Noise – 5

TIPL 1315
TI Precision Labs – Op Amps

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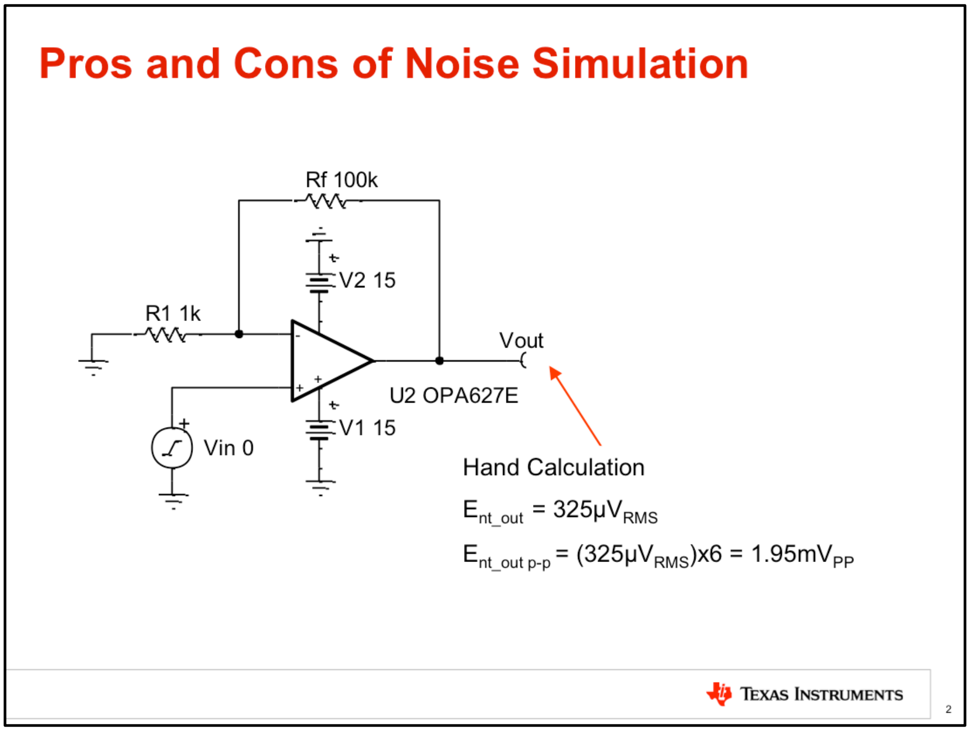
Hello, and welcome to the TI Precision Lab discussing intrinsic op amp noise, part 5.

In the last video we learned some rules of thumb that help to simplify noise calculations. In this video we will show how to perform noise simulations using Tina-TI, a free SPICE simulation program.



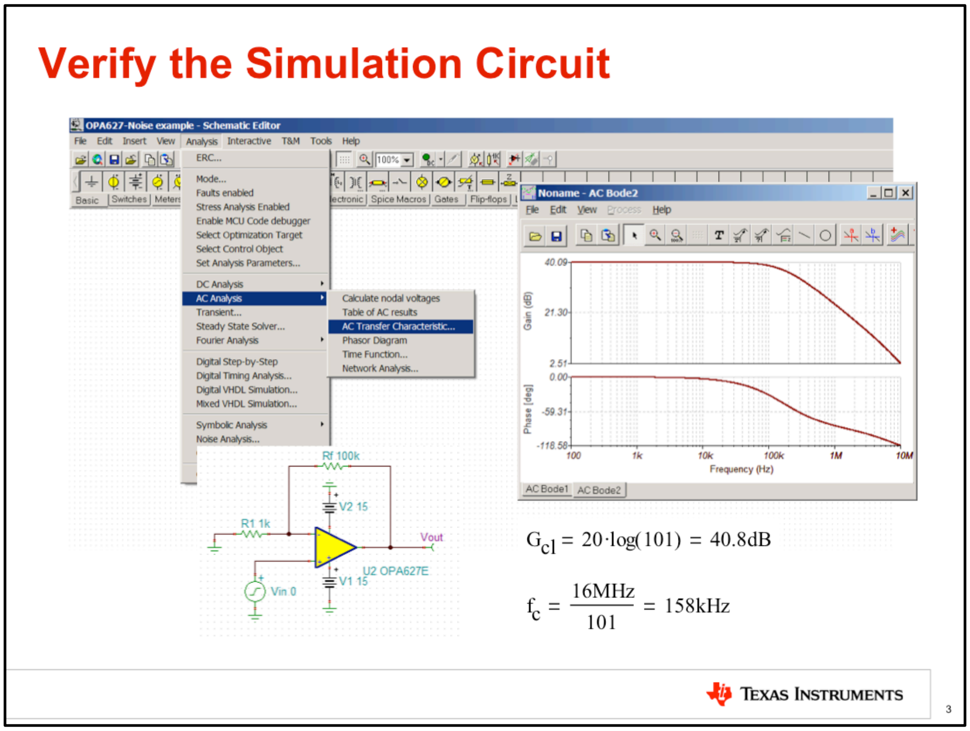
Pros and Cons of Noise Simulation

Hand Calculation

$E_{nt\_out} = 325\mu V_{RMS}$

$E_{nt\_out\ p\text{-}p} = (325\mu V_{RMS})x6 = 1.95mV_{PP}$

In the third noise video we calculated the output noise for the OPA627 circuit shown on this slide. In this presentation we will learn how to solve the same problem using simulation. Using simulation to solve noise problems is much easer than hand calculations, so naturally some engineers choose to skip the hand calculations and rely only upon simulation. Don't fall into this trap! The hand calculations give useful insight into the dominant noise sources, which helps greatly when working to reduce noise. Furthermore, there may be an issue with the simulation that produces an erroneous result. On the other hand, having agreement between simulation and hand calculation gives you strong confidence that your answer is correct.



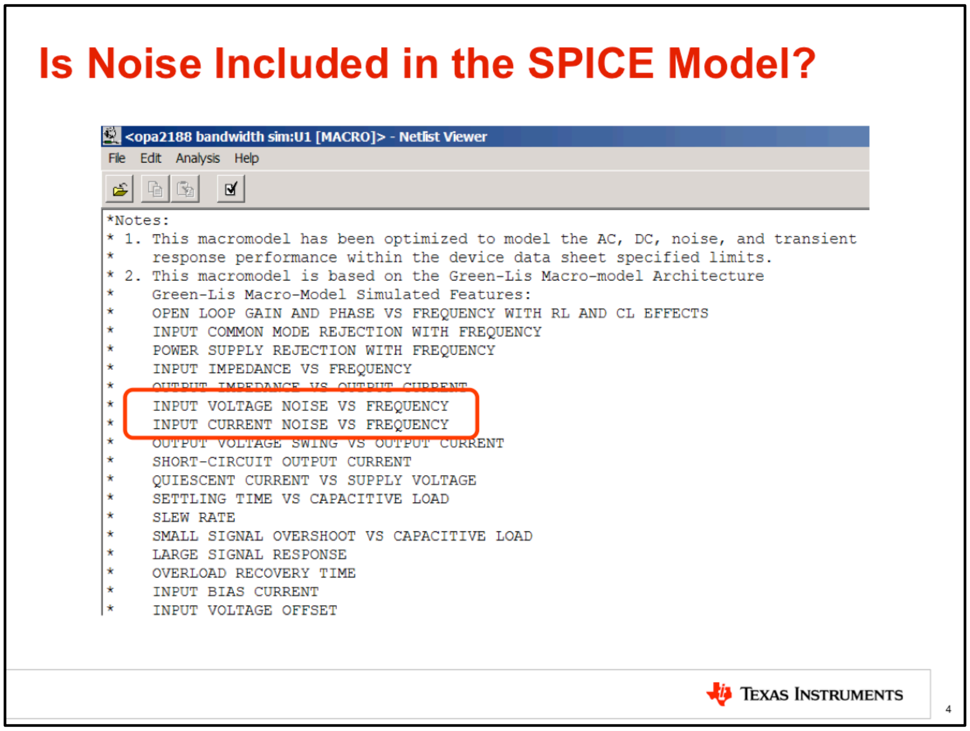
Verify the Simulation Circuit

$$G_{cl} = 20 \cdot \log(101) = 40.8\text{dB}$$

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

Texas Instruments

Before doing a noise simulation, you need to be verify that the circuit is connected properly. This is important because SPICE will not necessarily issue an error or warning if the circuit is miswired. Often, circuits that are miswired just give an incorrect noise simulation result, which can trick you into thinking that your system has really great noise performance. The easiest way to be confident that your circuit is connected correctly is to run an ac transfer characteristic. Refer to the videos on Bandwidth for a review of how to run an ac transfer characteristic simulation. A very simple hand calculation for gain and bandwidth can confirm that the simulation circuit is working as intended.



Is Noise Included in the SPICE Model?

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*Notes:
* 1. This macromodel has been optimized to model the AC, DC, noise, and transient
*    response performance within the device data sheet specified limits.
* 2. This macromodel is based on the Green-Lis Macro-model Architecture
*    Green-Lis Macro-Model Simulated Features:
*    OPEN LOOP GAIN AND PHASE VS FREQUENCY WITH RL AND CL EFFECTS
*    INPUT COMMON MODE REJECTION WITH FREQUENCY
*    POWER SUPPLY REJECTION WITH FREQUENCY
*    INPUT IMPEDANCE VS FREQUENCY
*    OUTPUT IMPEDANCE VS OUTPUT CURRENT
*    INPUT VOLTAGE NOISE VS FREQUENCY
*    INPUT CURRENT NOISE VS FREQUENCY
*    OUTPUT VOLTAGE SWING VS OUTPUT CURRENT
*    SHORT-CIRCUIT OUTPUT CURRENT
*    QUIESCENT CURRENT VS SUPPLY VOLTAGE
*    SETTLING TIME VS CAPACITIVE LOAD
*    SLEW RATE
*    SMALL SIGNAL OVERSHOOT VS CAPACITIVE LOAD
*    LARGE SIGNAL RESPONSE
*    OVERLOAD RECOVERY TIME
*    INPUT BIAS CURRENT
*    INPUT VOLTAGE OFFSET
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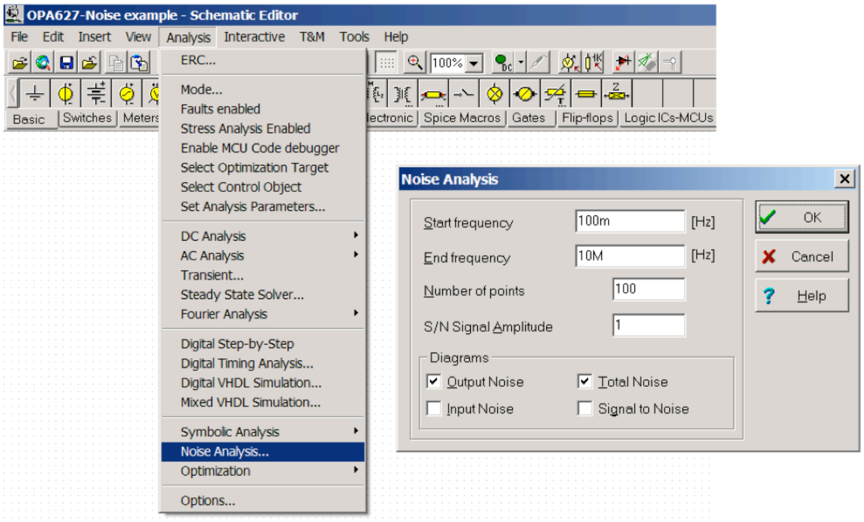
Another important thing to check before doing a simulation is if the op amp's SPICE model includes noise characteristics. If you double-click on Texas Instruments models in TINA-TI and click "Enter Macro," a net list viewer will open. The top of the net list on TI models includes a description of what is modeled. The key parameters to look for are **input voltage noise vs. frequency** and **input current noise vs. frequency**.

Other SPICE software packages will have similar net list viewers. In the next video, we will show a more comprehensive method that confirms the accuracy of the noise model. It is important to be aware of the fact that not all SPICE models will model noise. In fact, this applies to other parameters as well. Always be aware of what your model covers, and always compare your simulated result to a hand calculation.

Running a Noise Analysis Simulation

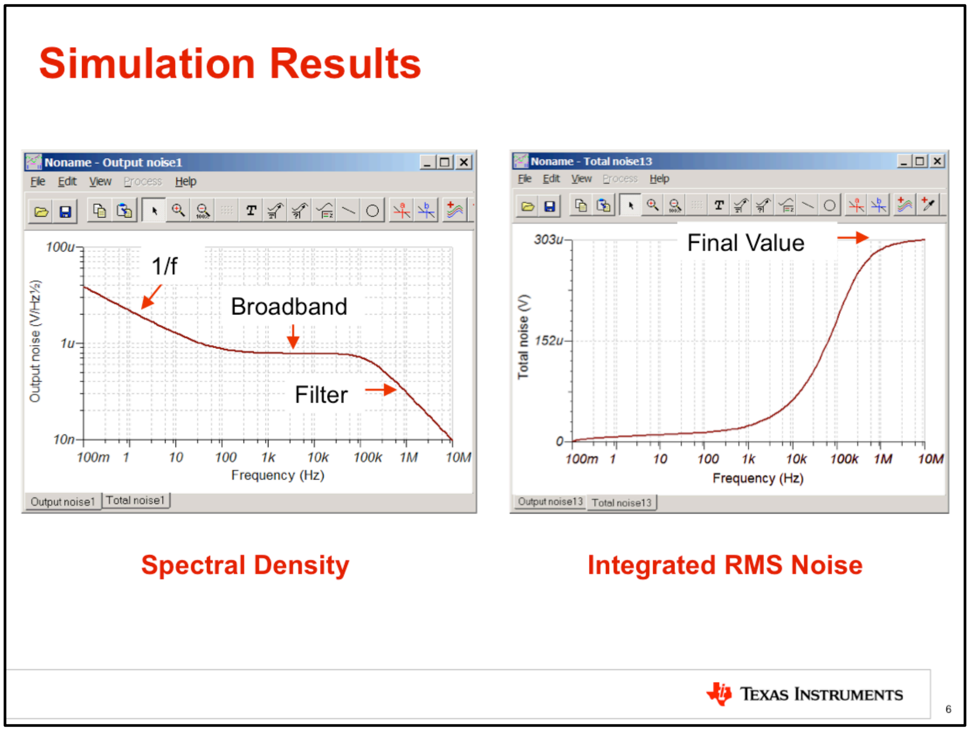


Start frequency 100m [Hz]
End frequency 10M [Hz]
Number of points 100
S/N Signal Amplitude 1

Diagrams
☑ Output Noise
☑ Total Noise
☐ Input Noise
☐ Signal to Noise

To run a noise analysis simulation in Tina SPICE, click “Analysis” in the menu bar, then click “Noise Analysis.” This brings up the “Noise Analysis” window. Enter the Start frequency and End frequency according to your application. In this example, we are analyzing the same circuit from the hand calculation in Noise 3. The bandwidth of this example circuit is 158kHz.

In general, it is good choose an end frequency that is one or two decades greater than the bandwidth of your circuit. This is done so that we can integrate the skirt of the low pass filter response. The start frequency is generally selected to be 0.1Hz, or 100mHz, so that the 1/f noise is included. The default number of points is 100. This is normally sufficient for most calculations, although you can add more points to improve accuracy. Select the “output noise” and “total noise” diagrams. **Output noise** is the noise spectral density measured at any meter or probe. If you have several meters placed on the simulation schematic, you will get one curve for each meter. The **Total noise** is the RMS noise integrated using the methods that were discussed in previous videos. Let’s take a look at the results for this example.



Simulation Results

Spectral Density

Integrated RMS Noise

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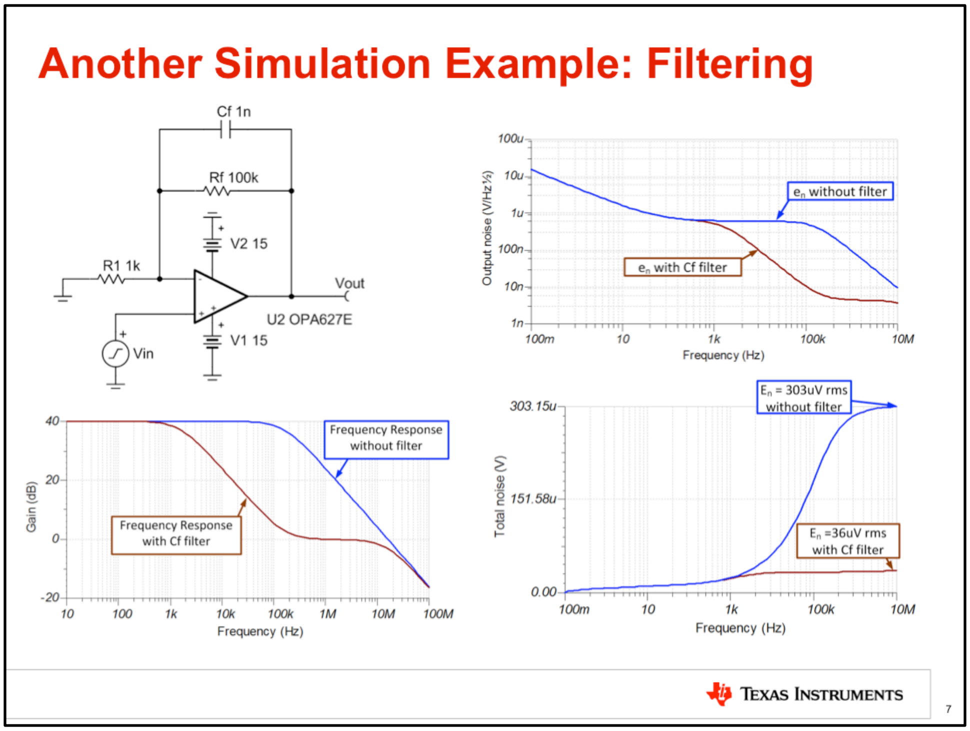
This slide shows the simulation results. The graph on the left is the spectral density plot, called “Output Noise” by TINA-TI. Note that the 1/f, broadband and filtered regions are clearly visible. The filtered region results purely from the op amp’s inherent bandwidth limitations, since there is no filter on the circuit.

The graph on the right is the integrated RMS noise, called “Total Noise” by TINA-TI. This graph is calculated using the same equations introduced in the hand calculation section. That is, the voltage noise spectral density is squared, integrated across frequency, and the square root is taken on the result. The total noise plot shows the noise integrated up to a given frequency with a brick wall filter. For example, the noise integrated from 0.1Hz to 100kHz is about 152uV rms. Ultimately, the most important information that can be taken from this graph is the total noise across the circuit’s entire bandwidth. For this example, the total noise across the entire bandwidth is about 303uV rms. Notice that the integrated noise converges to a final value. This occurs because the low pass filter response of the op amp limits the total noise. In general, you should look for the integrated noise curve to converge as in this example. If it does not converge you may have to increase the “End Frequency” in your simulation.

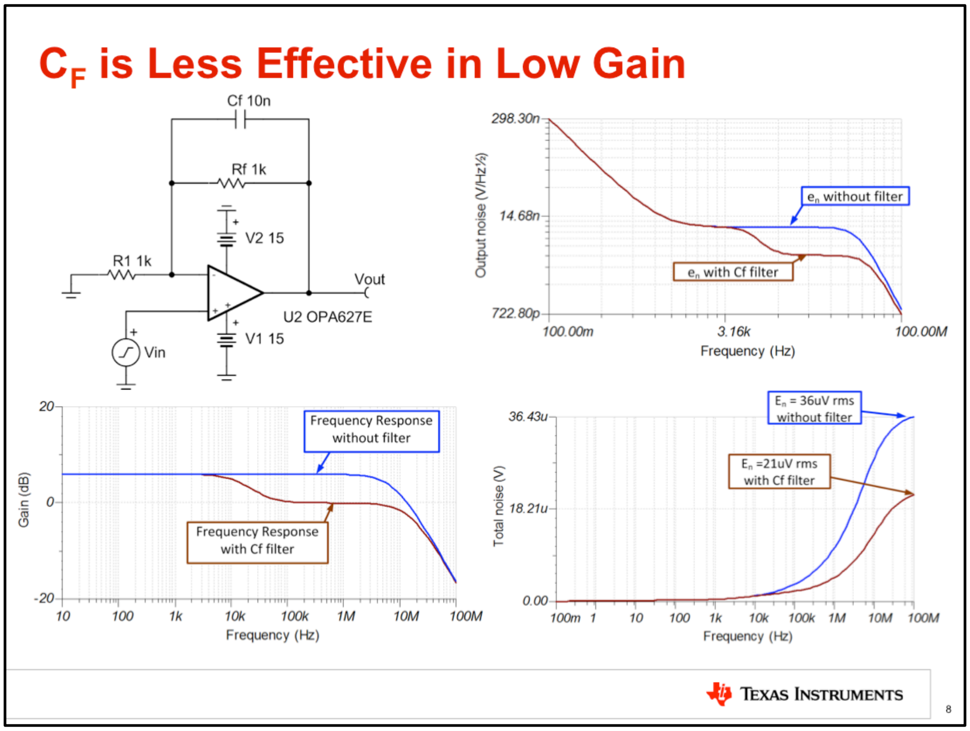
So, how does the simulation result compare with the hand calculations from noise video 3? The total noise from the hand calculation was 324uV rms and the



Another Simulation Example: Filtering

Now that we know how to do noise simulations let's try a few more examples. This example is the same circuit that we just simulated, except that a filter capacitor Cf of 1nF is added. This filter will decrease the impedance of the parallel combination of Rf and Cf at high frequencies. This causes the closed-loop gain to reduce with frequency, because the closed-loop gain is equal to the impedance of the feedback network divided by R1, +1. At some frequency the capacitor effectively becomes a short, which reduces the closed-loop gain to 1V/V or 0dB. The gain will remain at 0dB until the op amp's bandwidth limit causes the gain to further decrease further. Notice that this curve on the bottom left shows the effects with and without the filter. You can see that when the filter capacitor is acting like a short, the attenuation is about 40dB.

The output noise, or spectral density, curve, on the top right is simulated from the input noise spectral density multiplied by the circuit's gain vs. frequency. Thus, the filter attenuates the noise by about 40dB maximum. Finally, the integrated noise curve on the bottom right tells us that the total output noise is reduced from 303uV rms to about 36uV rms. The filter reduced noise by a factor of 8.5! As long as your application doesn't need the bandwidth, this is a very effective way to reduce noise. However, this method works best with amplifiers that have high gain. Let's consider an amplifier with lower gain.



C_F is Less Effective in Low Gain

e_n without filter

e_n with Cf filter

Frequency Response without filter

Frequency Response with Cf filter

E_n = 36uV rms without filter

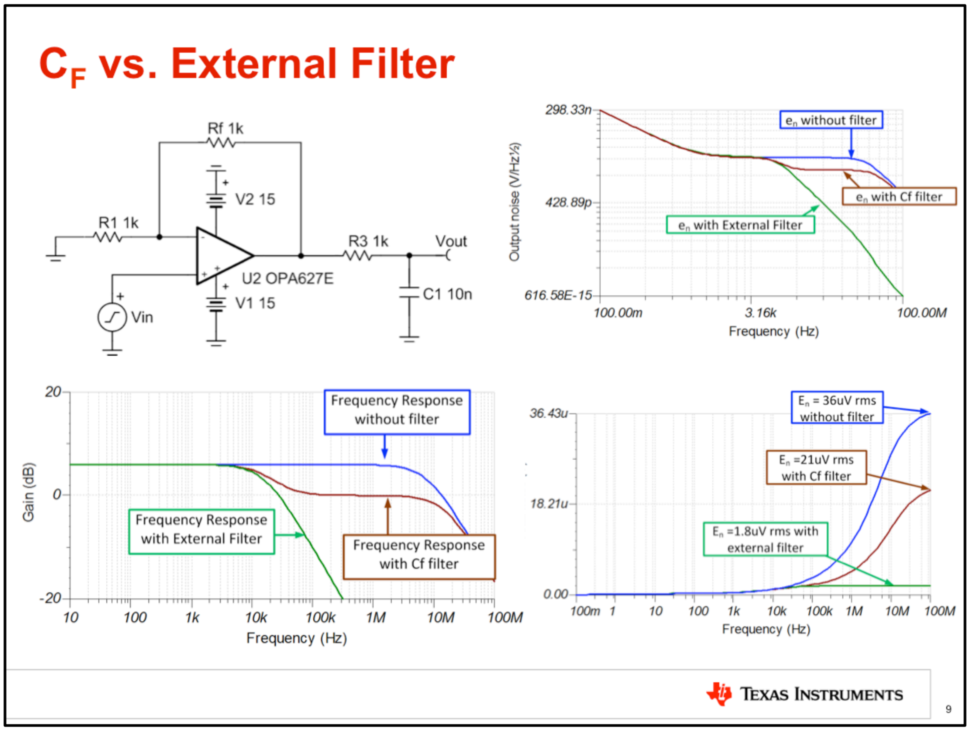
E_n =21uV rms with Cf filter

Texas Instruments

In this example the closed-loop gain is 2V/V or 6dB. The filter behaves in the same way, except that the effective attenuation when the capacitor is acting like a short is only 6dB. In general, this type of filter will reduce the gain from the dc gain to a gain of 1V/V. Thus, this filter is most effective for circuits with high gain.

Looking at the spectral density curve on the top right, you can see the noise reduction from the filter occurs in the broadband region. Finally, the integrated noise curve on the bottom right with and without the filter shows that noise is reduced from 36 to 21uV. Noise is reduced by a factor of 1.7 for this circuit, but was reduced by a factor of 8.5 for the previous high- gain circuit!

We can see from this example that the Cf filter is not as effective for low gain circuits. In this case, how do we properly filter noise from low gain circuits?

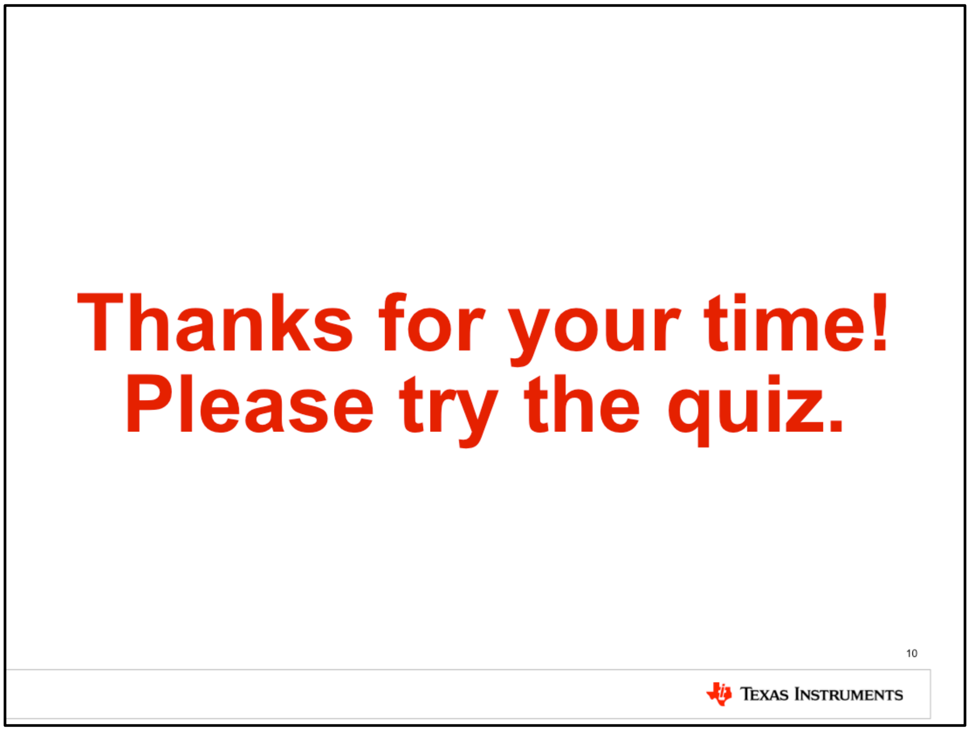


C_F vs. External Filter

Using an external filter, which is a filter outside the op amp feedback loop, is the most effective way to reduce noise in circuits with low gain.

Looking at the gain vs. frequency curves on the bottom left, we see that the gain for the circuit with an external filter continuously rolls off, where as the gain for the circuit with the C_F filter reduces to 0dB and remains constant until the op amp roll-off region. The external filter provides significantly more attenuation than the Cf filter.

The benefit of the external filter is also clear when looking at the spectral density curve on the top right. Finally, the integrated noise curve on the bottom right compares the noise without the filter, with a Cf filter and with an external filter. The external filter reduces noise by a factor of 20! The only disadvantage to using the external filter is that the output impedance is now high as compared to the op amp output. This is ok if the next stage has a high input impedance; however, there will be significant errors for low impedance loads.



Thanks for your time! Please try the quiz.

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