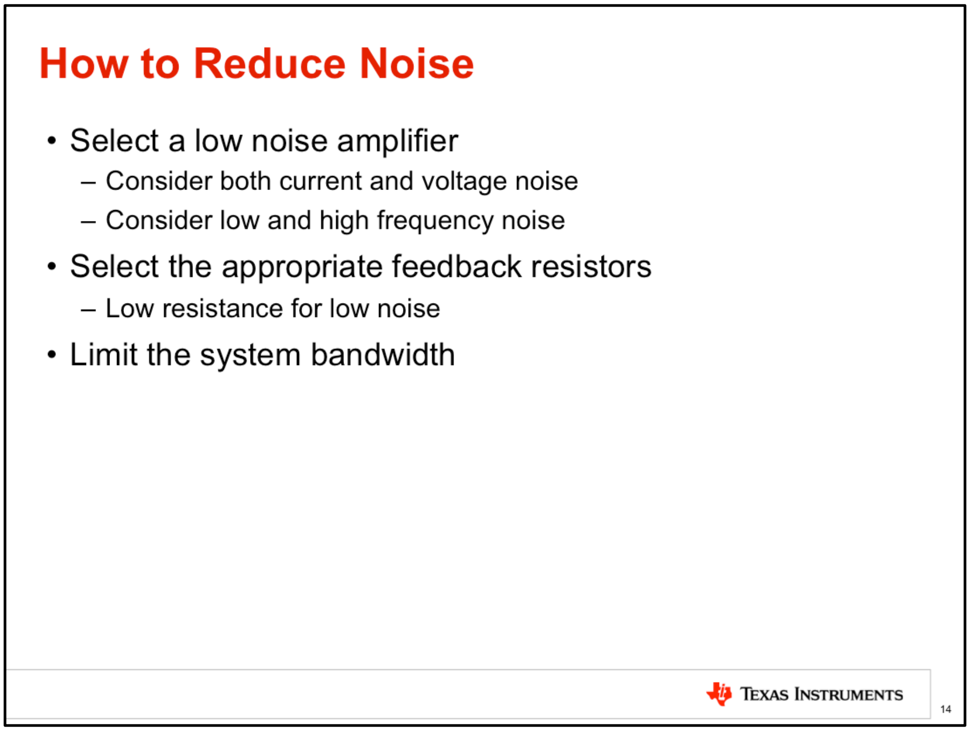
Now that we have applied all the rules, let's do the simplified calculation for the entire system. In this example we can ignore current noise, 1/f noise, resistor noise, and second stage noise. The only factor we need to consider is the voltage noise of the input stage. To find the system output noise, first find the noise bandwidth of the input stage. Second, use the broadband noise equation to calculate the RMS input noise, and then multiply this by the total gain for both stages. In this example, the total noise is 2.5mV rms.

So this was a pretty simple calculation, but how accurate is it?



This slide shows the how to do the full calculation considering all the factors. Notice that the final result of 2.59mV rms is **very** close to the simplified result of 2.5mV rms. Perhaps more importantly, applying the rules helped us to gain insight into the key factor affecting the noise performance of this system – the first stage input voltage noise. Now we know what can be modified to reduce the overall system noise.



Here are the most common system factors which can be adjusted to reduce the total noise. Remember, usually one of these factors is the main contributor to overall noise!

Assuming the amplifier noise is the circuit limitation, you can choose a lower noise device to get better performance. Make sure that you consider both current noise and voltage noise when making the selection. Also, make sure that the feedback and source resistance used in your application is low enough so that the resistor noise is not a significant factor. Finally, always limit your bandwidth to the minimum bandwidth that is acceptable for your system. Limiting the bandwidth is often the easiest way to reduce your total noise. Let's consider an example.

With and Without a Filter!

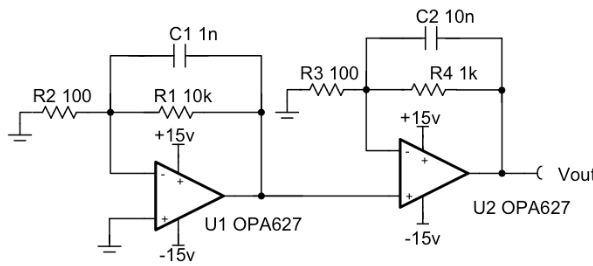
$$f_1 = \frac{1}{2 \cdot \pi \cdot 10k\Omega \cdot 1nF} = 15.9kHz$$

$$f_2 = \frac{1}{2 \cdot \pi \cdot 1k\Omega \cdot 10nF} = 15.9kHz$$

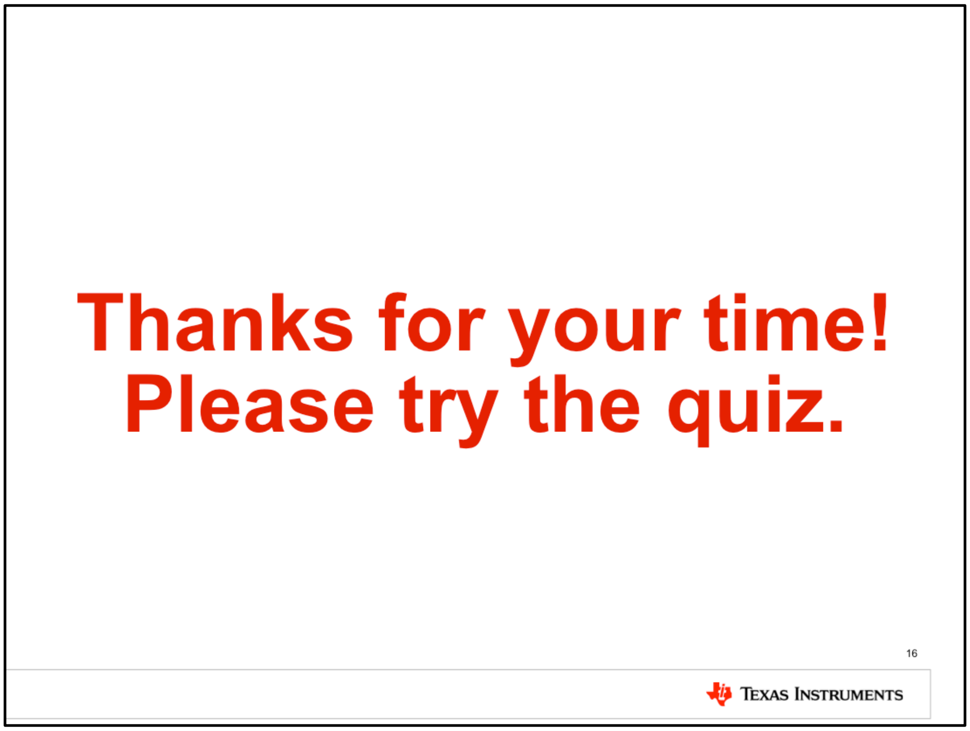
$$BW_n = 1.57 \cdot (15.9kHz) = 25kHz$$

$$E_{n\_with\_filter} = 101 \cdot 11 \cdot \left(4.5 \frac{nV}{\sqrt{Hz}}\right) \cdot \sqrt{25kHz} = 790\mu V \ \ rms$$

$$E_{n\_no\_filter} = 2.5mV\,rms \quad with \quad f_c = 158kHz$$



This slide shows the effect of limiting the bandwidth from the unfiltered bandwidth of 158kHz to a filtered bandwidth of 15.8kHz. The unfiltered circuit is the same circuit that we have been looking at throughout this presentation. The filtered circuit simply uses two feedback capacitors, C1 and C2, to set the bandwidth to of each stage to 15.8kHz. Using the bandwidth, you can find the noise bandwidth and total noise using the same methods already described. In this example, the noise was reduced from 2.5mV rms to 790µV rms with filtering.



That concludes this video – thank you for watching! Please try the quiz to check your understanding of this video's content.