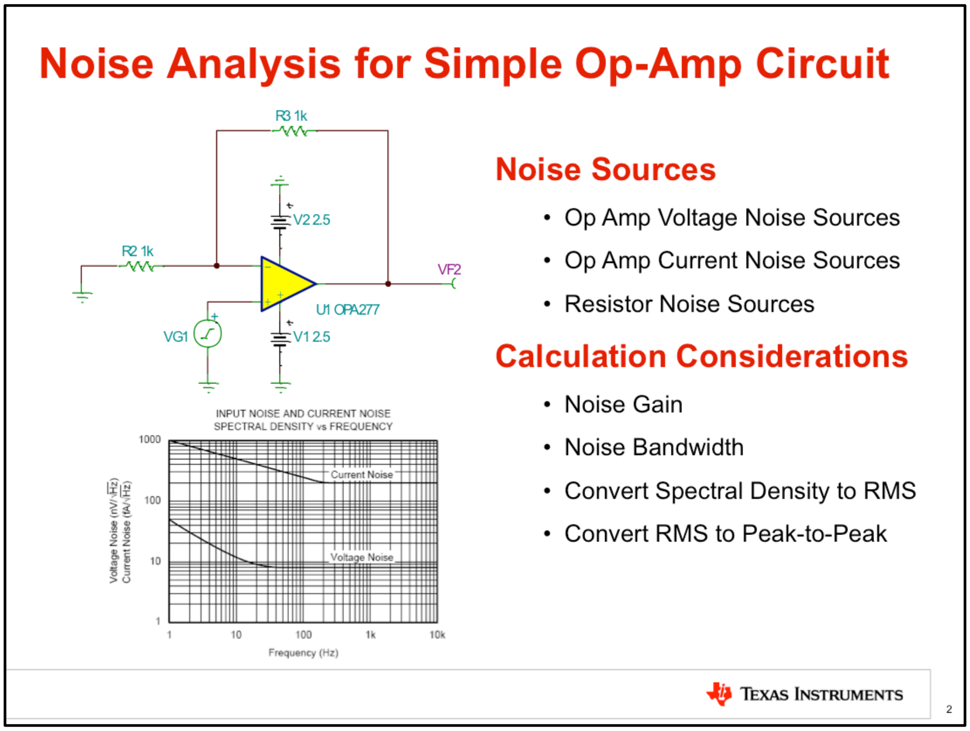
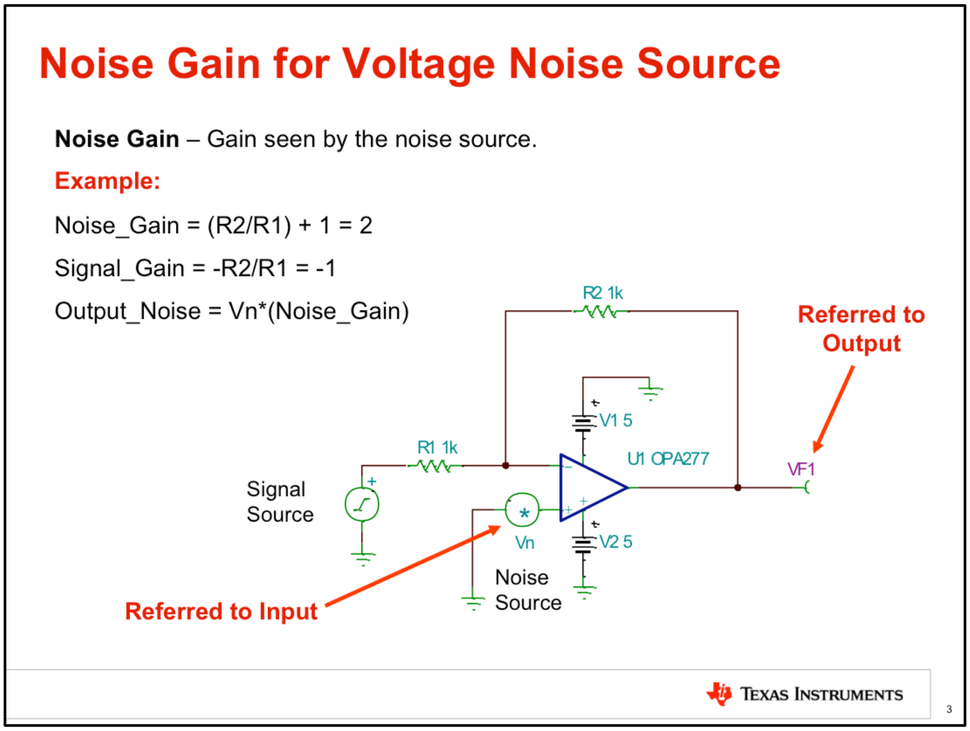
Hello, and welcome to the TI Precision Lab discussing intrinsic op amp noise, part 2.

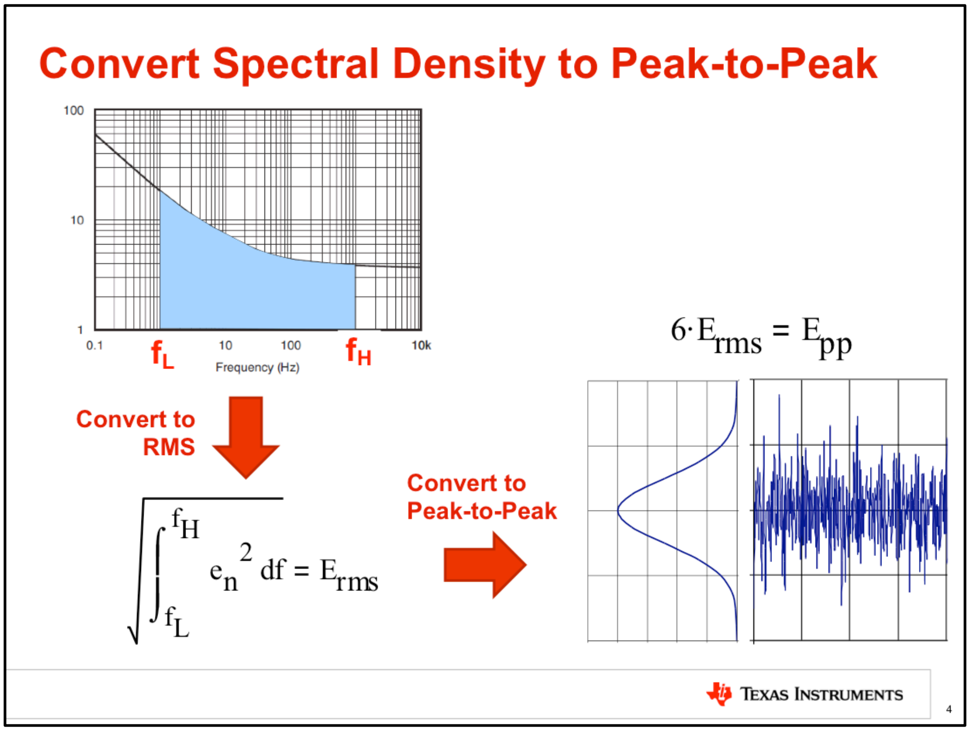
In this video we'll continue the noise discussion by going into further detail on the regions of op amp noise and how to convert spectral noise density to RMS noise.



Noise analysis involves looking at op amp noise voltage sources, op amp noise current sources, and resistor noise sources. The gain and bandwidth limitations of the op-amp will also effect the total noise calculation. In this following videos on noise, I'll explain how to include all of these factors in order to calculate peak-to-peak output noise.



A key concept that we must understand before doing a noise analysis is **noise gain**. Noise gain is the gain seen by the noise voltage source, which is always on the non-inverting input of the amplifier. It can be different from the signal gain. The example above shows a circuit with a noise gain of 2 and a signal gain of -1. In other words, the circuit is an inverting amplifier with respect to the signal source, but a non-inverting amplifier to the noise voltage source.

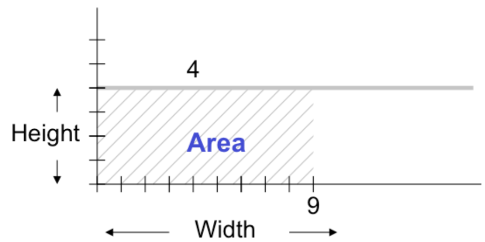


This slide summarizes the general procedure for converting voltage spectral density to RMS noise voltage, and for converting RMS to peak-to-peak voltage. To convert voltage spectral density to RMS, you must square the voltage spectral density, integrate across the desired bandwidth, and take the square root of the result. This is effectively integrating the power spectral density and taking the square root to convert back to voltage or current. Remember that $P = V^2 / R$ and $P = I^2 \times R$. We will discuss this in more detail soon.

Once the RMS noise voltage is calculated, it can be converted to peak-to-peak by multiplying by 6. As discussed in the first noise video, the factor of 6 is a statistical estimate, representing ±3 standard deviations or 6σ, and there is a 0.3% chance that noise will exceed the peak-to-peak estimate at any instant in time.

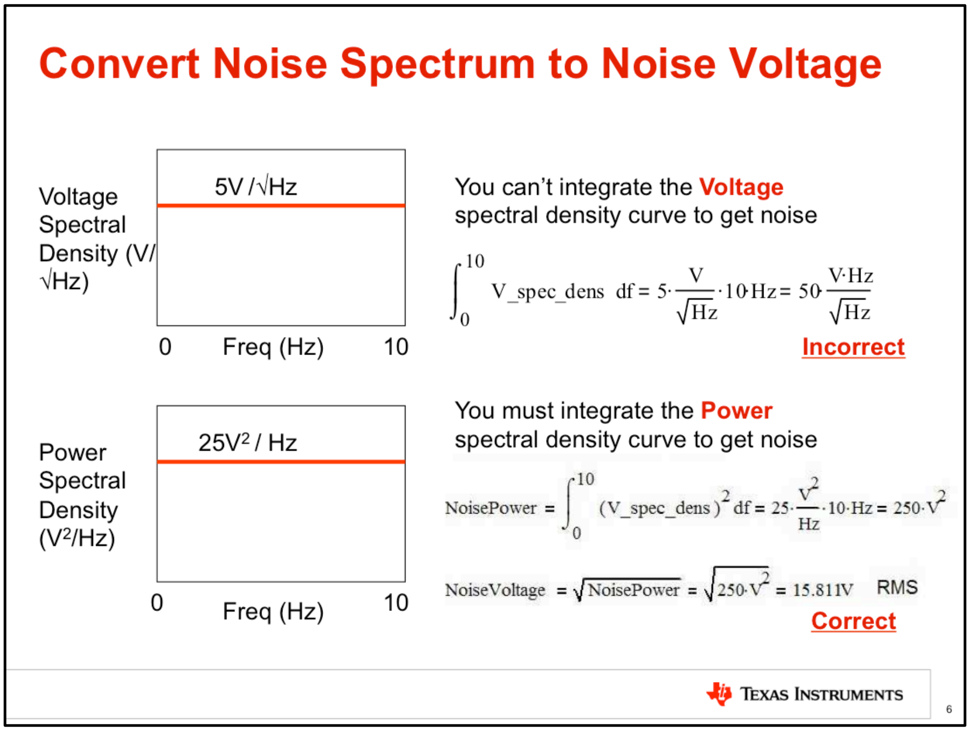
Calculus Reminder

$$\int_0^9 4\,dx = 4 \cdot 9 = 36 \qquad \text{Height x Width}$$



Integral = Area under the curve

In order to gain a deeper understanding of the conversion from spectral density to RMS, we will need to use a little calculus. As a quick reminder, remember that the integral of a function is the area under its curve. The area of a rectangle is simply the width times the height, so the integral of a rectangle is also the width times the height. This simple fact will be useful in doing a dimensional analysis for noise.

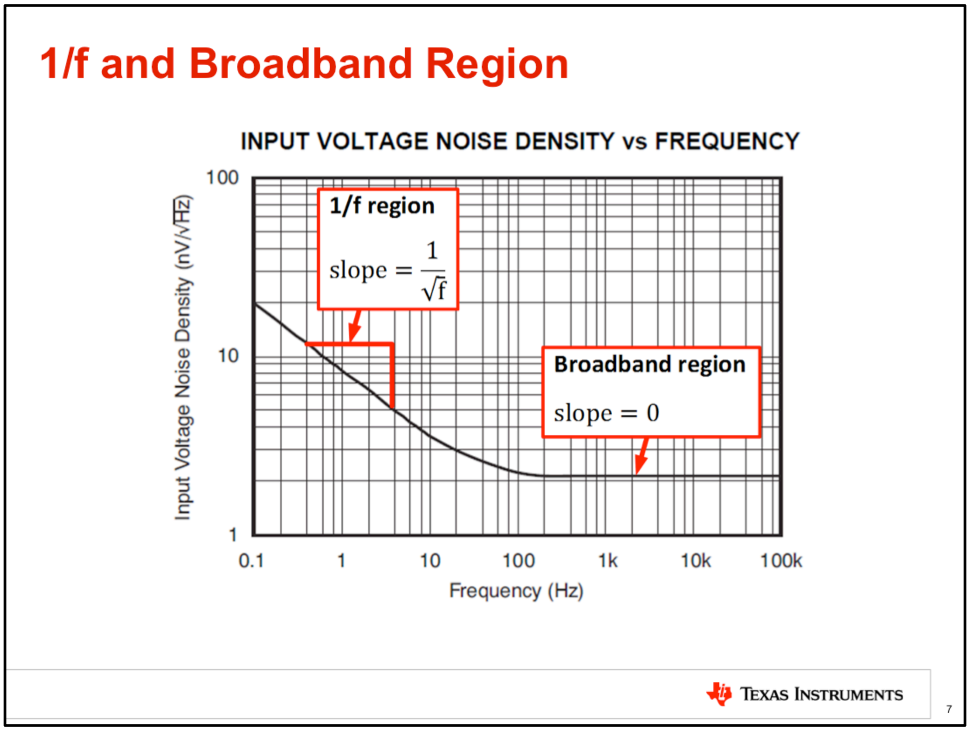


In this slide we will reiterate the method for converting from voltage spectral density to RMS voltage. A common misunderstanding with noise analysis is that total noise can be computed by integrating the **voltage** or **current** spectral density, when in fact you must integrate the **power** spectral density.

The example at the top of the slide shows what happens when integrating voltage spectral density. Remember from the previous slide that the integral of a rectangle is the width times the height, so in this case the result is 5 V/√Hz x 10Hz. Notice that the units for this example are very unusual, V*Hz / √Hz. In fact, the units should be Volts. The point is that through dimensional analysis you can see that integrating voltage spectral density directly is not the correct way to convert spectral density to rms.

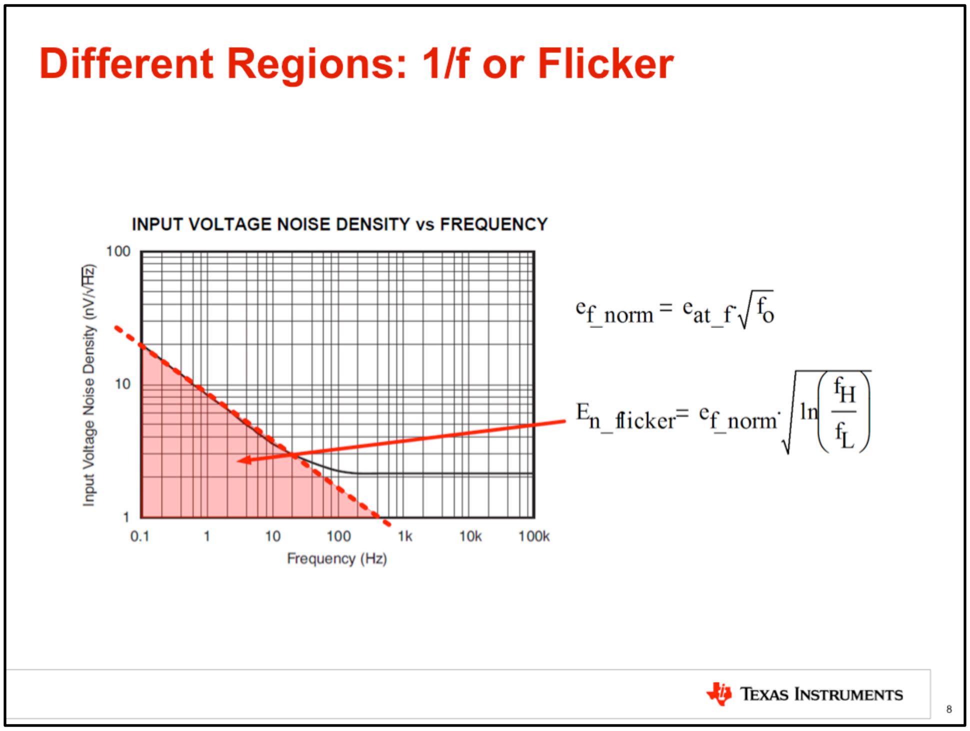
The example at the bottom, on the other hand, integrates power spectral density. Again, remember that that power is equal to V^2/R for voltage and I^2*R for current. When integrating power spectral density and taking the square root of the result, you get the correct units of Volts. Thus, when computing total noise, make sure to integrate the power spectrum.

Now that we understand how to properly integrate a spectral density curve, let's consider the different regions.

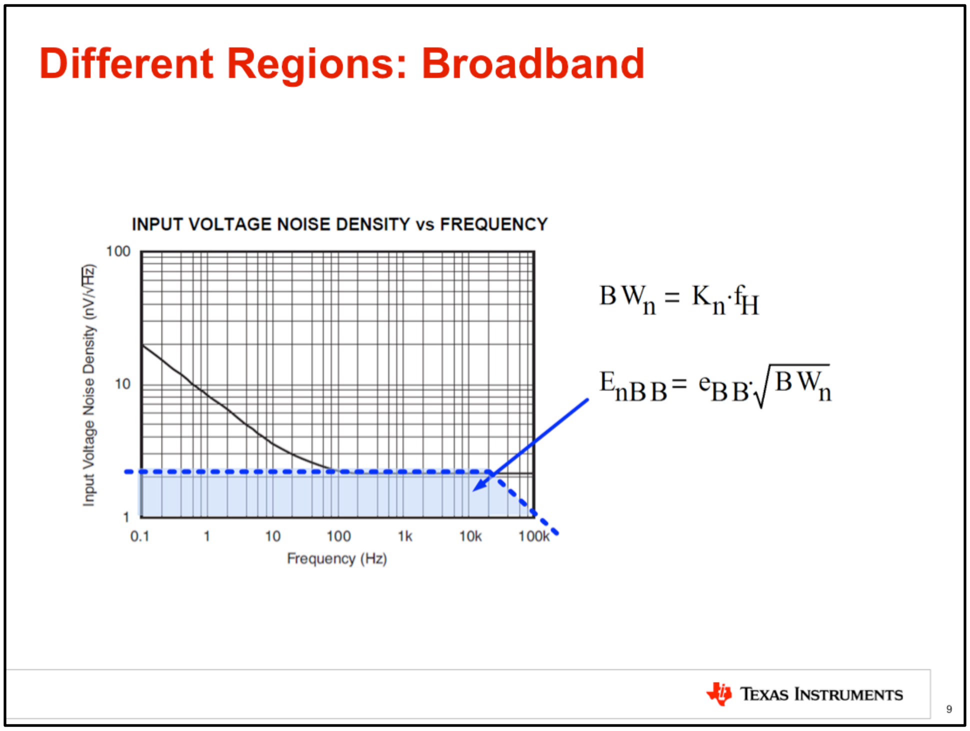


The spectral density curve has two regions: the 1/f region and the broadband region. In the previous presentation we looked at 1/f and broadband noise in the time domain. 1/f noise occurs at low frequency, and has a slope of one divided by the square root of frequency for both voltage and current spectral density. Remember that power spectral density is voltage spectral density squared, so for power spectral density the slope of 1/f noise is equal to one divided by frequency. This is where it gets the name 1/f. Broadband, or white noise, has a flat spectral density.

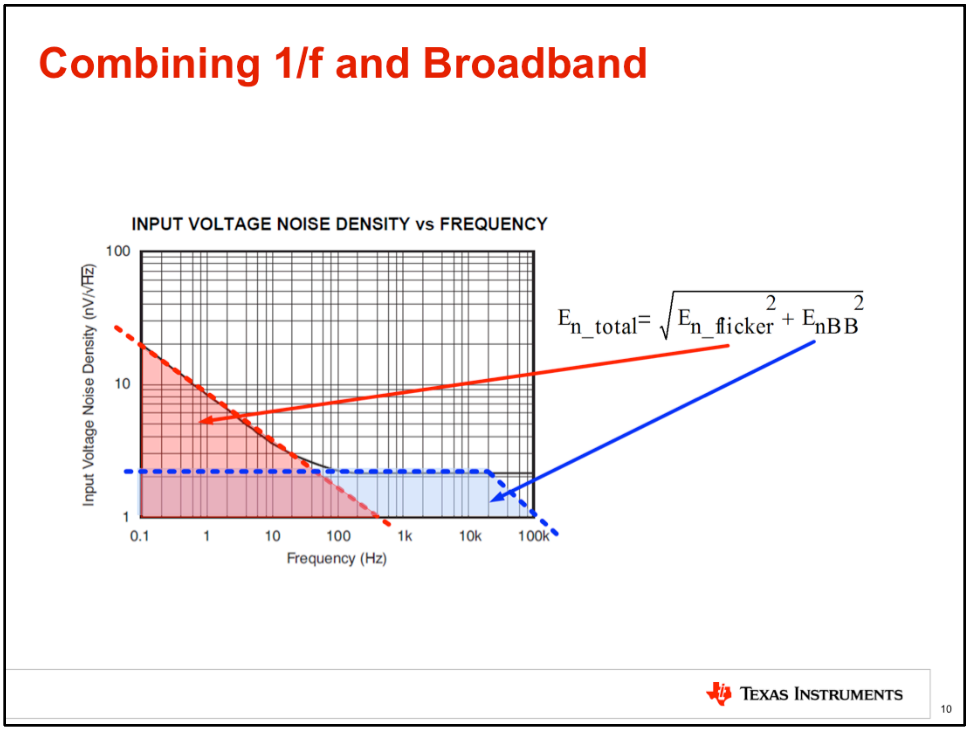
Let’s take a closer look at 1/f noise.



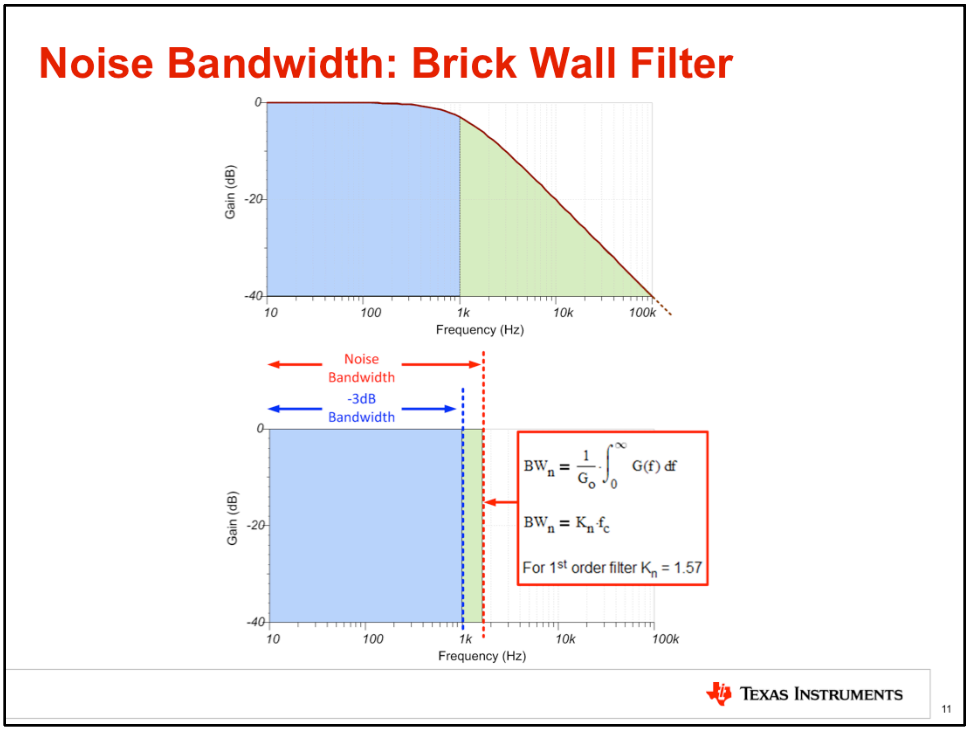
To get the total RMS noise associated for the 1/f region, we have to integrate the power spectral density and take the square root of the result. Using this method gives the formulas shown on the right. Later on, we will discuss these equations in detail and work through a real-world example.



Now let's consider the broadband region. Notice that a low pass filter is added at the end of the broadband region. All real-world circuits will have some kind of bandwidth limitation. Without bandwidth limitation, the total integrated noise would be infinite. Notice that the broadband region extends back to low frequency.



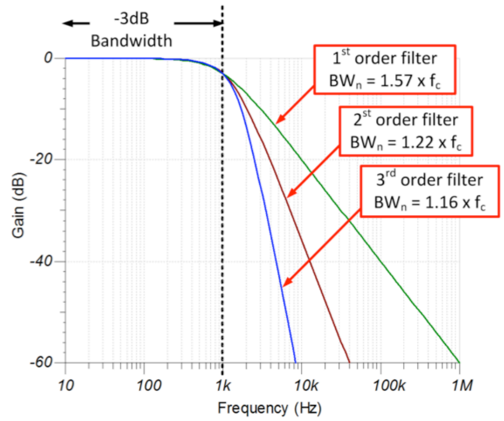
In fact, if we consider both regions at the same time, you can see that the 1/f and broadband region both are present at all frequencies. At low frequencies, 1/f noise is dominant, but broadband noise is still present. At higher frequencies, the broadband noise is dominant, but 1/f is still present. To find the total combined noise, you must add the contribution of the two regions using the root sum of the squares.



Let's move on to the topic of noise bandwidth. As mentioned previously, the noise bandwidth of a real-world system has a low-pass filter response due to the circuit's inherent bandwidth limitations. The area under the skirt of the low pass response, shown in green, is added to the flat band response, shown in blue, to create a rectangle-shaped low pass filter. This rectangular filter, called a **brick wall** filter, has the same area as the low pass filter. It is called a brick wall because the stop band drops off vertically like a "brick wall". The point of doing this transformation is that a rectangle is easy to integrate so the noise calculations are greatly simplified.

Notice that the formula used to calculate the noise bandwidth involves calculus. In general, this formula is only needed once, and allows us to determine easy-to-use correction factors for different order filters. In this example, the formula was used to compute the correction factor of 1.57 for a 1^{st}-order filter. On the following slide we will see correction factors for other order filters.

Noise Bandwidth: Brick Wall Factor



Noise Bandwidth

$BW_n = f_H * K_n$

Number of Poles	K_n Brickwall Correction Factor
1	1.57
2	1.22
3	1.16
4	1.13
5	1.12

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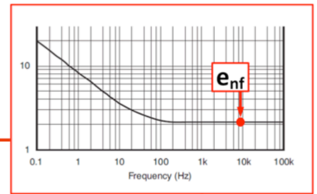
This slide gives a table of brick wall correction factors that can be used to calculate noise bandwidth. To convert the -3dB bandwidth to the noise bandwidth, just multiply by the correction factor $\mathbf{K_n}$. Notice that the brick wall correction factor begins to approach one as the number of poles increases. This makes sense, since higher-order filters have a steeper roll-off, like a brick wall. One thing to consider is that gain peaking can affect the noise bandwidth, so in practical circuits the actual noise bandwidth may differ somewhat.

Broadband Noise Equations



$$BW_n = K_n * f_H$$

Where:

BW_n	Noise bandwidth (bandwidth of brick wall filter)
K_n	Brick wall correction factor, includes the "skirt" of the low pass filter
f_H	-3dB upper cutoff frequency

$$E_{n_{BB}} = e_{BB}\sqrt{BW_n}$$

Where:

$E_{n_{BB}}$	Total RMS broadband noise
e_{BB}	Broadband voltage noise spectral density
BW_n	Noise bandwidth

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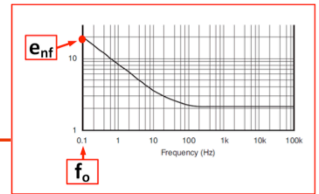
Now that we have the noise bandwidth relationship, we can use it to convert the op amp noise spectral density curve to RMS noise. The first equation given in this slide is the noise bandwidth equation that we have already discussed. Simply use the table on the previous slide to select the appropriate value for K_n and convert your signal bandwidth to noise bandwidth.

The second equation on this slide shows how to convert spectral density to RMS noise. The RMS noise, E_{n_BB}, is calculated by multiplying the broadband noise spectral density by the square root of the noise bandwidth. The value for the broadband spectral density can be read from the spectral density curve given in the op amp's data sheet. The relationship for converting noise spectral density to RMS noise is of key importance and should be memorized. It helps to remember the units when memorizing the formula. Spectral density in nV/√Hz is multiplied by the square root of noise bandwidth; the √Hz from both factors cancels so that RMS voltage has units of Volts.

1/f Noise Equations



$$e_{n_{normal}} = e_{nf}\sqrt{f_o}$$

Where:

$e_{n_{normal}}$ 1/f voltage noise spectral density normalized to 1Hz

e_{nf} Noise at lowest given frequency on the 1/f curve

f_o Lowest given frequency on the 1/f curve

$$E_{n_{flicker}} = e_{n_{normal}}\sqrt{\ln\left(\frac{f_H}{f_L}\right)}$$

Where:

$E_{n_{flicker}}$ Total RMS 1/f noise

$e_{n_{normal}}$ 1/f voltage noise spectral density normalized to 1Hz

f_H Upper cutoff frequency

f_L Lower cutoff frequency (typically set to 0.1Hz)

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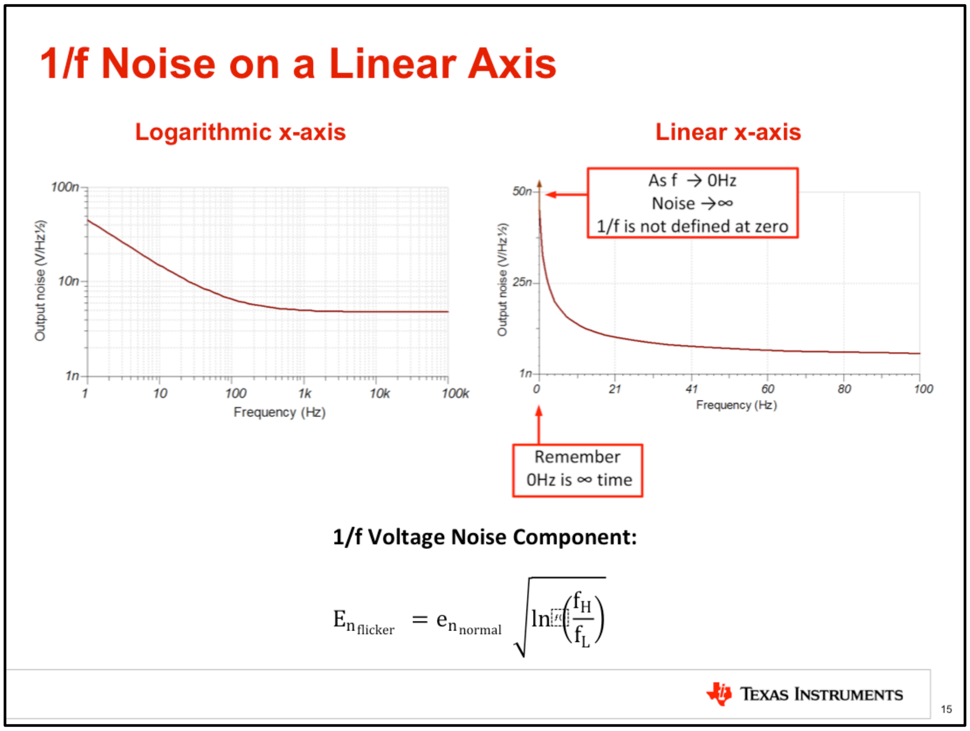
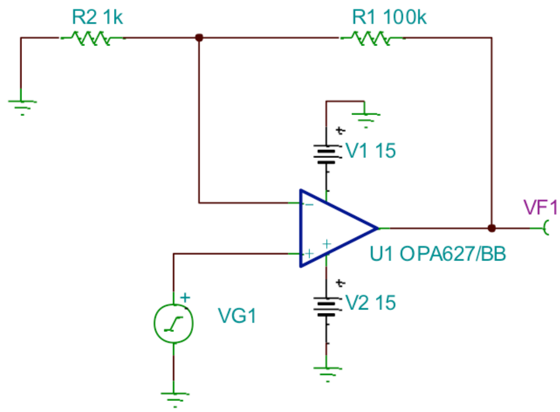
Let's move on to the 1/f noise equations. The first equation gives the 1/f noise normalized to 1Hz, given by e_{n_normal}. This means that we take a point on the 1/f curve and translate the spectral density to a level corresponding to what would be read at 1Hz. In general, it is best to choose e_{nf} at the lowest frequency possible, because this will ensure that 1/f is dominant.

The second equation computes the total RMS noise from the 1/f region. Notice that the equation uses the normalized 1/f noise from the previous equation as well as both the upper and lower cutoff frequency. It's easy to understand why the upper cutoff frequency is used, because it represents the same system bandwidth limitation as seen in broadband noise. But why do we need a lower cutoff frequency limitation?



Remember that we normally look at noise spectral density on a graph with a logarithmic x-axis. If we instead consider the spectral density curve with a linear x-axis, it becomes clear that noise increases to infinity at 0 Hz. The fact that noise is infinite at 0 Hz sounds alarming, until you consider that 0 Hz corresponds to infinite time. Infinite time is not practical to consider, so for practical considerations we use 0.1Hz for f_L, the lower cutoff frequency. 0.1Hz corresponds to 10 seconds. In a later noise video we will take a deeper look into low frequency noise and the effect of observing noise over long time durations.

Next Video - Example Noise Calculation



Given
OPA627
Noise Gain of 101

Find (RTI, RTO)
Voltage Noise
Current Noise
Resistor Noise

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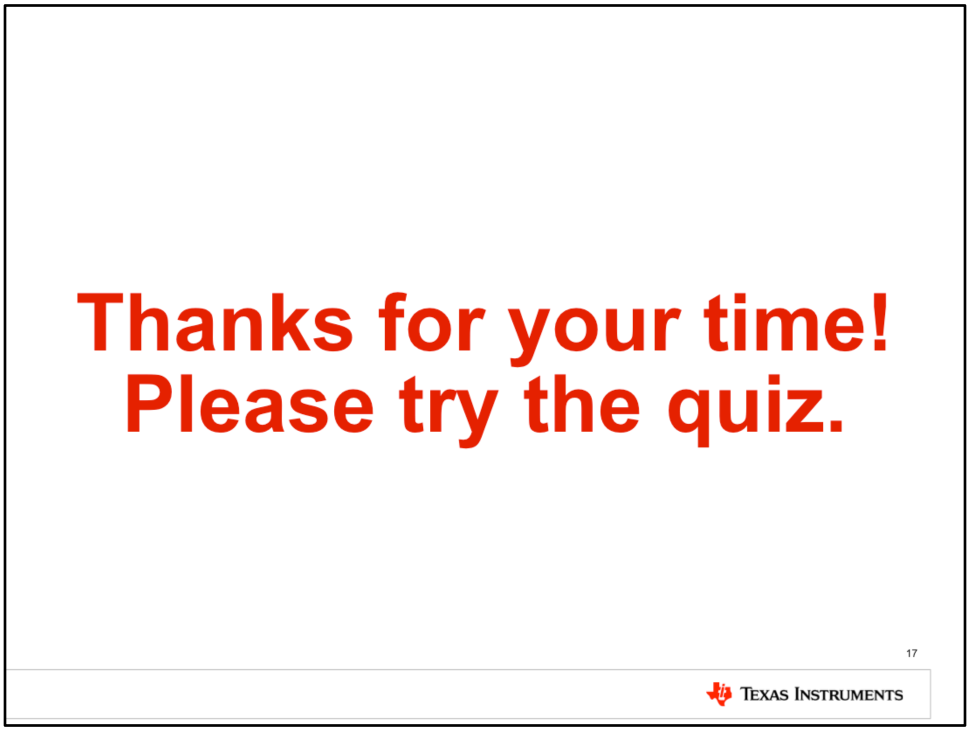
In the next video we will perform a full example noise calculation. This example will use the OPA627 in a non-inverting configuration. The total noise at the output will be the sum of op-amp voltage noise, op-amp current noise, and resistor noise. We will consider both the 1/f region and the broadband region in the spectral density curve. Finally, we will have to consider the noise bandwidth and the noise gain of the circuit.



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