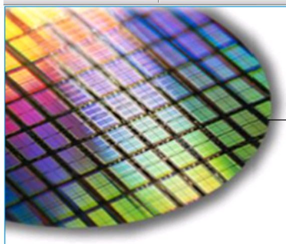

Amplifier Noise Principles for the Practical Engineer

Matt Duff
Applications Engineer – Instrumentation Amplifiers
Analog Devices, Inc.

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Outline

- Noise
  - Extrinsic
  - Intrinsic
- Three main sources of intrinsic noise
  - Resistance
  - Amplifier
    - Voltage Noise
    - Current Noise
  - ADC
- Why so many units?
  - nV/rt(Hz), μVrms, μVp-p
  - Unit conversion
- Noise Math & Shortcuts
- Tips
  - Applying gain
  - Source resistance
  - Feedback resistance

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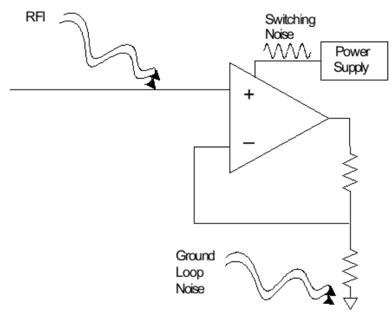
Extrinsic Noise

- Noise coupling in from external sources
- Examples
  - RFI Coupling
  - Power Supply Noise
  - Ground loops
    - Digital circuitry
    - 50/60 Hz
- Not focus of this talk



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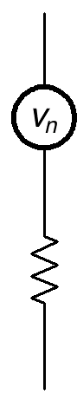
Types of Resistor noise

- Excess Noise
  - Depends on type:
    - Carbon composition = bad performance
    - Thick film = OK performance
    - Thin film, wirewound = good performance
  - Increases with applied voltage
  - 1/f characteristic
  - Can ignore if using good resistors
- Intrinsic thermal noise
  - Independent of type
  - Independent of voltage applied
  - White noise characteristic
  - Need to calculate in design



ANALOG DEVICES

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Thermal noise of an ideal resistor

$$v_n = \sqrt{4k\,T\,R\,\Delta f}$$

- v_n: rms noise
- k: constant
- T: Temperature (in Kelvin)
- R: resistance
- Δf: bandwidth

Resistor noise shortcut

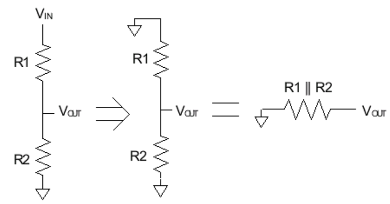
$$1\ \text{k}\Omega \rightarrow 4\ \text{nV}/\sqrt{(\text{Hz})}$$

Noise scales as square root of resistance

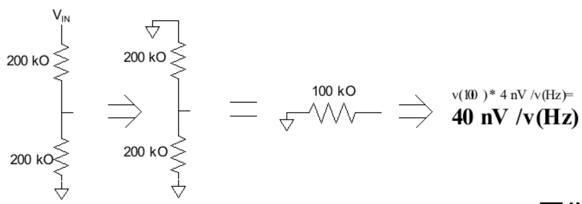
- 4 kΩ → (2)(4) nV/√(Hz) = 8 nV/√(Hz)
- 9 kΩ → (3)(4) nV/√(Hz) = 12 nV/√(Hz)
- 16 kΩ → (4)(4) nV/√(Hz) = 16 nV/√(Hz)
- 100 kΩ → (10)(4) nV/√(Hz) = 40 nV/√(Hz)

Common Resistor Circuits: Resistor Divider

Theory:



Example:



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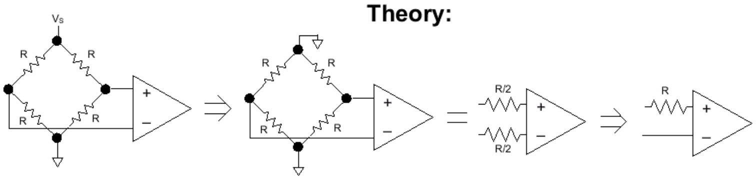
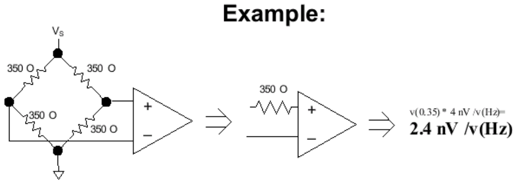
Common Resistor Circuits – Bridge

Theory:

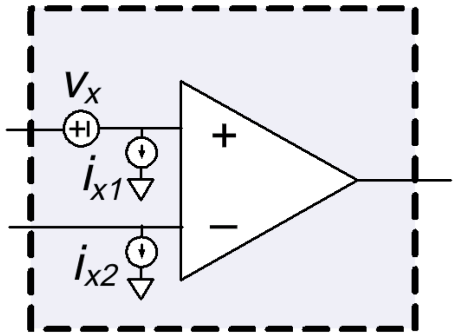


Example:



ANALOG DEVICES

Amplifier Noise



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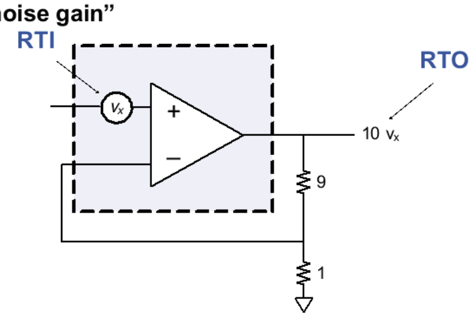
Amplifier Voltage Noise: Referred to What?

- Options
  - Referred to Input (RTI)
  - Referred to Output (RTO)
- If not stated, referred to Input
- Multiply by “noise gain”



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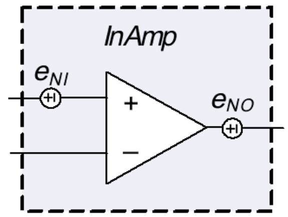
Instrumentation Amplifiers are Different

- **Op Amps**
  - All noise dependent on gain
- **In Amps**
  - Some noise dependent on gain (e_{NI})
  - Some noise independent of gain (e_{NO})
- **Total In Amp Noise, referred to input**
  - $\sqrt{(e_{NI}^2 + (e_{NO}/G)^2)}$



example from AD8221 datasheet:

Voltage Noise, 1 kHz	RTI Noise = $\sqrt{(e_{NI}^2 + (e_{NO}/G)^2)}$		
Input Voltage Noise, e_{NI}	V_{IN+}, V_{IN-}, V_{REF} = 0 V	8	nV/√Hz
Output Voltage Noise, e_{NO}	V_{IN+}, V_{IN-}, V_{REF} = 0 V	75	nV/√Hz

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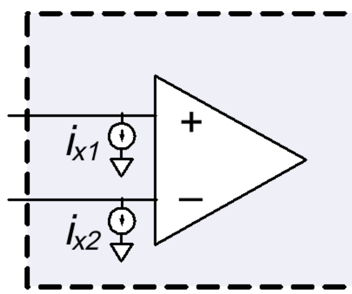
Amplifier Current Noise

- **Units:**
  - fA/√(Hz)
  - pArms
  - pA p-p



example from AD8295 datasheet:

Current Noise	f = 1 kHz	40	fA/√Hz
	f = 0.1 Hz to 10 Hz	6	pA p-p

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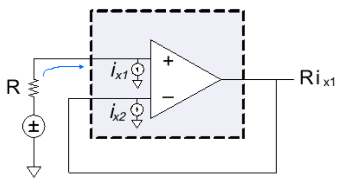
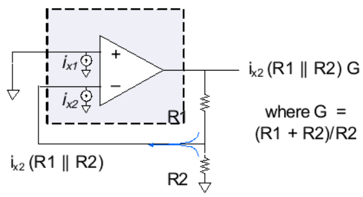
Amplifier Current Noise: Effect depends on resistance

- Source resistance



- Feedback network



ADC Noise:

- Sometimes voltage units provided:

Table 6. RMS Noise (nV) vs. Gain and Output Data Rate

Filter Word (Decimal)	Output Data Rate (Hz)	Settling Time (ms)	Gain of 1	8	16	32	64	128
1023	4.7	852.5	340	53	34	18	12	11
640	7.5	533	410	67	40	24	14	13
480	10	400	430	76	45	28	16	15

- But most of the time, signal to noise ratio (SNR)
  - With distortion: SINAD

Signal-to-Noise Ratio, SNR	f_{IN} = 20 kHz, V_{REF} = 4.096 V, internal reference	87.0	88.5	dB
	f_{IN} = 20 kHz, V_{REF} = 5.0 V, external reference	89.0	90.0	dB

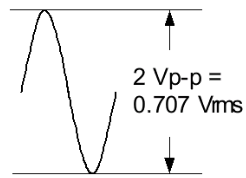
- In emergency use ideal equation
  - SNR = 6.02 * Bits + 1.76
  - Gives better performance than reality

ADC Noise – Converting SNR to μVrms

Conversion Equation:

$$\frac{\text{Full Scale Voltage in } \mu\text{Vrms}}{10^{\frac{SNR}{20}}} = \text{ADC noise in } \mu\text{Vrms}$$

Key Point: Use RMS value for full scale range!



Example:

- 2 V ADC input range
- 69 dB SNR

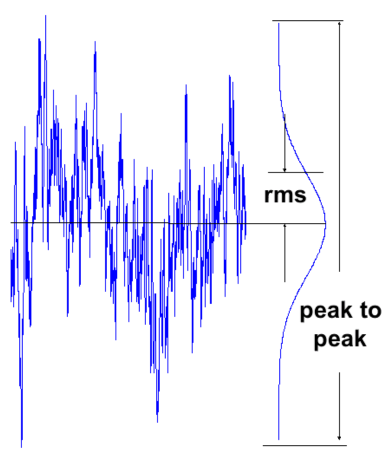
$$\frac{(2 \times 10^{6}\ \mu\text{V})(0.5)(.707)}{10^{\frac{69}{20}}} = 251\ \mu\text{Vrms}$$

20

Peak to Peak and RMS noise

- **Peak to peak noise**
  - Distance from min and max points on waveform
  - Depends on only two points
    - Less accurate
      - Variable
      - Measure longer -> bigger result
    - Easy to compute
      - Max - Min
- **RMS noise**
  - One standard deviation
    - (mean is zero)
  - Depends on all points
    - More accurate
      - Repeatable
      - Measure longer -> more accurate result
    - Lengthy to compute

$$\sqrt{\frac{x_1^2 + x_2^2 + \ldots + x_n^2}{n}}$$



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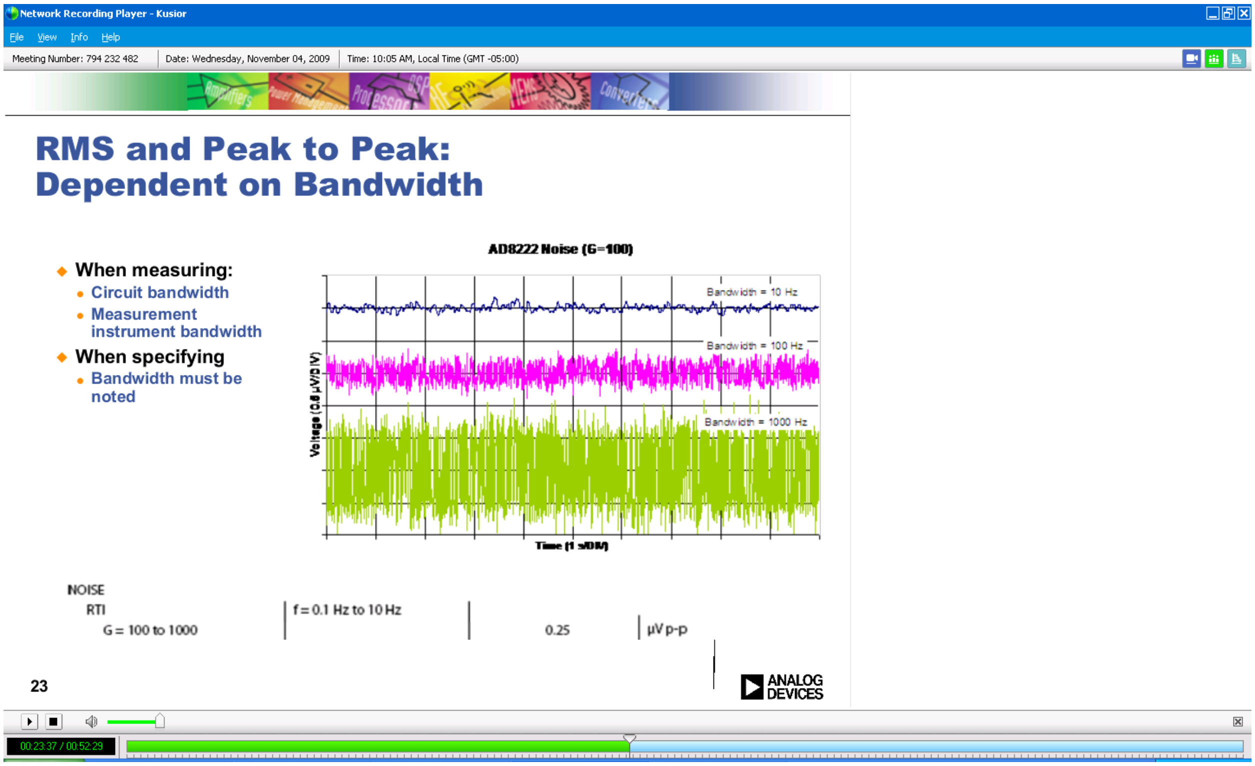
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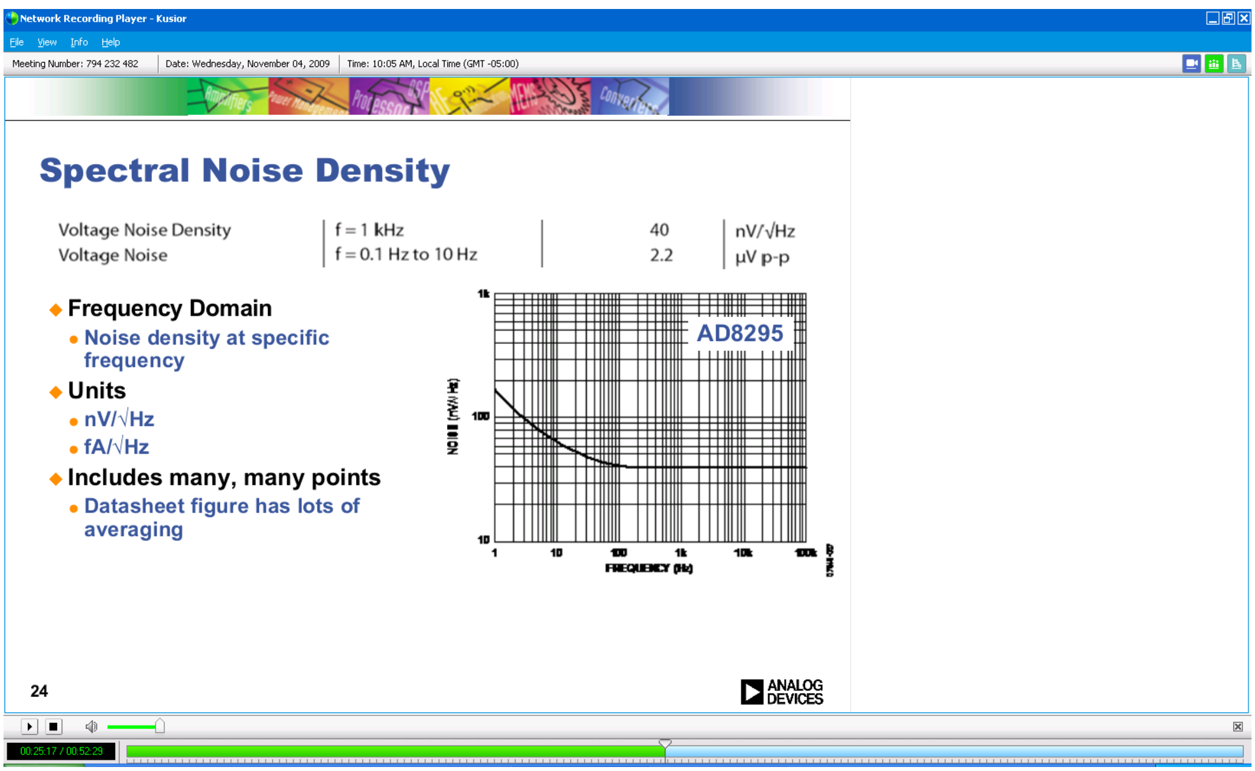
File View Info Help
Meeting Number: 794 232 482
Date: Wednesday, November 04, 2009
Time: 10:05 AM, Local Time (GMT -05:00)
RMS and Peak to Peak:
Dependent on Bandwidth
When measuring:
Circuit bandwidth
Measurement instrument bandwidth
When specifying
Bandwidth must be noted
AD8222 Noise (G=100)
Bandwidth = 10 Hz
Bandwidth = 100 Hz
Bandwidth = 1000 Hz
Time (1 s/DIV)
NOISE
RTI
G = 100 to 1000
f = 0.1 Hz to 10 Hz
0.25
µV p-p
23
ANALOG DEVICES
00:23:37 / 00:52:29


Network Recording Player - Kusior
File View Info Help
Meeting Number: 794 232 482
Date: Wednesday, November 04, 2009
Time: 10:05 AM, Local Time (GMT -05:00)
Spectral Noise Density
Voltage Noise Density
f = 1 kHz
40
nV/√Hz
Voltage Noise
f = 0.1 Hz to 10 Hz
2.2
µV p-p
Frequency Domain
Noise density at specific frequency
Units
nV/√Hz
fA/√Hz
Includes many, many points
Datasheet figure has lots of averaging
AD8295
1k
100
10
1
10
100
1k
10k
100k
FREQUENCY (Hz)
24
ANALOG DEVICES
00:25:17 / 00:52:29

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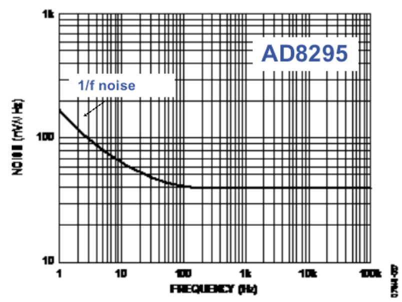
Spectral Noise Density – 1/f corner

- 1/f noise
  - Noise density increases at low frequencies
- White noise
  - Noise density flat at high frequencies
- 1/f corner
  - Where 1/f noise and white noise trendlines intersect



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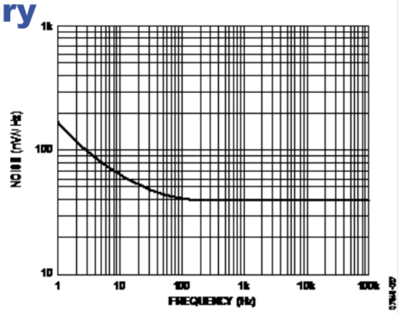
nV/√(Hz) -> μVrms: theory

- Theoretical Equation

$$Noise_{RMS} = \sqrt{\int_{f_{LOW}}^{f_{HIGH}} (SD_f)^2\, df}$$

- Where
  - SD_f: spectral density at frequency f
  - f_{LOW}: low frequency cutoff
  - f_{HIGH}: high frequency cutoff



27

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00:31:38 / 00:52:29

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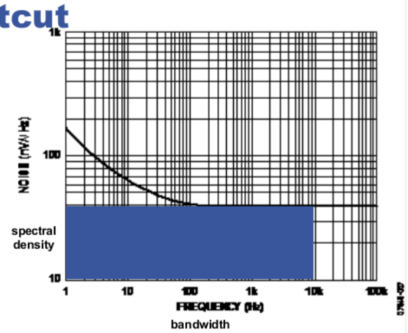
nV/√(Hz) -> µVrms shortcut

- Assumption
  - Mostly white noise
    - 1/f corner << bandwidth



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00:32:51 / 00:52:29

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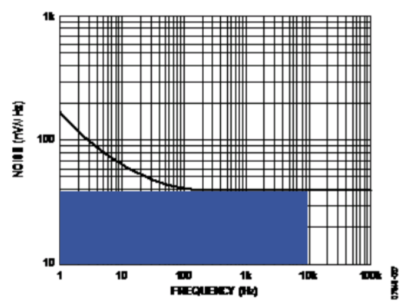
Equivalent Noise Bandwidth

- Equivalent Noise bandwidth for Butterworth filters
  - 1 pole: 1.57
  - 2 pole: 1.11
  - 3 pole: 1.05



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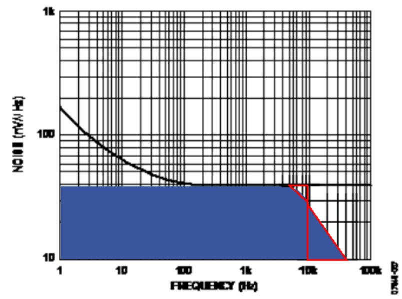
00:34:10 / 00:52:29

Equivalent Noise Bandwidth

- Equivalent Noise bandwidth for Butterworth filters
  - 1 pole: 1.57
  - 2 pole: 1.11
  - 3 pole: 1.05



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nV/√(Hz) -> µVrms

- Not mostly white noise?
  - 1/f corner near bandwidth
- Options
  - Use theoretical formula?
  - Use amplifier with low 1/f corner
  - Compare uVp-p numbers
    - 0.1 to 10 Hz
  - Autozero/Chopper

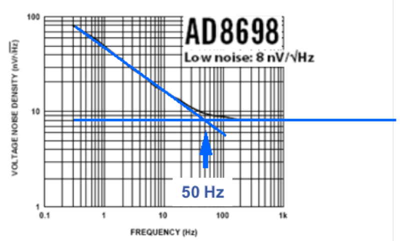

Figure 16. Voltage Noise Density vs. Frequency

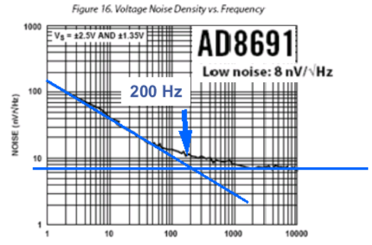

Figure 27. Voltage Noise Density

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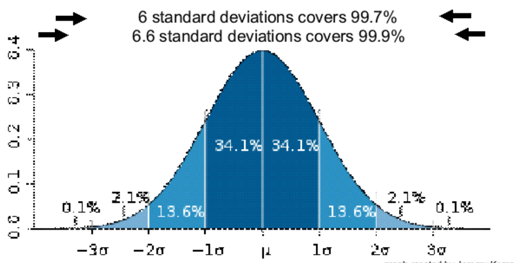
μVrms -> μVp-p

- To get peak to peak noise
  - In theory: peak to peak noise infinite
  - In practice: multiply rms by 6
    - Multiplier of '6' is rule of thumb: 99.73% of points
- Examples
  - 1 μVrms * 6 ≈ 6 μVp-p
  - 1 μVrms * 6.6 ≈ 6.6 μVp-p



graph created by Jeremy Kemp

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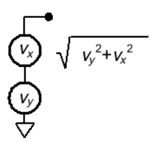
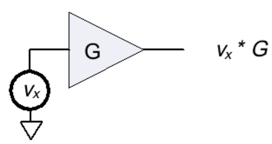
Noise Math

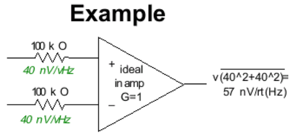
- Addition
  - Noise adds as sum of squares



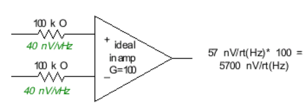
- Multiplication
  - Gain and attenuation work just like normal signals



Example



Example



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Noise shortcuts

- 1 k Ω resistor -> 4 nV/√Hz
- When adding noise sources, larger sources dominate
  - Sum of squares addition
  - Ignore signals < 1/5th largest signal
- If first stage gain is large
  - Later stages typically have little effect

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00:43:24 / 00:52:29

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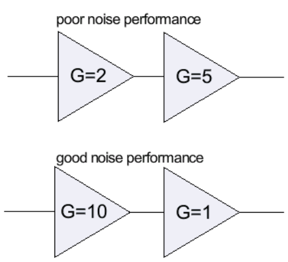
Noise Tip #1: Apply Gain Early

- Noise adds as sum of squares



ANALOG DEVICES

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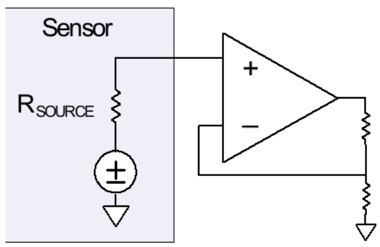
Noise Tip #2: Watch out for source impedance

- Source Resistance adds noise
- Current noise calculation



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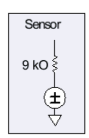
Source impedance example

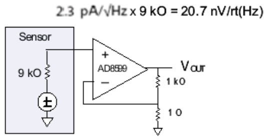
- Given the following sensor:

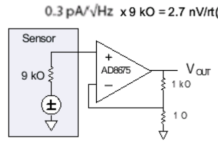


Sensor Noise :
v9 x 4 nV/√Hz
= 12 nV/√Hz

- Which op amp is better?

Ultralow Distortion, Ultralow Noise Op Amp	36 V Precision, 2.8 nV/√Hz Rail-to-Rail Output Op Amp
FEATURES	**FEATURES**
1.1 nV/√Hz	**2.8 nV/√Hz**
2.3 pA/√Hz x 9 kO = 20.7 nV/rt(Hz)	0.3 pA/√Hz x 9 kO = 2.7 nV/rt(Hz)





Noise contributors (RTI):

	AD8599		AD8675
Sensor noise = 4 xv 9 =	12	Sensor noise = 4 xv 9 =	12
Amp Voltage noise =	1.1	Amp Voltage noise =	2.8
Amp Current noise = 2.3 x 9 =	20.7	Amp Current noise = 0.3 x 9 =	2.7
Total Noise = v(12^2+1.1^2 + 20.7^2) =	**24 nV/rt(Hz)**	Total Noise = v(12^2+2.8^2 + 2.7^2) =	**12.3 nV/rt(Hz)**

Network Recording Player - Kusior

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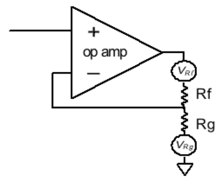
Noise Tip #3: Watch out for feedback resistors

- **Rf acts like voltage source at output**
- **Rg acts likes inverting configuration voltage source**

Noise model of
noninverting configuration



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Summary

- **Noise**
  - **Extrinsic**
  - **Intrinsic**
- **Three main sources of intrinsic noise**
  - **Resistance**
  - **Amplifier**
    - Voltage Noise
    - Current Noise
  - **ADC**
- **Why so many units?**
  - **RMS noise, peak to peak noise, spectral density**
  - **How to convert between units**
- **Noise Math & Shortcuts**
- **Tips**
  - **Gain Early**
  - **Source Impedance**
  - **Feedback resistors**

ANALOG DEVICES

00:50:46 / 00:52:29