Noise – 3

TIPL 1313
TI Precision Labs – Op Amps

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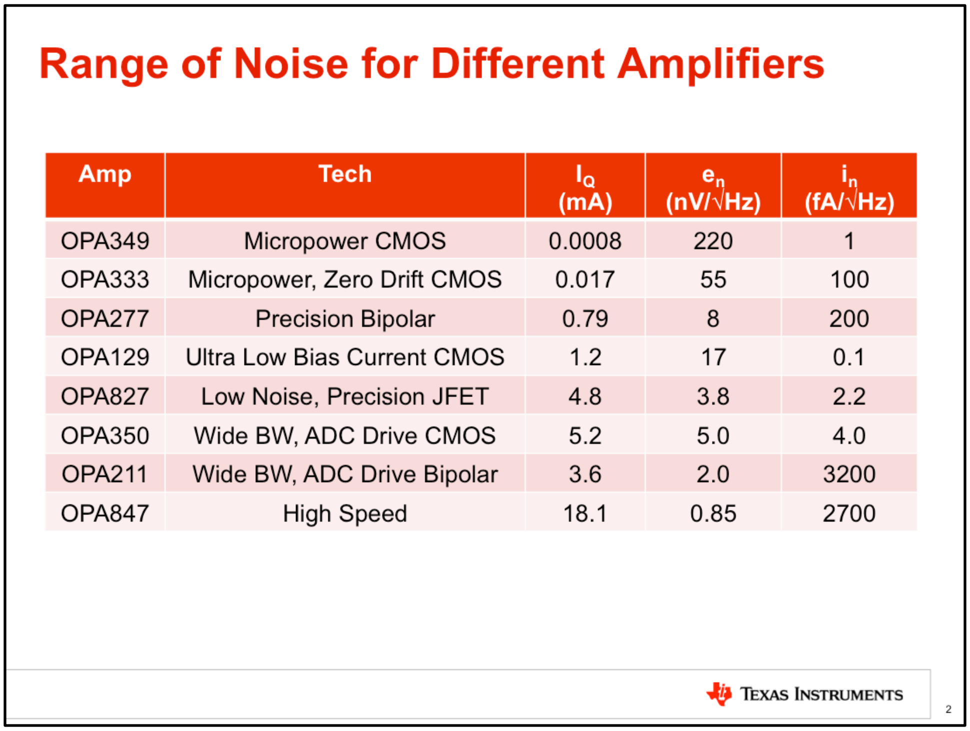
Hello, and welcome to the TI Precision Lab discussing intrinsic op amp noise, part 3.

In this video we'll continue the noise discussion by doing a full noise calculation for a simple amplifier circuit.

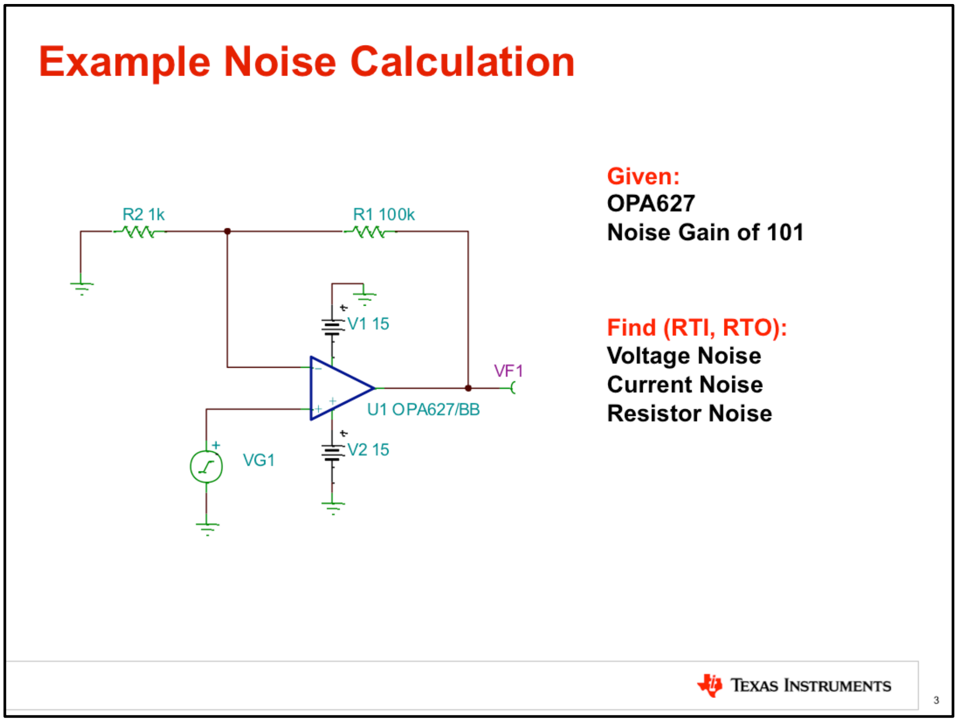


Range of Noise for Different Amplifiers

Amp	Tech	I_Q (mA)	e_n (nV/√Hz)	i_n (fA/√Hz)
OPA349	Micropower CMOS	0.0008	220	1
OPA333	Micropower, Zero Drift CMOS	0.017	55	100
OPA277	Precision Bipolar	0.79	8	200
OPA129	Ultra Low Bias Current CMOS	1.2	17	0.1
OPA827	Low Noise, Precision JFET	4.8	3.8	2.2
OPA350	Wide BW, ADC Drive CMOS	5.2	5.0	4.0
OPA211	Wide BW, ADC Drive Bipolar	3.6	2.0	3200
OPA847	High Speed	18.1	0.85	2700

Before we start to look at the hand calculation, however, let's take a look at a range of different amplifiers and the associated current and voltage noise. Voltage noise is closely related to the device's quiescent current. Voltage noise and quiescent current are inversely proportionate, so amplifiers with high quiescent current tend to have lower noise. For example, comparing the OPA349 to the OPA333 you can see that the amplifier with higher quiescent current has lower noise. Furthermore, Bipolar amplifiers tend to have lower noise then CMOS amplifiers for a given current. For example, compare the OPA350 CMOS amplifier to the OPA211 bipolar amplifier. Notice that the bipolar amplifier has lower noise then the CMOS amplifier even though the quiescent current is higher.

Current noise, on the other hand, is not related to quiescent current. Current noise is lower for CMOS amplifiers than for Bipolar amplifiers. Generally, you will notice amplifiers that have low bias current also have low current noise. This table gives examples that represent the extreme range of noise values for amplifiers. In other words, most amplifiers be in the range of hundreds of nV/rtHz to one or fewer nV/Hz for voltage noise, and thousands of fA/rtHz to one or less fA/rtHz.

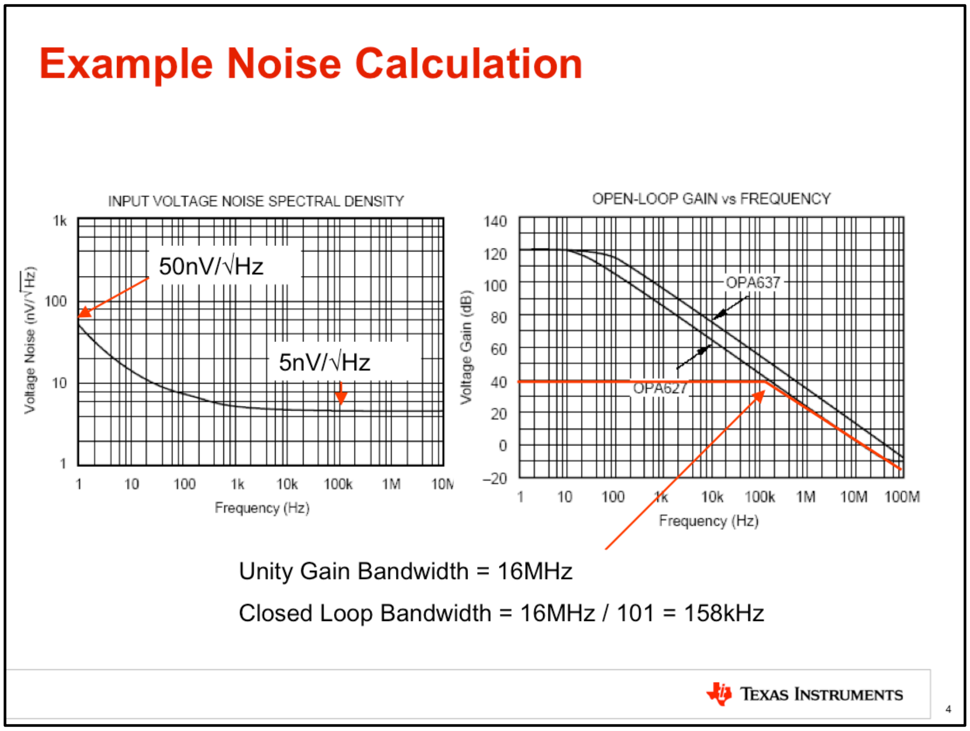


Example Noise Calculation

Given:
OPA627
Noise Gain of 101

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

In this calculation, we will examine an OPA627 in a non-inverting configuration with a gain of 101 V/V. 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. We will also have to consider the noise bandwidth and the noise gain of the circuit.



Example Noise Calculation

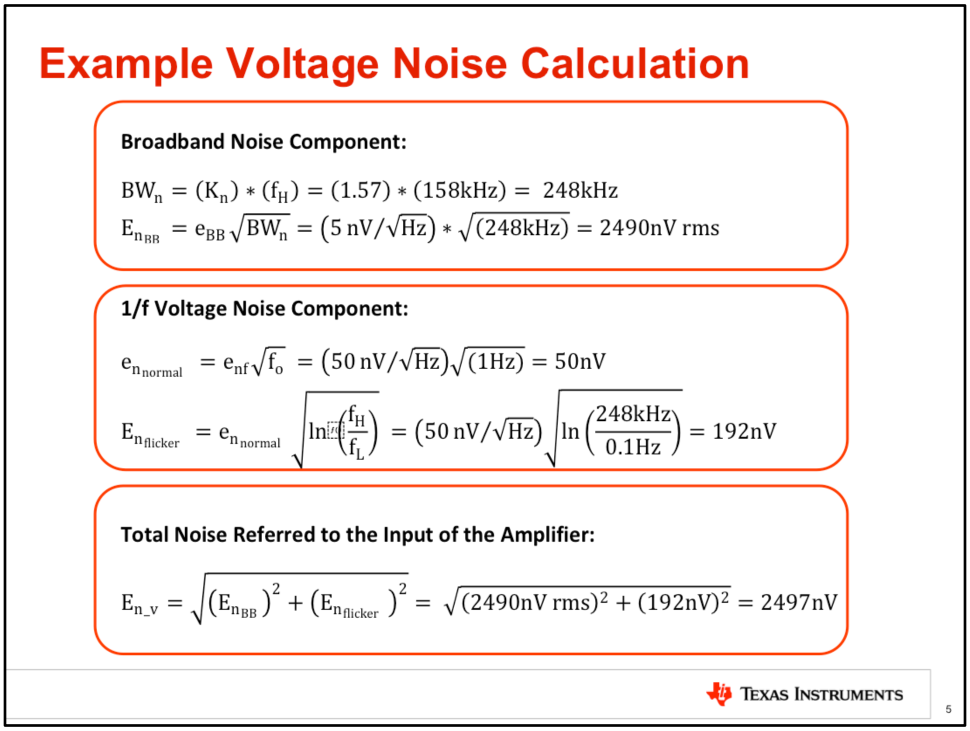
50nV/√Hz

5nV/√Hz

Unity Gain Bandwidth = 16MHz

Closed Loop Bandwidth = 16MHz / 101 = 158kHz

The left hand curve is the voltage spectral density curve. Remember from earlier videos that it has a 1/f and broadband region. The right hand curve is the open loop gain (AOL) curve. The bandwidth of the our circuit is determined by the AOL curve because there is no other filter. Dividing the OPA637’s unity gain bandwidth of 16MHz by our gain of 101, we get a closed-loop bandwidth of 158kHz. This can also be seen graphically.



Example Voltage Noise Calculation

Broadband Noise Component:

$$BW_n = (K_n) * (f_H) = (1.57) * (158\text{kHz}) = 248\text{kHz}$$

$$E_{n_{BB}} = e_{BB}\sqrt{BW_n} = \left(5\,\text{nV}/\sqrt{\text{Hz}}\right) * \sqrt{(248\text{kHz})} = 2490\text{nV rms}$$

1/f Voltage Noise Component:

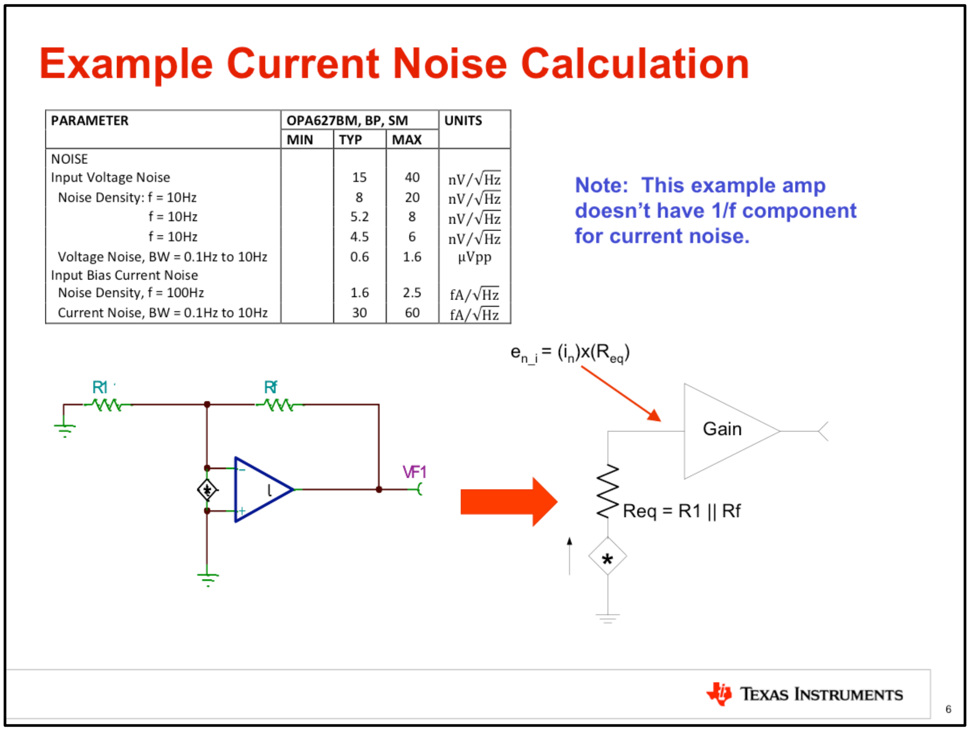
$$e_{n_{normal}} = e_{nf}\sqrt{f_o} = \left(50\,\text{nV}/\sqrt{\text{Hz}}\right)\sqrt{(1\text{Hz})} = 50\text{nV}$$

$$E_{n_{flicker}} = e_{n_{normal}}\sqrt{\ln\left(\frac{f_H}{f_L}\right)} = \left(50\,\text{nV}/\sqrt{\text{Hz}}\right)\sqrt{\ln\left(\frac{248\text{kHz}}{0.1\text{Hz}}\right)} = 192\text{nV}$$

Total Noise Referred to the Input of the Amplifier:

$$E_{n\_v} = \sqrt{\left(E_{n_{BB}}\right)^2 + \left(E_{n_{flicker}}\right)^2} = \sqrt{(2490\text{nV rms})^2 + (192\text{nV})^2} = 2497\text{nV}$$

Now that we have learned all the equations for the op-amp voltage noise in the previous videos, let's compute it for this example. Inspection of the results shows that the 1/f noise component of 192nV is not significant in this example compared to the broadband noise of 2490nV. This is fairly typical of wide bandwidth examples. Also note that the results are added using root sum of squares, for a total input-referred noise of 2497nV.



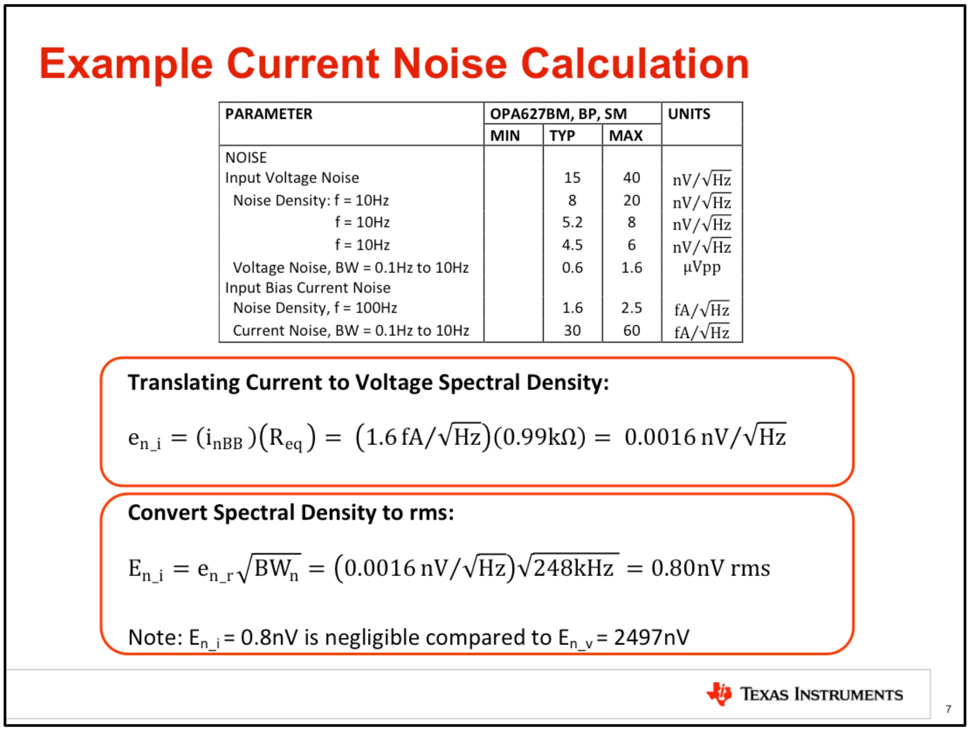
Example Current Noise Calculation

PARAMETER	OPA627BM, BP, SM			UNITS
	MIN	TYP	MAX	
NOISE				
Input Voltage Noise		15	40	$nV/\sqrt{Hz}$
Noise Density: f = 10Hz		8	20	$nV/\sqrt{Hz}$
f = 10Hz		5.2	8	$nV/\sqrt{Hz}$
f = 10Hz		4.5	6	$nV/\sqrt{Hz}$
Voltage Noise, BW = 0.1Hz to 10Hz		0.6	1.6	μVpp
Input Bias Current Noise				
Noise Density, f = 100Hz		1.6	2.5	$fA/\sqrt{Hz}$
Current Noise, BW = 0.1Hz to 10Hz		30	60	$fA/\sqrt{Hz}$

Note: This example amp doesn't have 1/f component for current noise.

$e_{n\_i} = (i_n)x(R_{eq})$

Now that we have the op-amp voltage noise component, let's compute the effect of current noise. For a non-inverting amplifier, the current noise flows through the parallel combination of R1 || Rf. This relationship can be derived using the same op amp analysis techniques that would be used for a dc current source. The current noise is multiplied by the equivalent resistance to generate an input referred noise voltage. Let's look at the numbers for this example.



Example Current Noise Calculation

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Translating Current to Voltage Spectral Density:

$$\mathrm{e_{n\_i}} = (\mathrm{i_{nBB}})(\mathrm{R_{eq}}) = (1.6\,\mathrm{fA}/\sqrt{\mathrm{Hz}})(0.99\mathrm{k}\Omega) = 0.0016\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$$

Convert Spectral Density to rms:

$$\mathrm{E_{n\_i}} = \mathrm{e_{n\_r}}\sqrt{\mathrm{BW_n}} = (0.0016\,\mathrm{nV}/\sqrt{\mathrm{Hz}})\sqrt{248\mathrm{kHz}} = 0.80\mathrm{nV\ rms}$$

Note: E_{n_i} = 0.8nV is negligible compared to E_{n_v} = 2497nV

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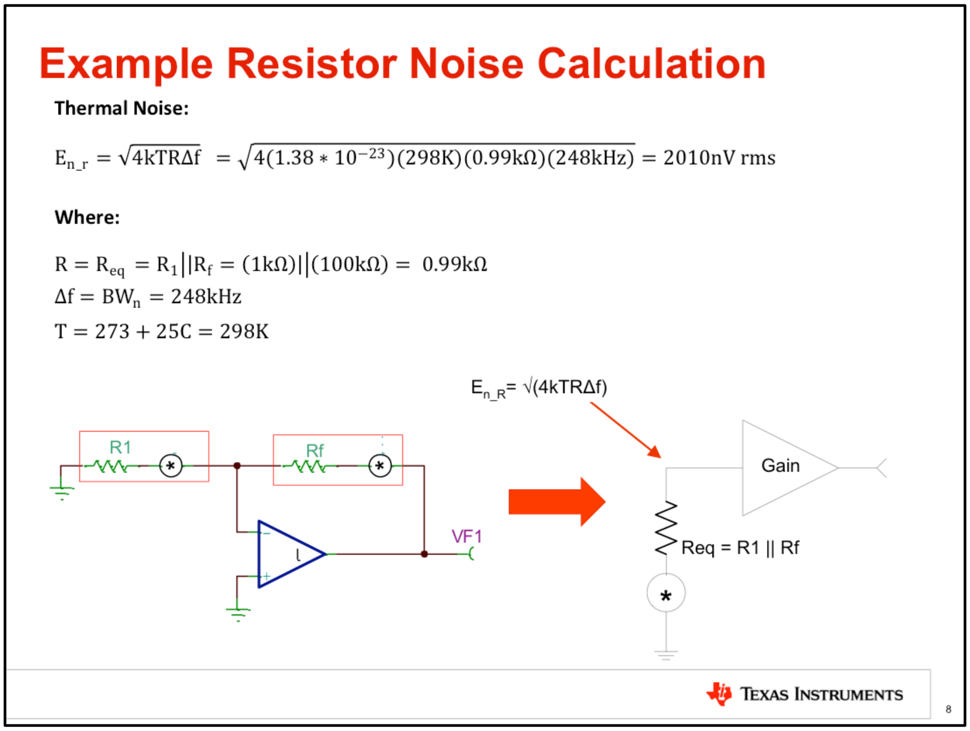
Here are the numbers. For this example the noise current density is very small, at just 1.6 fA/rtHz. The equivalent input resistance is also small, at approximately 1k. Multiplying these together, we get an extremely small noise voltage density of 0.0016nV/rtHz. Converting to RMS using the noise bandwidth, we get 0.8 nVrms. For all practical purposes we could neglect this number since it is insignificant compared to the voltage noise of 2497nV, but we will include it for the sake of completeness. Later we will see an example where current noise dominates.



Example Resistor Noise Calculation

Thermal Noise:

$$E_{n\_r} = \sqrt{4kTR\Delta f} = \sqrt{4(1.38 * 10^{-23})(298K)(0.99k\Omega)(248kHz)} = 2010nV\ rms$$

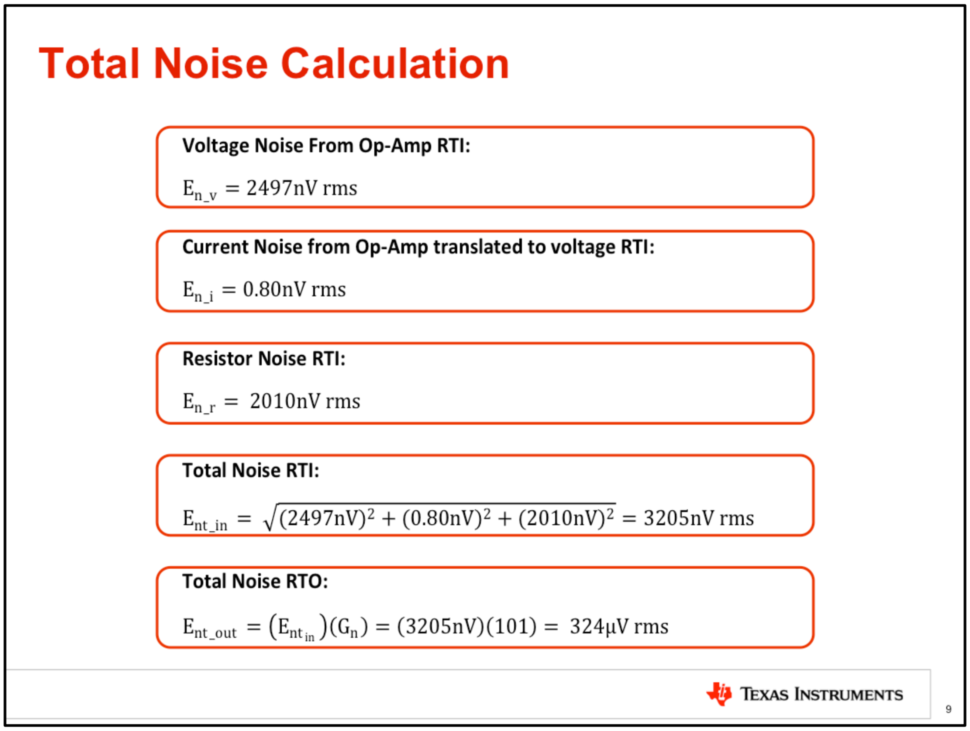
Where:

$R = R_{eq} = R_1||R_f = (1k\Omega)||(100k\Omega) = 0.99k\Omega$

$\Delta f = BW_n = 248kHz$

$T = 273 + 25C = 298K$

Let’s now finish up with calculating the circuit’s resistor thermal noise, also called Johnson noise. We use the equivalent resistance to do this, which is just under 1k in our example. After plugging our values into the equation from the previous video, we get a result of 2010nVrms. This is a significant amount of noise!



Total Noise Calculation

Voltage Noise From Op-Amp RTI:

$E_{n\_v} = 2497\text{nV rms}$

Current Noise from Op-Amp translated to voltage RTI:

$E_{n\_i} = 0.80\text{nV rms}$

Resistor Noise RTI:

$E_{n\_r} = 2010\text{nV rms}$

Total Noise RTI:

$E_{nt\_in} = \sqrt{(2497\text{nV})^2 + (0.80\text{nV})^2 + (2010\text{nV})^2} = 3205\text{nV rms}$

Total Noise RTO:

$E_{nt\_out} = \left(E_{nt_{in}}\right)(G_n) = (3205\text{nV})(101) = 324\mu\text{V rms}$

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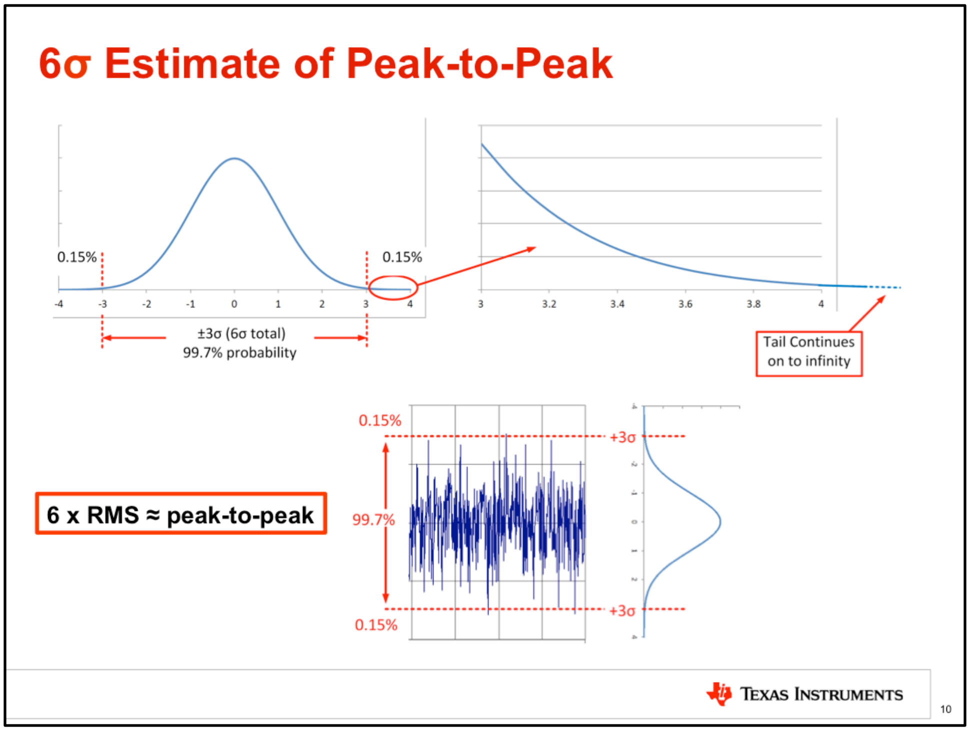
Now that we have the op amp voltage noise, the op amp current noise translated to voltage, and the op amp resistor noise, we can add them together using the root sum of squares. This gives us the total output noise voltage in RMS. Notice that the current noise does not contribute significantly to the total noise. The OPA627 is a JFET input op amp, which typically have very low input current noise densities.

In this example, the total input-referred noise calculates out to 3205nVrms. Multiplying by the gain of 101, we get an output noise voltage of 324uVrms. Frequently engineers want to know the peak-to-peak noise. How do we compute this?

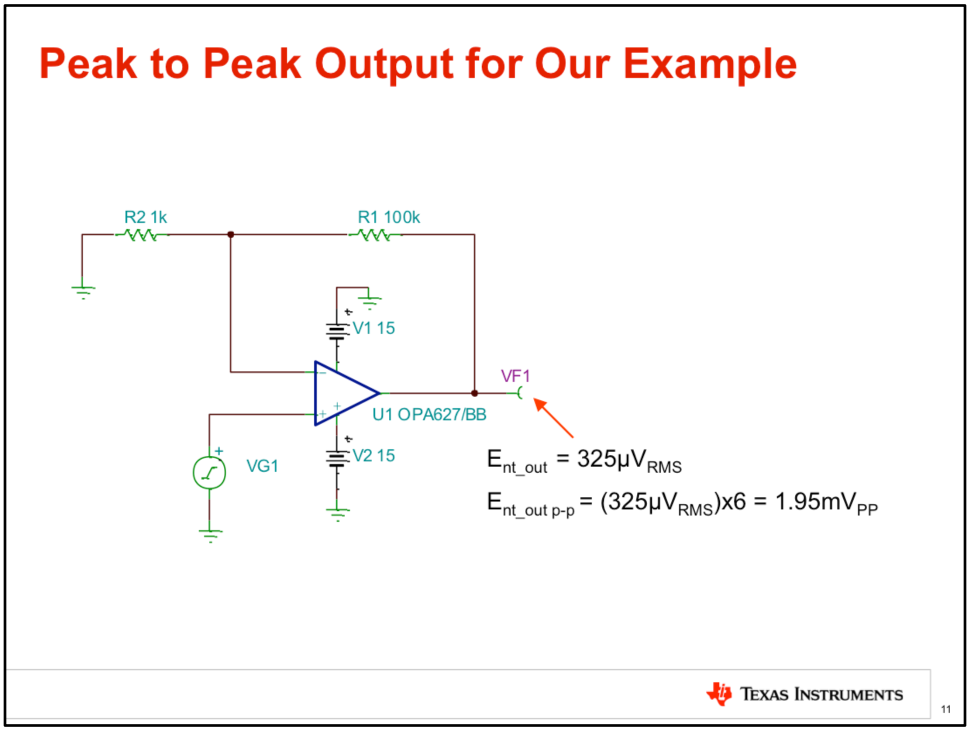


6σ Estimate of Peak-to-Peak

Tail Continues on to infinity

6 x RMS ≈ peak-to-peak

Multiplying the rms noise by 6, or even 6.6, is a common estimate for peak-to-peak noise. Remember that noise has a Gaussian distribution. The Gaussian distribution tells us that there is a 99.7% probability that any reading in time is within the limits of +/- 3 standard deviation or 6 standard deviations total. This means that there is a finite probability of 0.3% that a noise reading will be outside of this limit. Sometimes 6.6 standard deviations is used, because the probability of noise being inside of the limits is increased to 99.9%. It is important to realize that the tails of the Gaussian distribution extend infinitely, so there is no number of standard deviations that will produce a 100% probability that all noise is inside of the bounds. Thus, 6 or 6.6. are used as good estimates. One final thing to keep in mind is that RMS and standard deviation are equivalent for noise signals with no mean value. This is generally true for the intrinsic noise that we are considering.



Peak to Peak Output for Our Example

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

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

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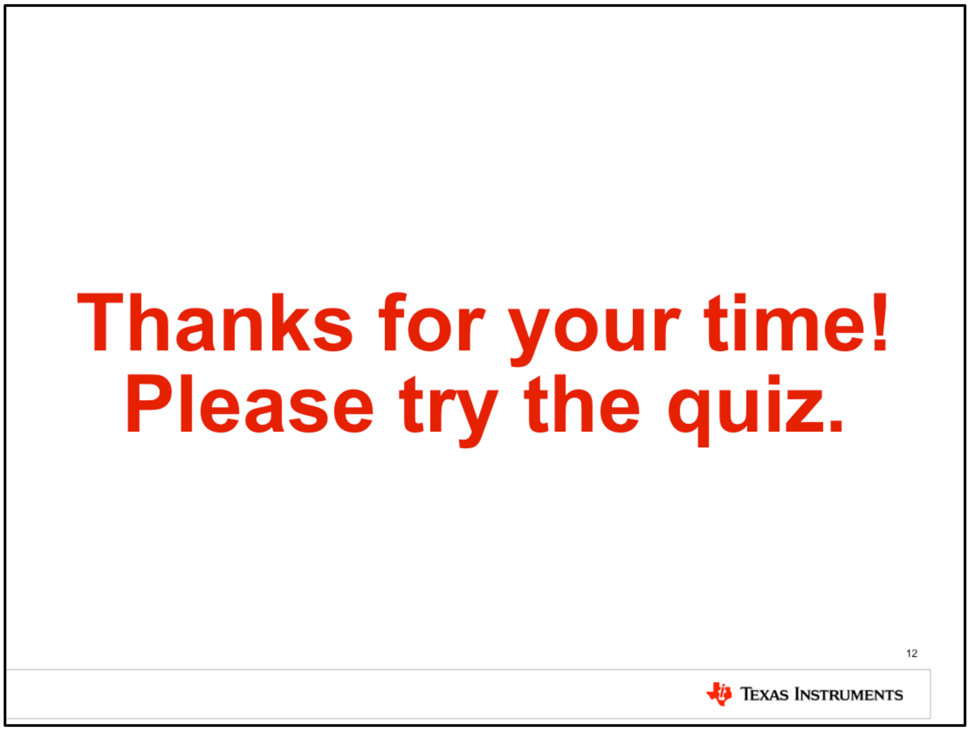
Multiplying the RMS output by 6 gives us the estimate of peak-to-peak output. In this example the peak-to-peak estimate is 1.95mVpp. In later videos we will simulate and measure this circuit with the same results.



Thanks for your time! Please try the quiz.

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