Noise – 5
TIPL 1315
TI Precision Labs – Op Amps

Presented by Ian Williams

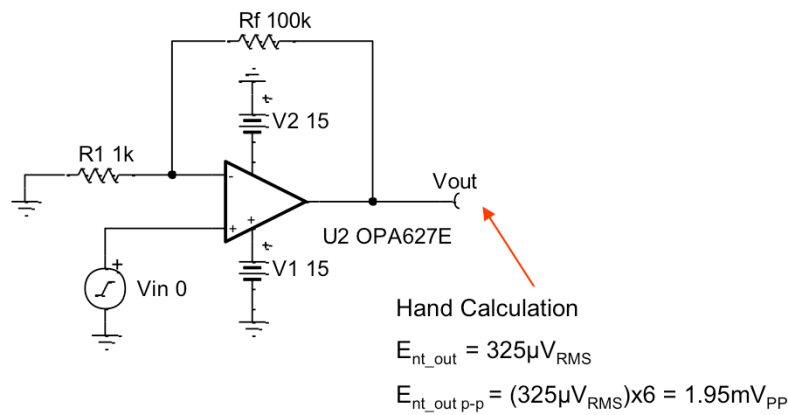Prepared by Art Kay and Ian Williams

TEXAS INSTRUMENTS

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

Rf 100k

V2 15

R1 1k

U2 OPA627E

V1 15

Vin 0

Vout

Hand Calculation

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

$E_{nt\_out\ p-p} = (325\mu V_{RMS}) \times 6 = 1.95 mV_{PP}$

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.
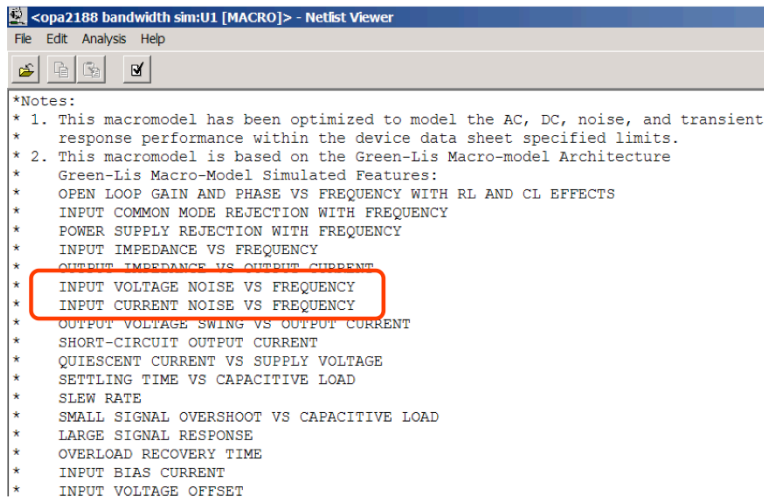
Verify the Simulation Circuit

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

$$f_c = \frac{16\text{MHz}}{101} = 158\text{kHz}$$
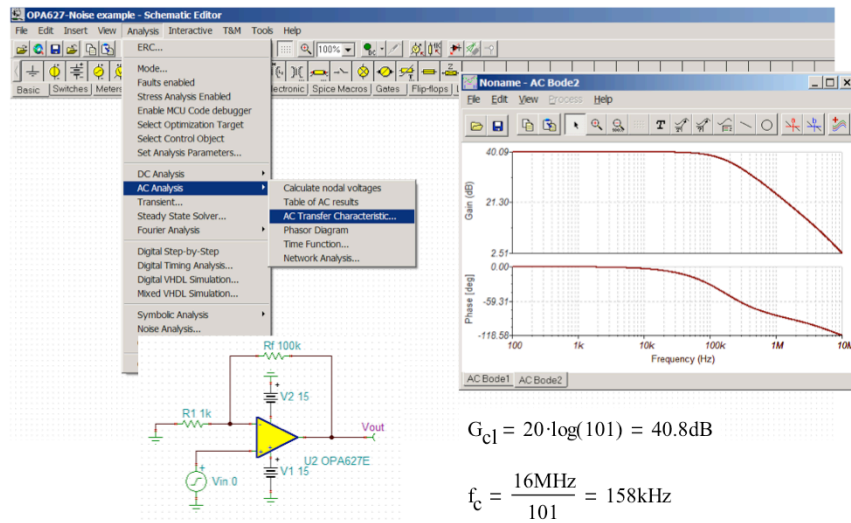
Before doing a noise simulation, you need to be verify that the circuit is connected properly. This is important because SPICE will not necessarily issue an error or warning if the circuit is miswired. Often, circuits that are miswired just give an incorrect noise simulation result, which can trick you 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?

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
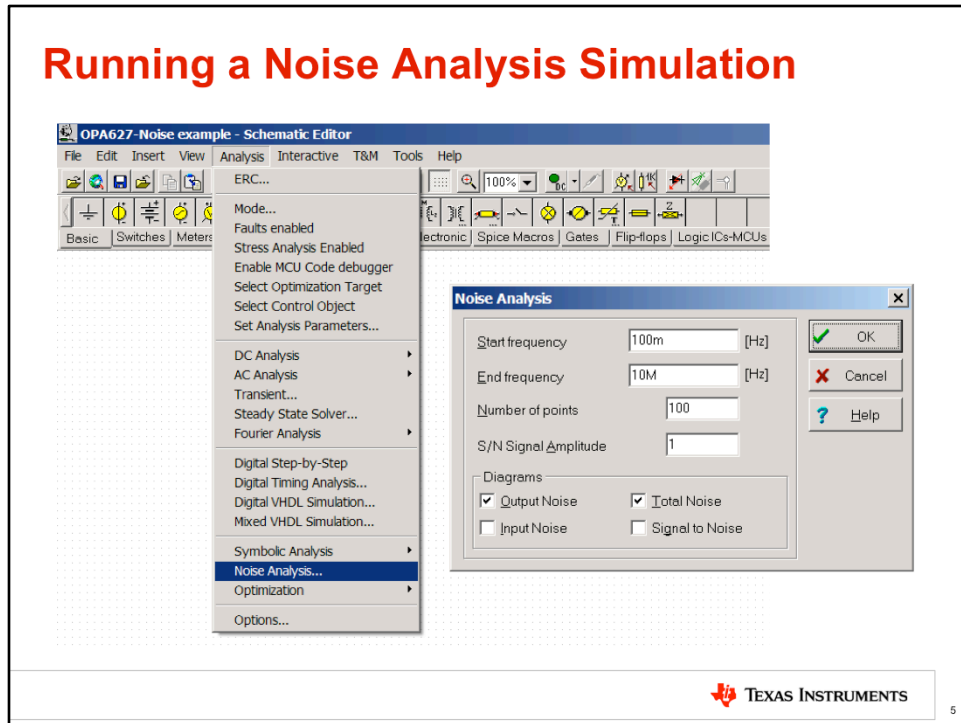
To run a noise analysis simulation in Tina SPICE, click "Analysis" in the menu bar, then click "Noise Analysis." This brings up the "Noise Analysis" window. Enter the Start frequency and End frequency according to your application. In this example, we are analyzing the same circuit from the hand calculation 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
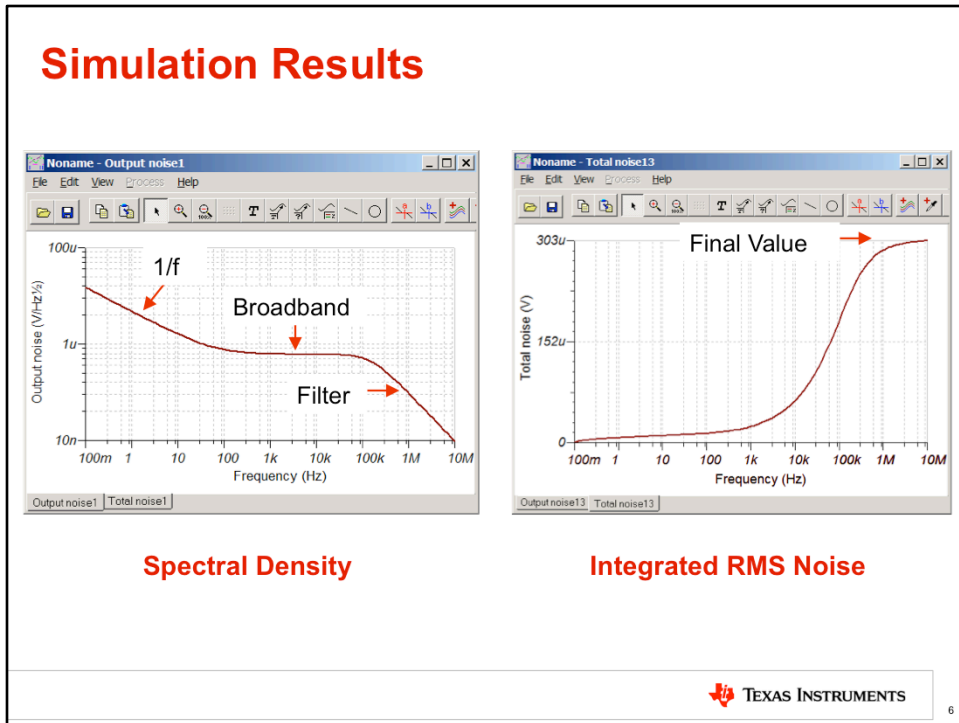
Spectral Density   Integrated RMS Noise

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
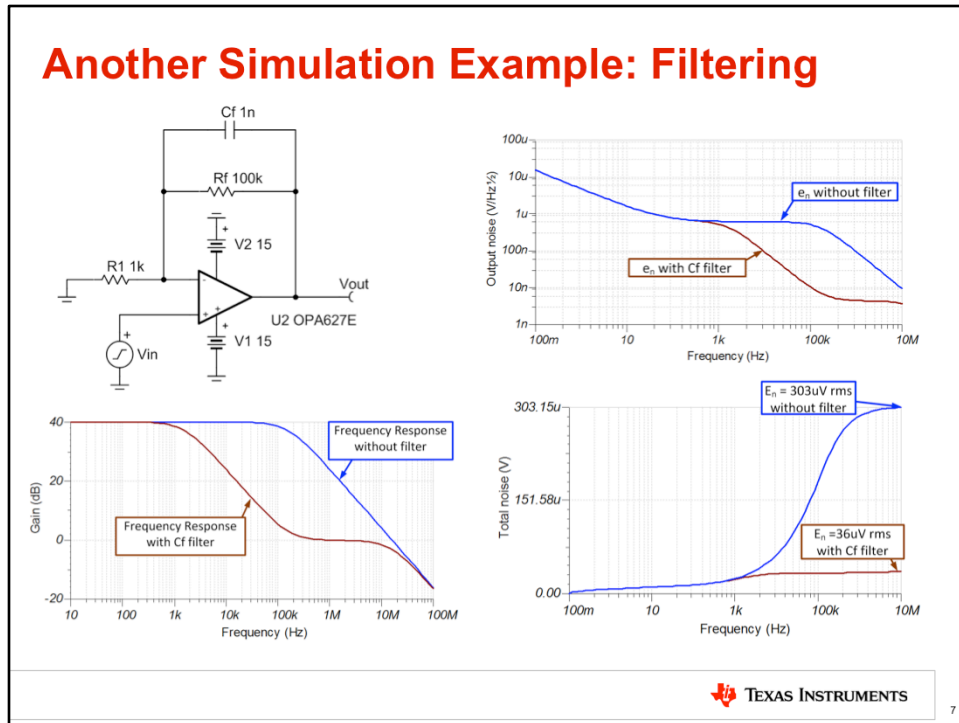
Now that we know how to do noise simulations let's try a few more examples. This example is the same circuit that we just simulated, except that a filter capacitor Cf of 1nF is added. This filter will decrease the impedance of the parallel combination of Rf and Cf at high frequencies. This causes the 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.
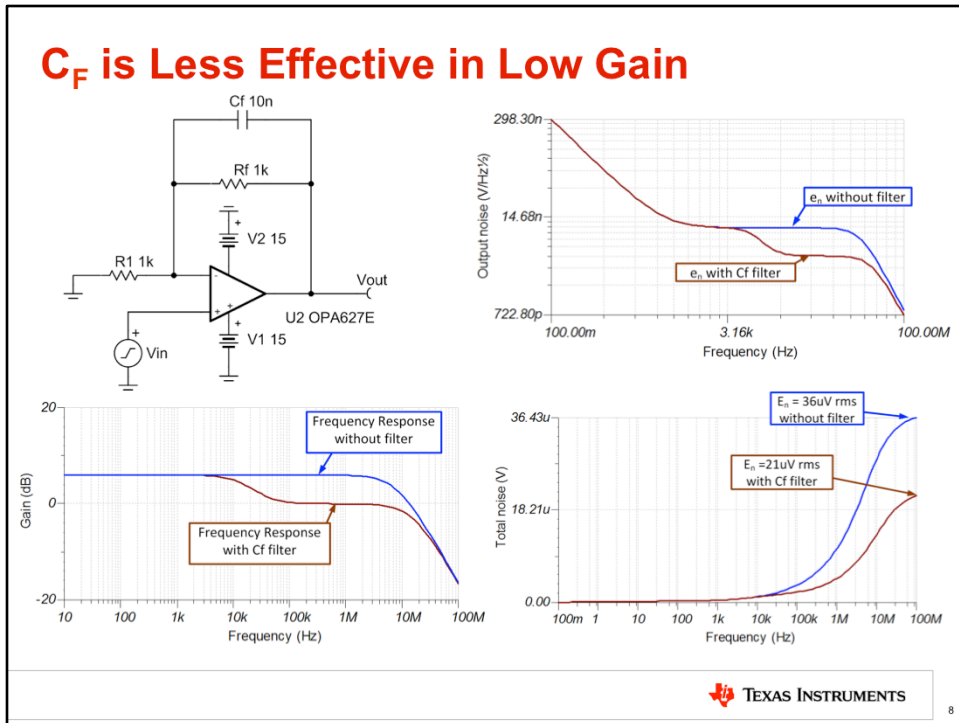
In this example the closed-loop gain is 2V/V or 6dB. The filter behaves in the same way, except that the effective attenuation when the capacitor is acting like a short is only 6dB. In general, this type of filter will reduce the gain from the dc gain to a gain of 1V/V. Thus, this filter is most effective 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?
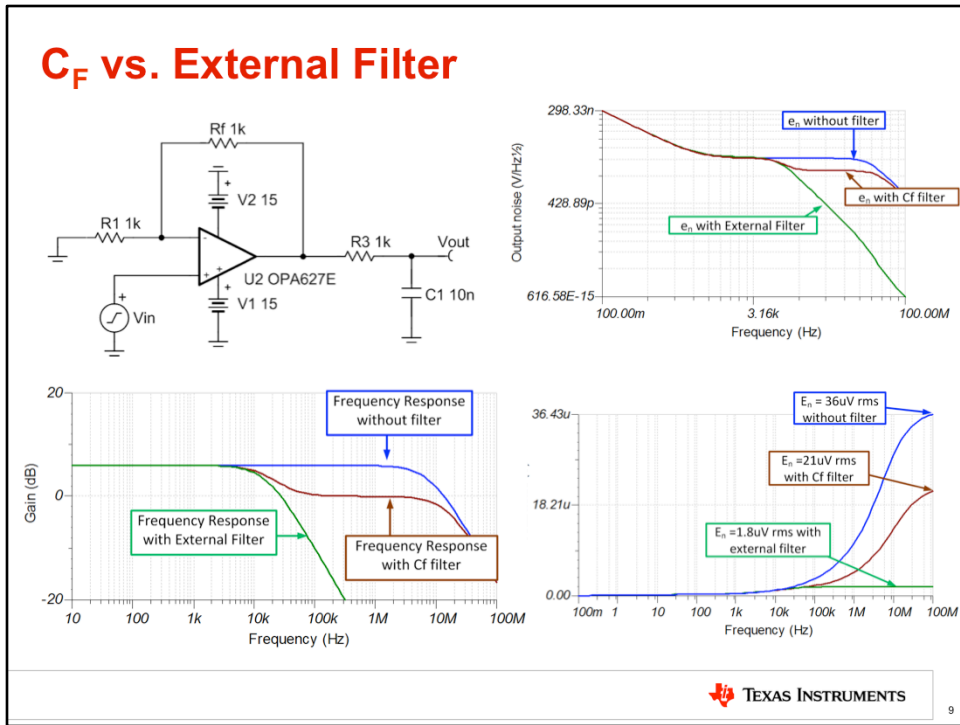
Using an external filter, which is a filter outside the op amp feedback loop, is the most effective way to reduce noise in circuits with low gain.

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.

Noise 5

Multiple Choice Quiz

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Quiz: Noise 5

1. Assume that a amplifier has a bandwidth of 100kHz. What should you set the start and end frequency to in order to find the total noise?
a. 1kHz to 100kHz
b. 100Hz to 10kHz
c. 0.1Hz to 10MHz
d. 0Hz to 100kHz

2. How can you test that the simulation circuit is connected correctly?
a. If no error check messages appear, it is connected correctly.
b. Noise will converge to a final value.
c. Run an ac transfer characteristic and compare the bandwidth to a hand calculation.
d. Carefully make sure that the circuit is wired correctly, and check all component values.

3. What is a quick way to ensure that noise is modeled?
a. Run a transient simulation and look for noise in the time domain.
b. Spice will issue a warning if noise is not modeled.
c. Check the model using the net list viewer. The modeled parameters are listed.

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Quiz: Noise 5

4. How do you find the integrated rms output noise using simulation?
a. Output Noise Diagram
b. Total Noise Diagram

5. How do you find the noise spectral density using simulation?
a. Output Noise Diagram
b. Total Noise Diagram

6. When looking at the total noise diagram, you should expect ____.
a. The noise to flatten out or converge to a final value at high frequency.
b. The noise to decrease or roll-off at high frequency.
c. The noise to increase abruptly in the 1/f region.
d. The peak noise to be 1 decade below the bandwidth.

Quiz: Input Offset Voltage (V$_{OS}$) & Input Bias Current (I$_B$)

7. When is a filter capacitor across the feedback resistor most effective?
a. When the amplifier is in high gain.
b. When the amplifier is in low gain.

8. What is the drawback of using an external RC low pass filter as opposed to a feedback capacitor filter?
a. This can cause instability under some conditions.
b. It introduces a leakage path to ground.
c. The output impedance of the amplifier is decreased.
d. The output impedance of the amplifier is increased.

Noise 5

Multiple Choice Quiz: Solutions

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Noise 5

Exercises

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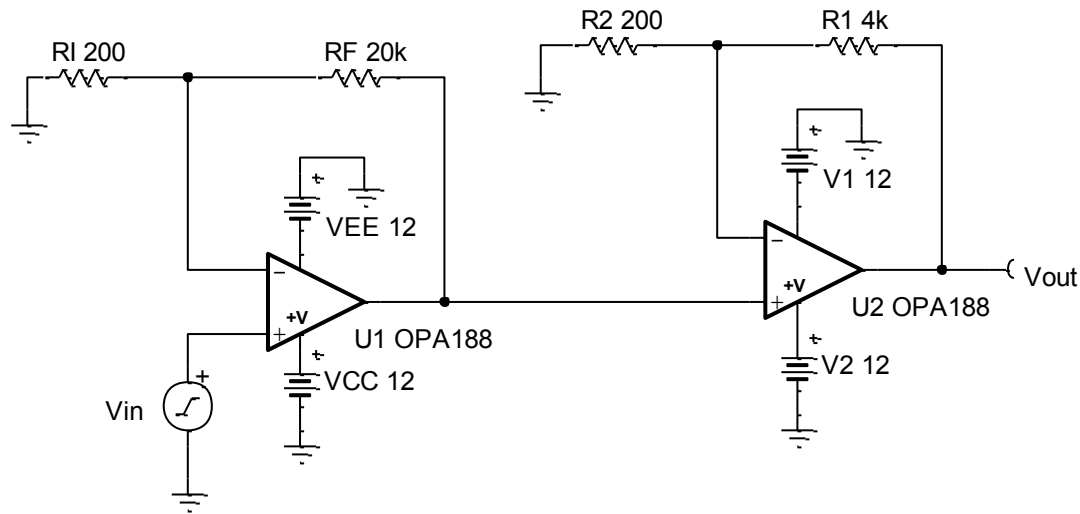
![Texas Instruments logo]

1. Use simulation to determine the noise spectral density and total rms noise for the circuit below. This circuit was solved by hand in the problems from noise 4. Compare the simulated results to the hand calculation results.
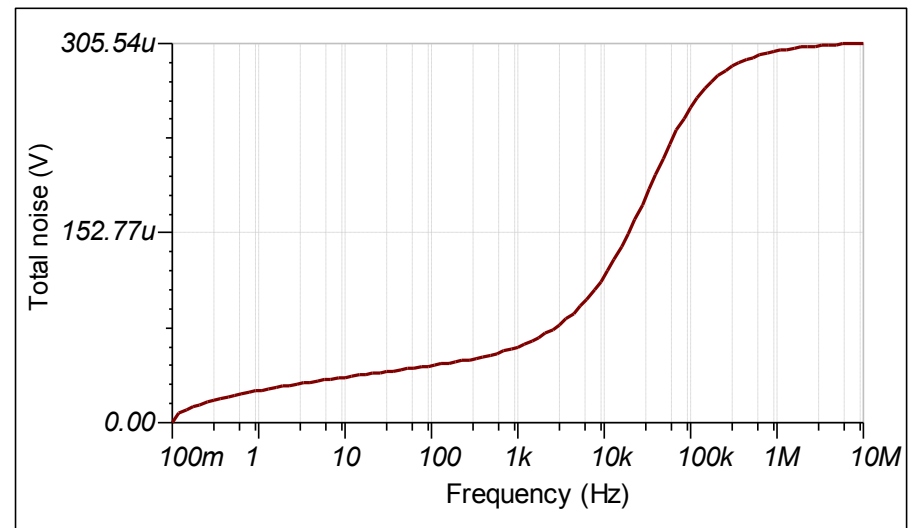
R1 100   Rf 20k

+12V

Vout

U1 OPA192

-12V

Vin
10mV ac

2. Use simulation to determine the noise spectral density and total rms noise for the circuit below. This circuit was solved by hand in the problems from noise 4. Compare the simulated results to the hand calculation results.
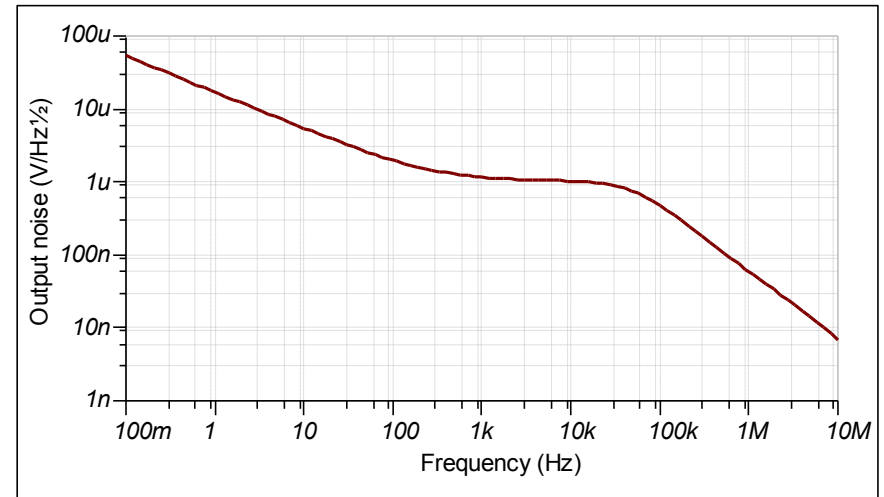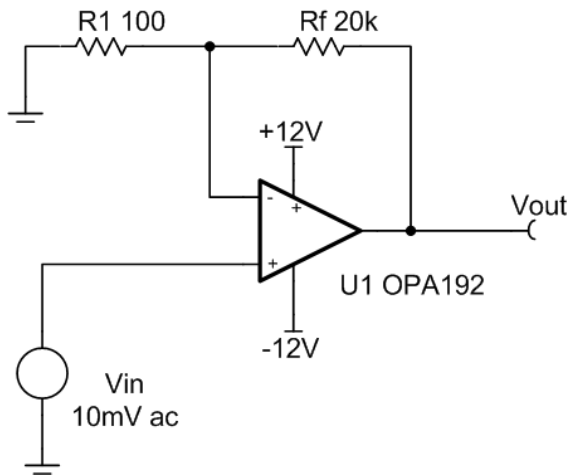
R1 1k   Rf 99k

+12V

Vout

U1 OPA211

-12V

Vin
10mV ac

3. **Use simulation to determine the noise spectral density and total rms noise for the circuit below. This circuit was solved by hand in the problems from noise 4. Compare the simulated results to the hand calculation results.**
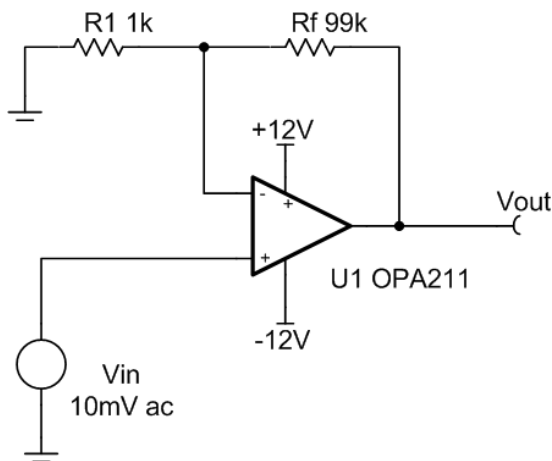
Noise 5

Solutions

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1. Use simulation to determine the noise spectral density and total rms noise for the circuit below. This circuit was solved by hand in the problems from noise 4. Compare the simulated results to the hand calculation results.

OPA192	rms output noise
Calculated	247uV
Simulated	305uV

R1 100   Rf 20k
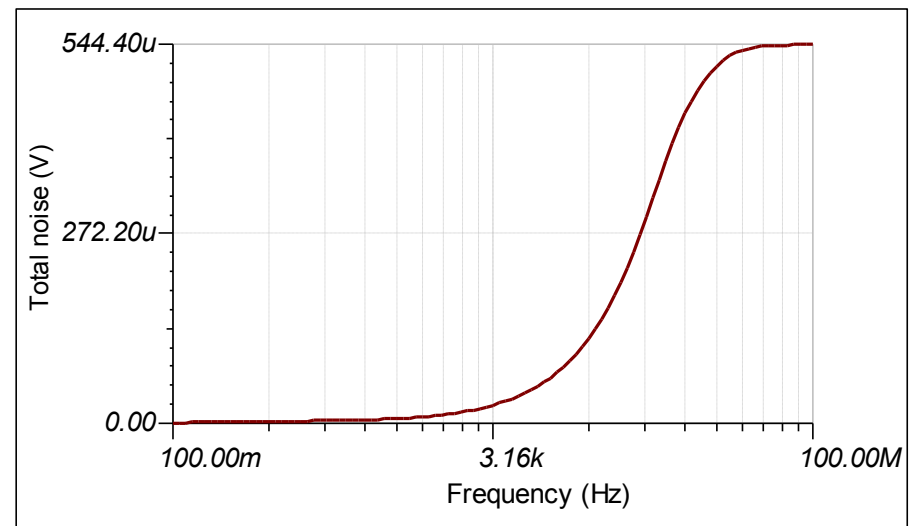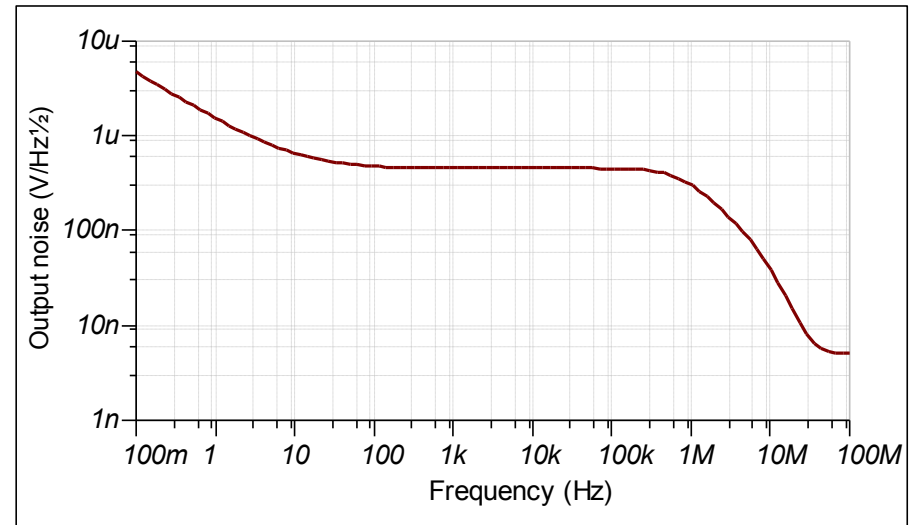
+12V

Vout

U1 OPA192

-12V

Vin
10mV ac

1315-noise 5-problem 1.TSC

2. Use simulation to determine the noise spectral density and total rms noise for the circuit below. This circuit was solved by hand in the problems from noise 4. Compare the simulated results to the hand calculation results.

OPA211	rms output noise
Calculated	501uV
Simulated	544uV

R1 1k
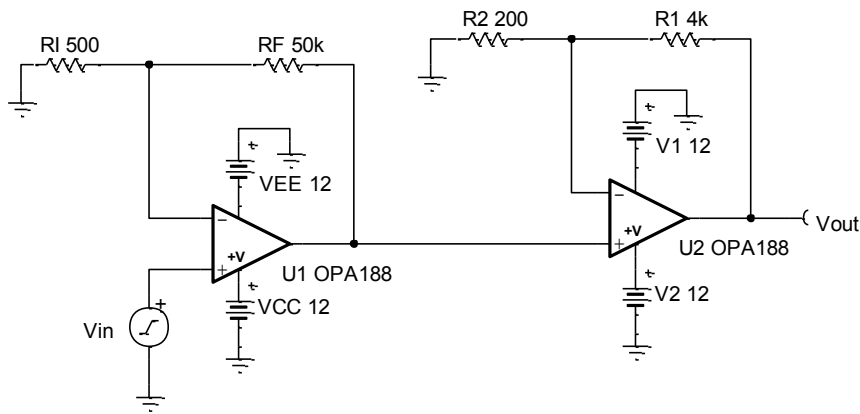Rf 99k
+12V
Vout
U1 OPA211
-12V
Vin
10mV ac

1315-noise 5-problem 2.TSC

3. Use simulation to determine the noise spectral density and total rms noise for the circuit below. This circuit was solved by hand in the problems from noise 4. Compare the simulated results to the hand calculation results.

OPA188	rms output noise
Calculated	3.30mV
Simulated	3.42mV

1315-noise 5-problem 3.TSC