深入学习运算放大器噪声以及ADI典型低噪声放大器产品

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Agenda

- Understand the main noise sources of amplifier circuits and how to find the corresponding noise parameters in an operational amplifier datasheet
- Understand the definition of each noise source and how to calculate the noise value in a real circuit
- How to use the simulation tool to quickly obtain the noise index of the amplifier circuit
- Familiar with ADI's typical low noise amplifier products

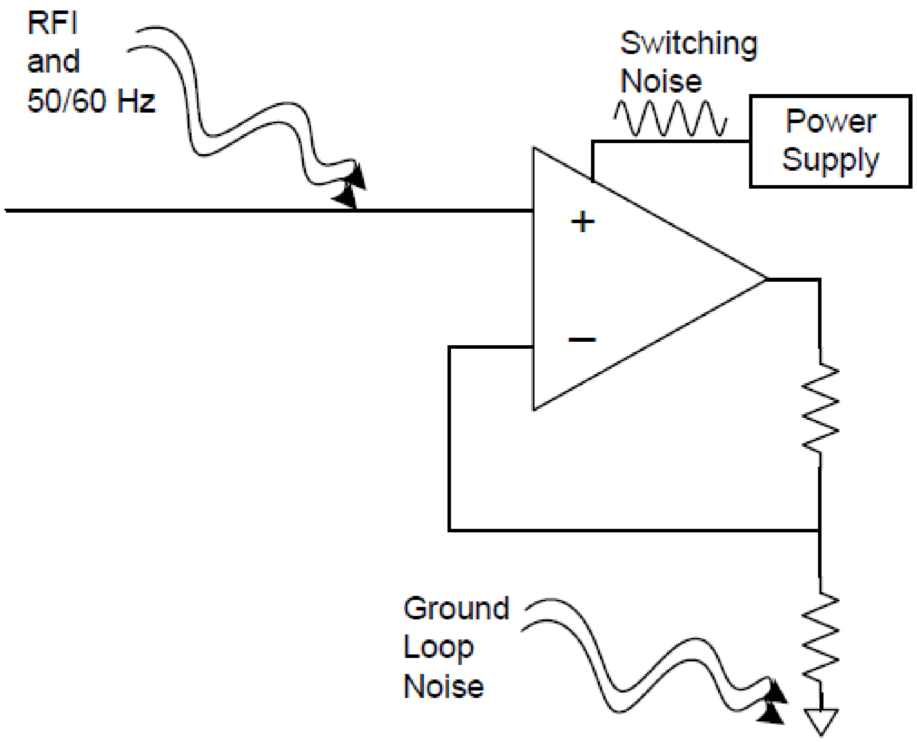
Where does noise come from?

-Extrinsic

-Intrinsic

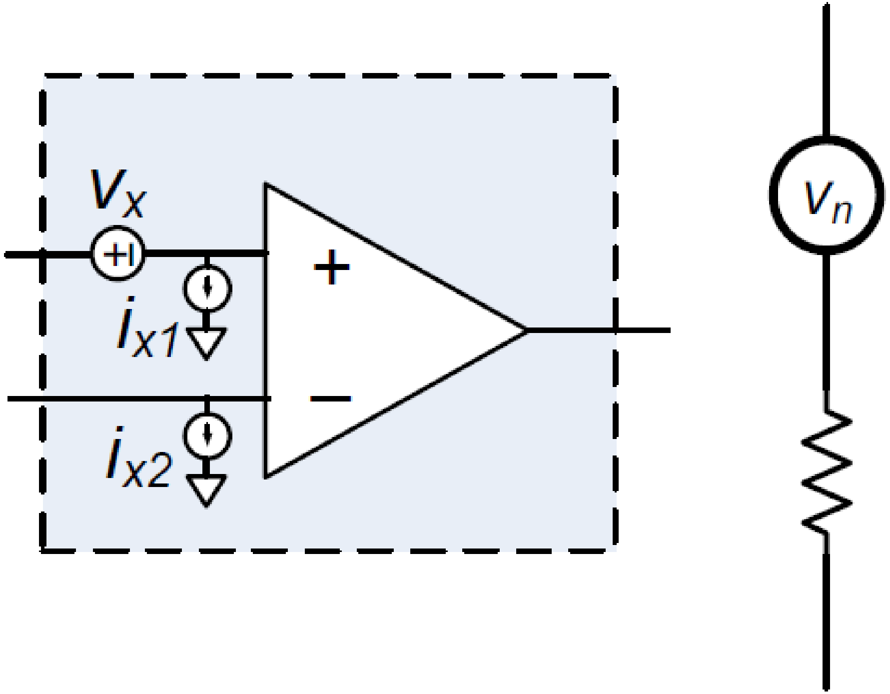
Extrinsic Noise

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



Intrinsic Noise

- **Intrinsic**
  - **Internal noise from components in signal chain**
    - Sensor
    - Resistors
    - Amplifier
    - A/D
  - **Specified on the datasheet**
  - **Focus of this talk**

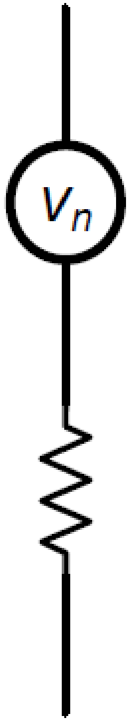


Main Sources of AMP Intrinsic Noise

-Resistor

-Amplifier

Resistor noise



Thermal noise of an ideal resistor

very complex !

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

- rms noise (v_n)
- constant ($4k$)
- Temperature (in Kelvin) (T)
- resistance (R)
- bandwidth (Δf)

Resistor noise shortcut

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

Noise scales as square root of resistance

$4\ k\Omega \rightarrow (2)(4)\ nV/\sqrt{(Hz)} = 8\ nV/\sqrt{(Hz)}$

$9\ k\Omega \rightarrow (3)(4)\ nV/\sqrt{(Hz)} = 12\ nV/\sqrt{(Hz)}$

$16\ k\Omega \rightarrow (4)(4)\ nV/\sqrt{(Hz)} = 16\ nV/\sqrt{(Hz)}$

$100\ k\Omega \rightarrow (10)(4)\ nV/\sqrt{(Hz)} = 40\ nV/\sqrt{(Hz)}$

Noise Spectral Density vs. Resistance

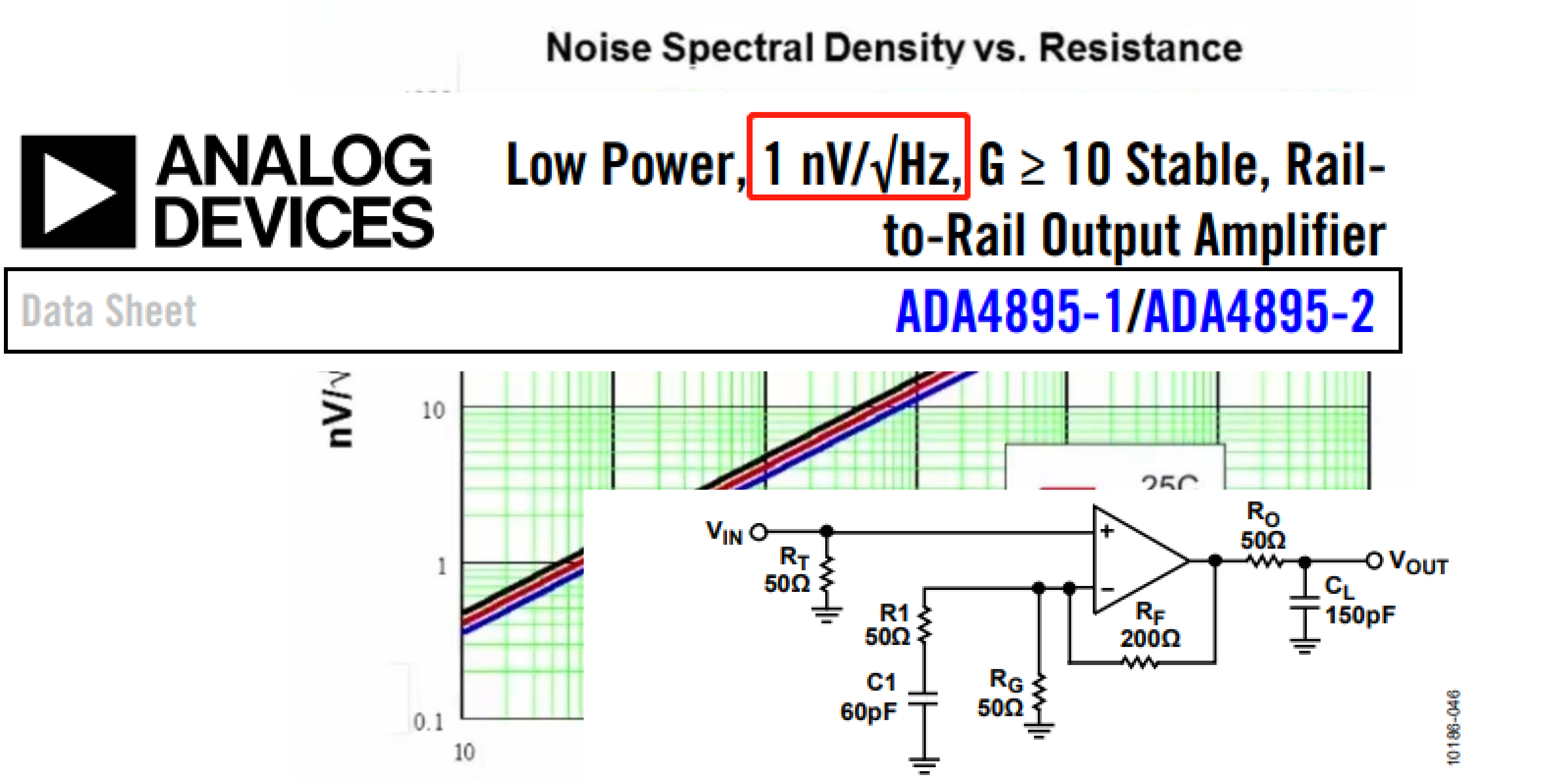
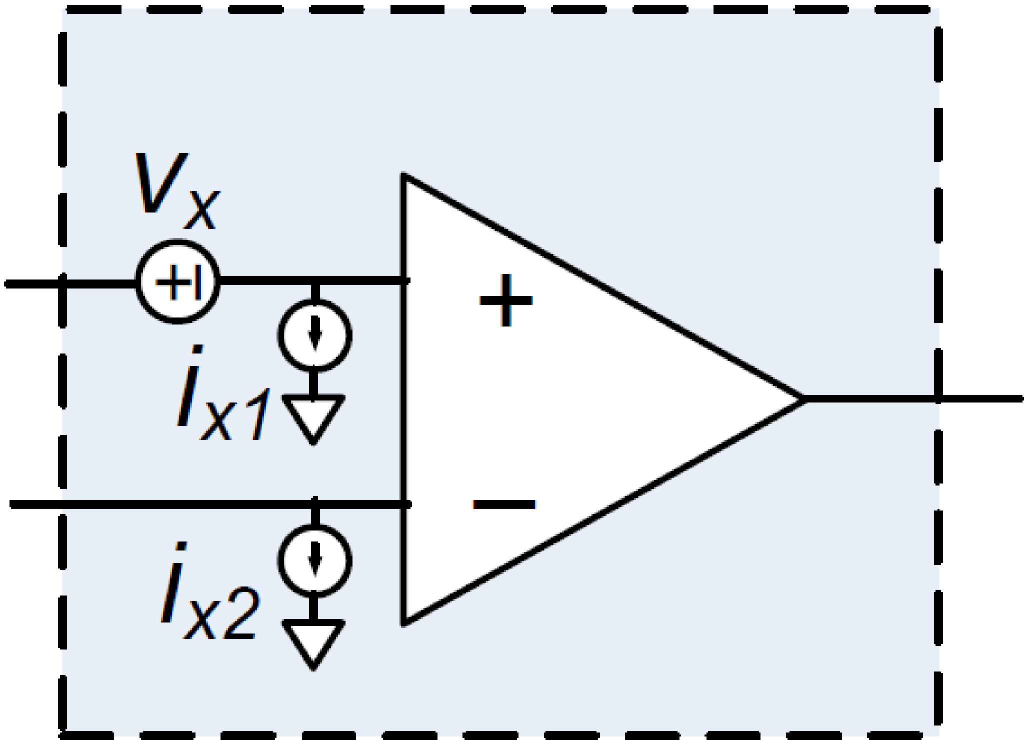
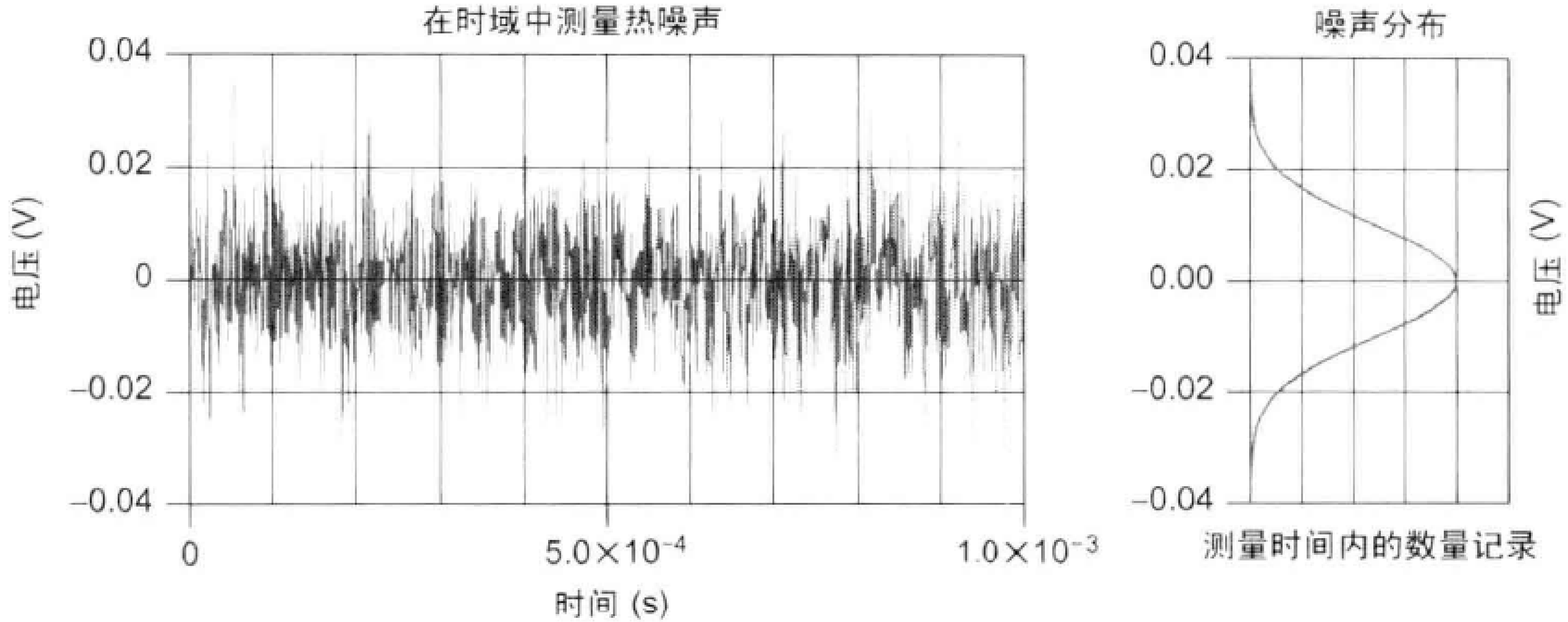


Figure 50. Configuring the ADA4895-1/ADA4895-2 for a Gain of +5 Stable

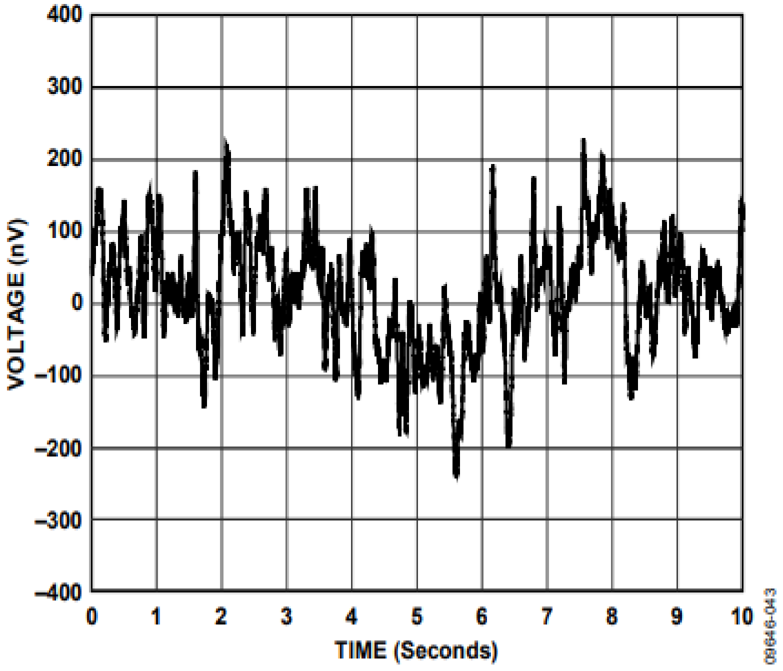
Amplifier Noise model



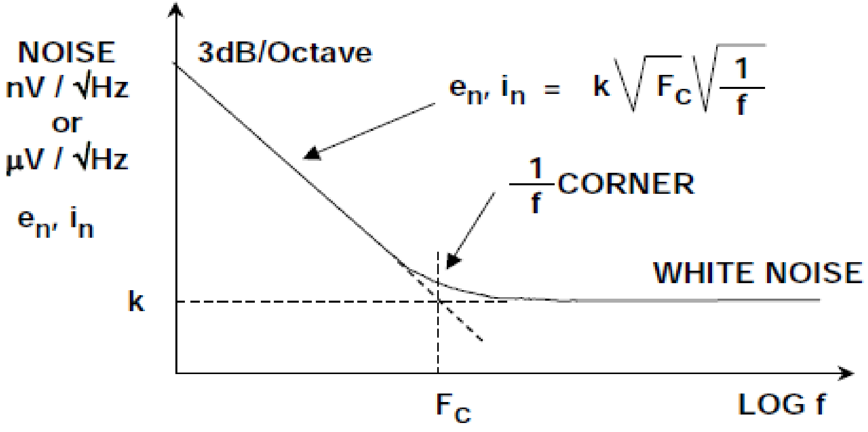
Broadband Noise



1/f Noise

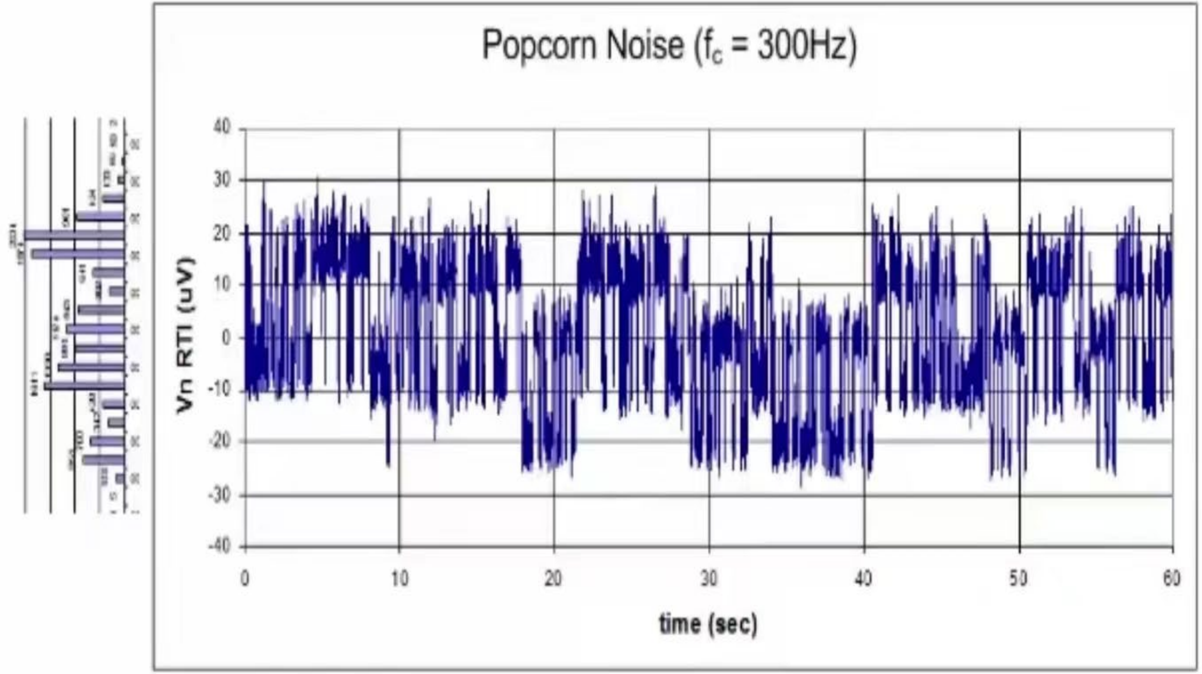


ADA4610-1Voltage Noise Density 0.1 Hz to 10 Hz



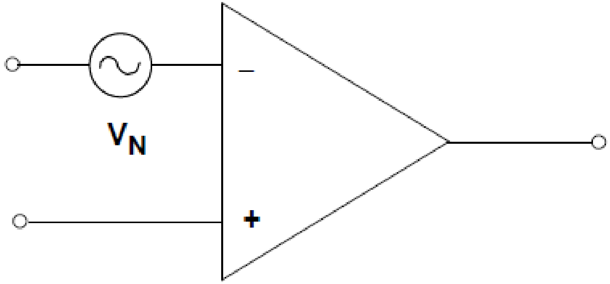
- 1/f Corner Frequency is a figure of merit for op amp noise performance (the lower the better)
- Typical Ranges: 2Hz to 2kHz
- Voltage Noise and Current Noise do not necessarily have the same 1/f corner frequency

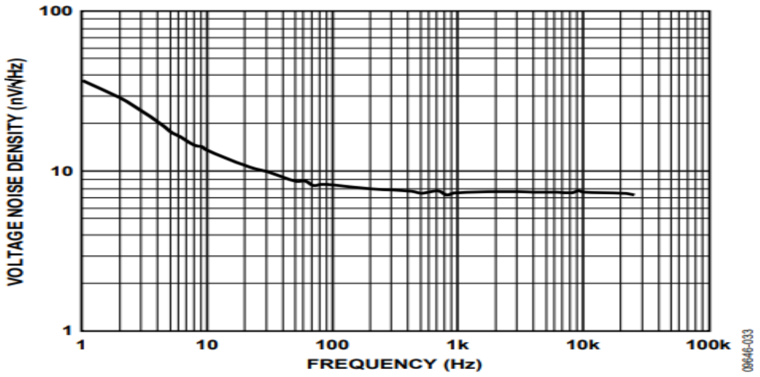
Burst Noise



Popcorn Noise (f_c = 300Hz)
Vn RTI (uV)
40
30
20
10
0
-10
-20
-30
-40
0
10
20
30
40
50
60
time (sec)

Input Voltage Noise



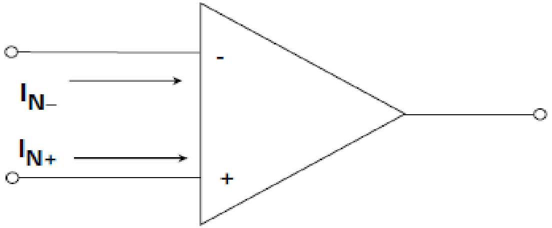


ADA4610-1Voltage Noise Density vs. Frequency, VSY = ±5 V

- Input Voltage Noise is bandwidth dependent and measured in nV/√Hz (noise spectral density)
- Normal Ranges are 1nV/√ Hz to 20nV/√Hz

NOISE PERFORMANCE				
Peak-to-Peak Voltage Noise	e_n p-p	0.1 Hz to 10 Hz bandwidth	0.45	μV p-p
Voltage Noise Density	e_n	f = 10 Hz	14	nV/√Hz
		f = 100 Hz	8.50	nV/√Hz
		f = 1 kHz	7.30	nV/√Hz
		f = 10 kHz	7.30	nV/√Hz

Input Current Noise

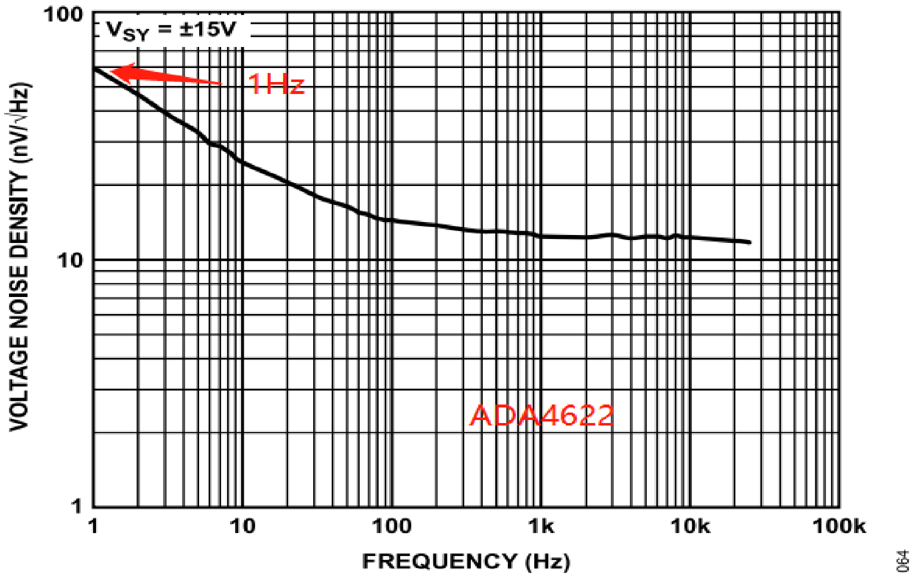


- Normal Ranges: 0.1fA/√ Hz to 10pA/√Hz
- In Voltage Feedback op amps the current noise in the inverting and non-inverting inputs is uncorrelated (effectively) but roughly equal in magnitude.
- In simple BJT and JFET input stages, the current noise is the shot noise of the bias current and may be calculated from the bias current.
- In bias-compensated input stages and in current feedback op amps, the current noise cannot be calculated.
- The current noise in the two inputs of a current feedback op amp may be quite different. They may not even have the same 1/f corner.

NOISE PERFORMANCE				
Voltage Noise	$e_{n\ p\text{-}p}$	0.1 Hz to 10 Hz	175	nV p-p
Voltage Noise Density	e_n	f = 10 Hz	10	nV/√Hz
		f = 1 kHz	8	nV/√Hz
Current Noise Density	i_n	f = 1 kHz	0.2	pA/√Hz

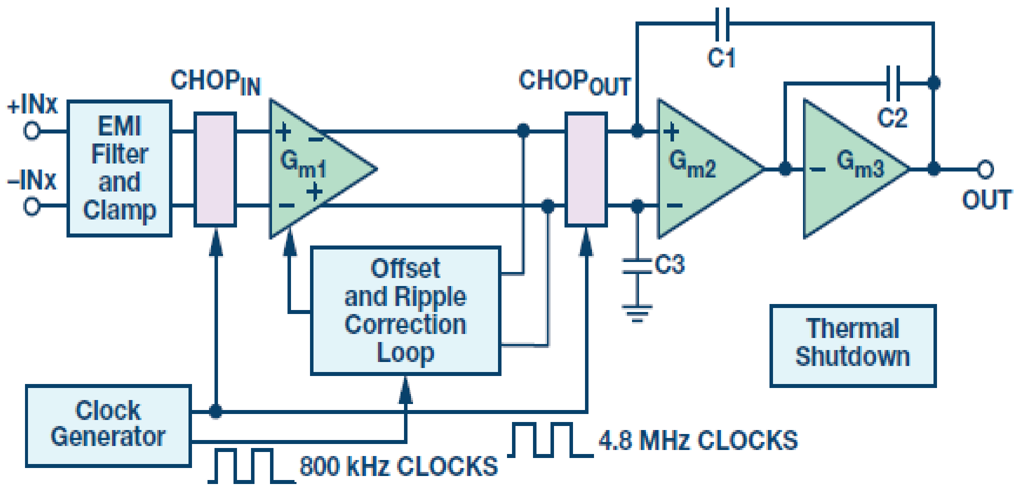
ADA4177 Datesheet

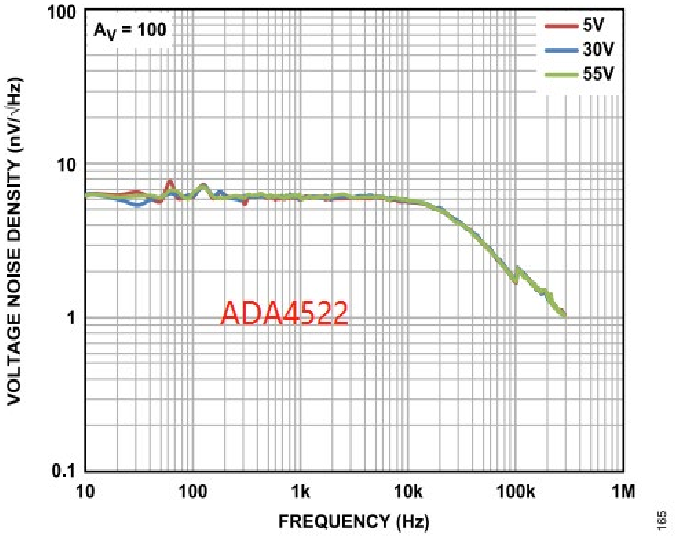
1/f Noise How to calculate ?



$$\frac{1}{f}\ Noise_{rms} = en_{1Hz}\left(\sqrt{\ln\left(\frac{f_h}{f_l}\right)}\right)$$

How to deal with 1/f Noise

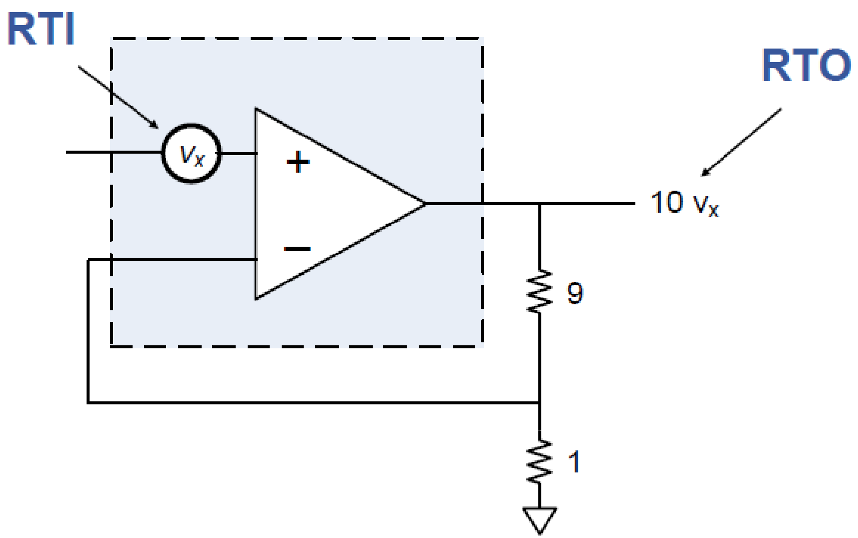




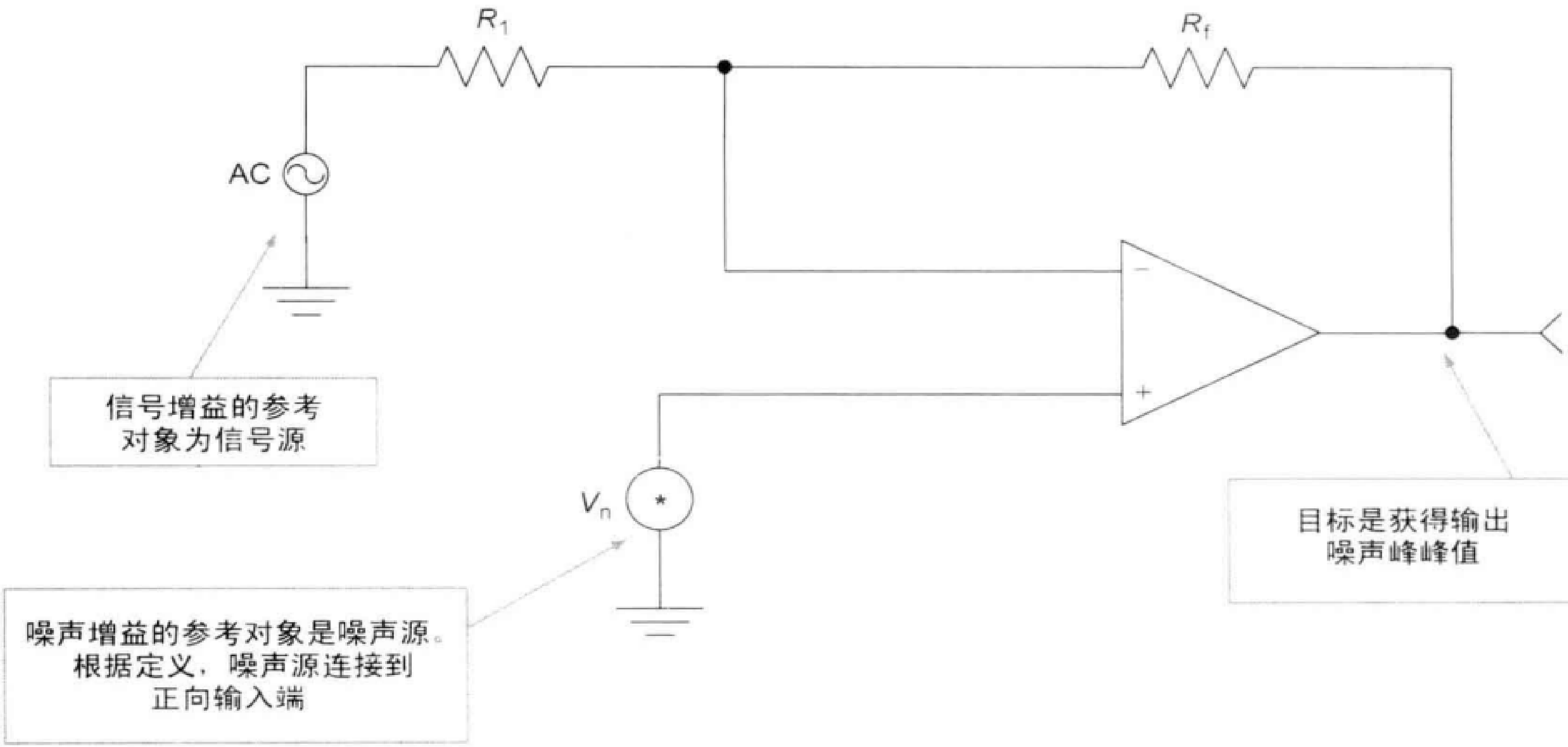
NOISE PERFORMANCE				
Total Harmonic Distortion Plus Noise	THD + N	A_V = 1, f = 1 kHz, V_{IN} = 0.6 V rms		
Bandwidth (BW) = 80 kHz			0.001	%
BW = 500 kHz			0.02	%
Peak-to-Peak Voltage Noise	$e_{N\ p\text{-}p}$	A_V = 100, f = 0.1 Hz to 10 Hz	117	nV p-p
Voltage Noise Density	e_N	A_V = 100, f = 1 kHz	5.8	nV/√Hz
Peak-to-Peak Current Noise	$i_{N\ p\text{-}p}$	A_V = 100, f = 0.1 Hz to 10 Hz	16	pA p-p
Current Noise Density	i_N	A_V = 100, f = 1 kHz	0.8	pA/√Hz

RTI RTO

- Options
  - Referred to Input (RTI)
  - Referred to Output (RTO)
- If not stated, referred to Input

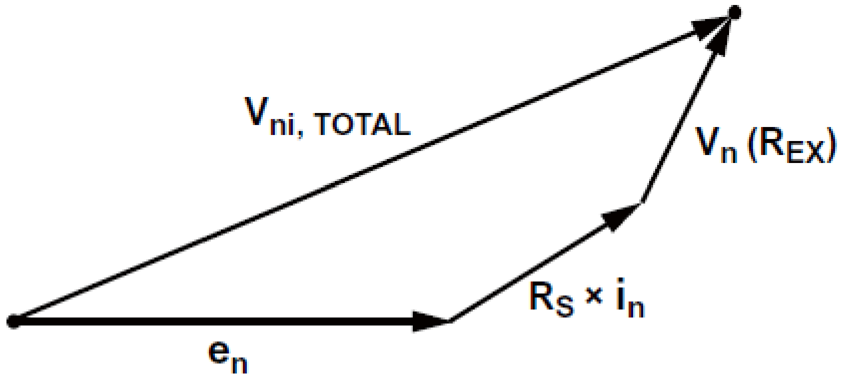


Noise Gain



R_1
R_f
AC
信号增益的参考
对象为信号源
V_n
目标是获得输出
噪声峰峰值
噪声增益的参考对象是噪声源。
根据定义，噪声源连接到
正向输入端

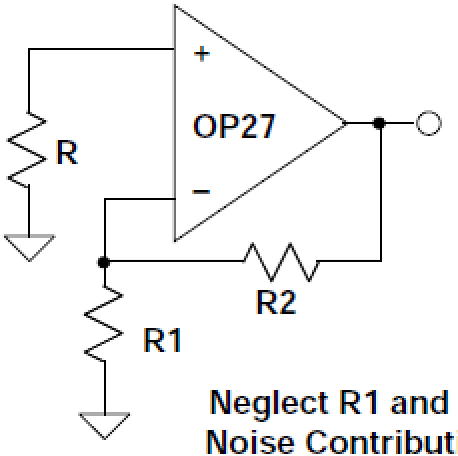
Total noise



$$V_{ni,TOTAL} = \sqrt{(e_n)^2 + (R_S \times i_n)^2 + V_n(R_{EX})^2}$$

Main noise

EXAMPLE: OP27
Voltage Noise = 3nV / √ Hz
Current Noise = 1pA / √ Hz
T = 25°C

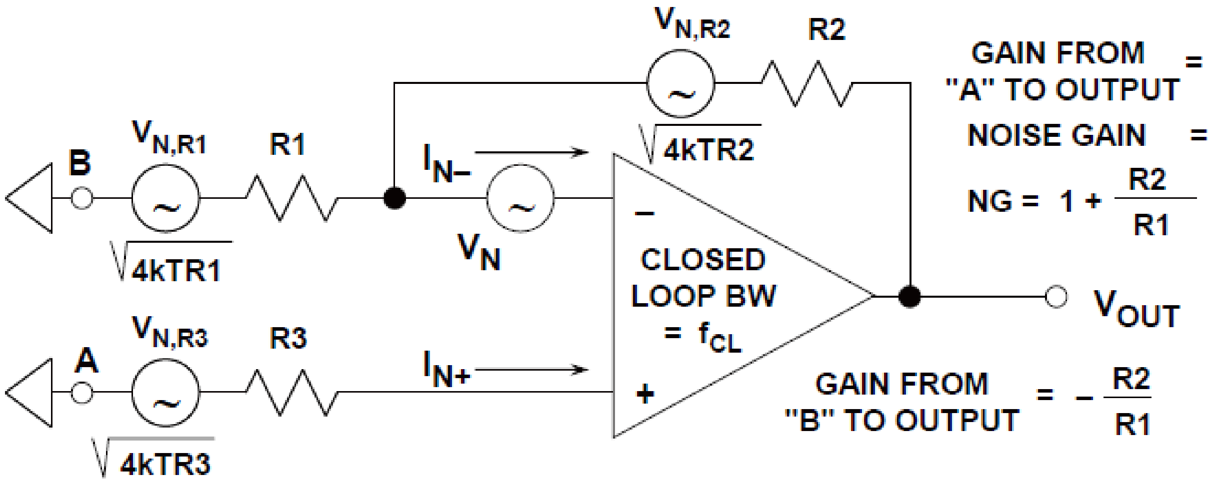


Neglect R1 and R2 Noise Contribution

CONTRIBUTION FROM	VALUES OF R		
	0	3kΩ	300kΩ
AMPLIFIER VOLTAGE NOISE	3	3	3
AMPLIFIER CURRENT NOISE FLOWING IN R	0	3	300
JOHNSON NOISE OF R	0	7	70

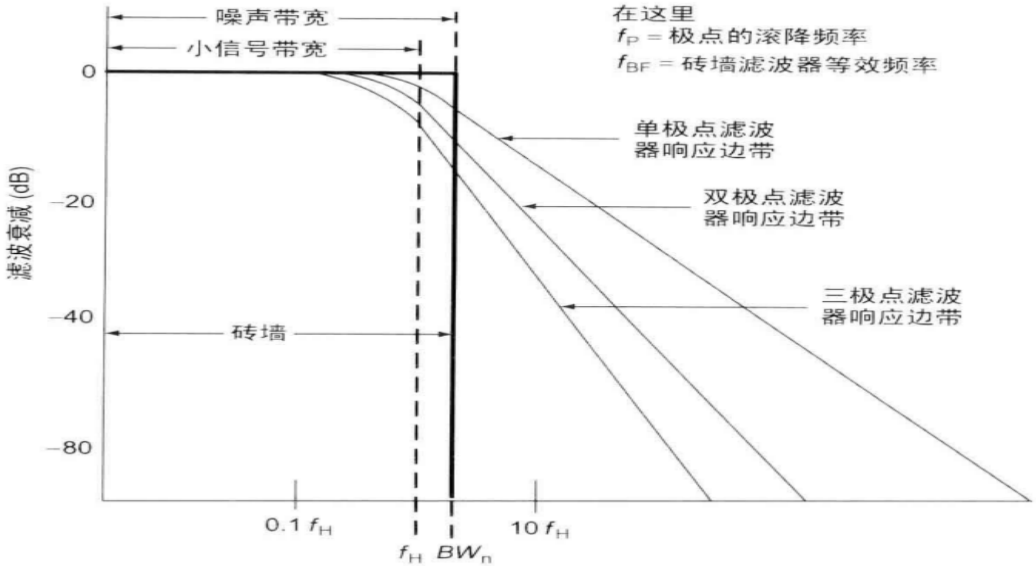
RTI NOISE (nV / √ Hz)
Dominant Noise Source is Highlighted

Amplifier noise model for monopole point system



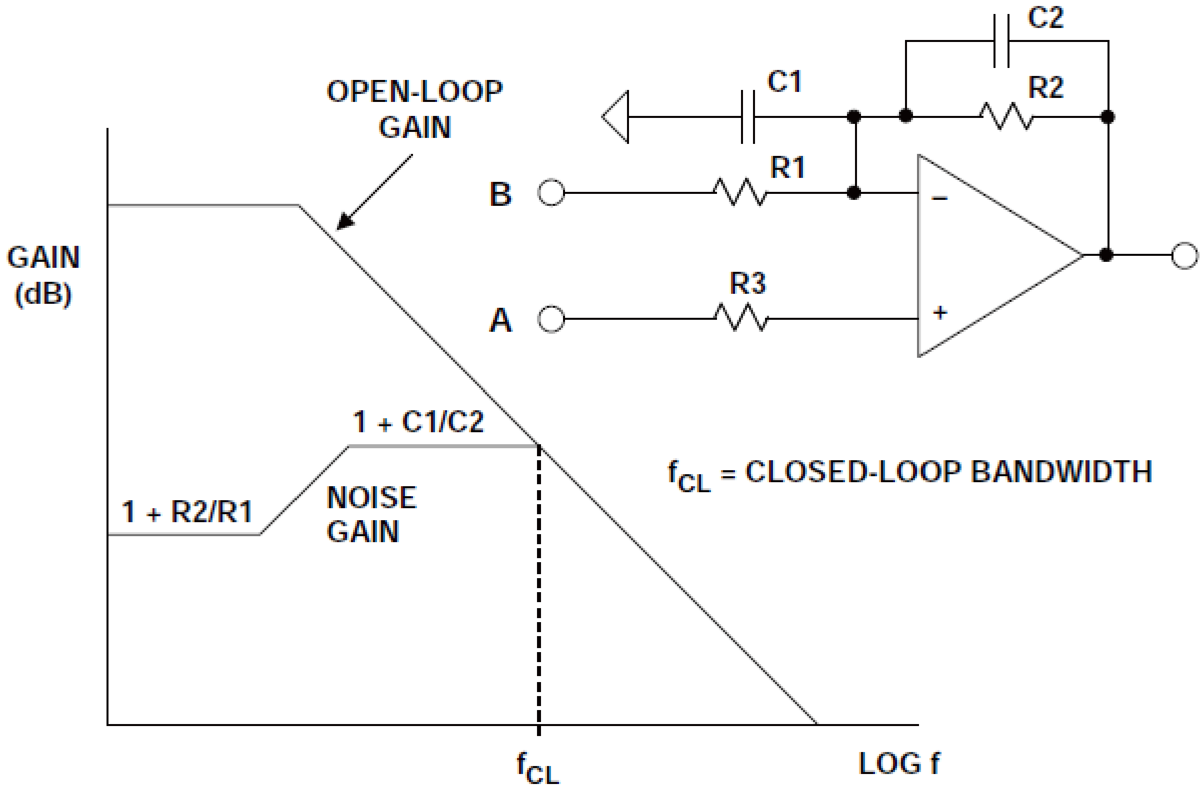
- RTI NOISE = $\sqrt{BW} \bullet \sqrt{V_N^2 + 4kTR3 + 4kTR1\left[\frac{R2}{R1+R2}\right]^2 + I_{N+}^2 R3^2 + I_{N-}^2\left[\frac{R1 \bullet R2}{R1+R2}\right]^2 + 4kTR2\left[\frac{R1}{R1+R2}\right]^2}$
- RTO NOISE = NG • RTI NOISE
- $BW = 1.57\, f_{CL}$

Noise bandwidth



滤波器极点数（阶数）	K_n AC 噪声带宽比
1	1.57
2	1.22
3	1.16
4	1.13
5	1.12

Noise gain determines stability



Why so many units?

-nV/√Hz, μVrms, μV p-p

-converting between units

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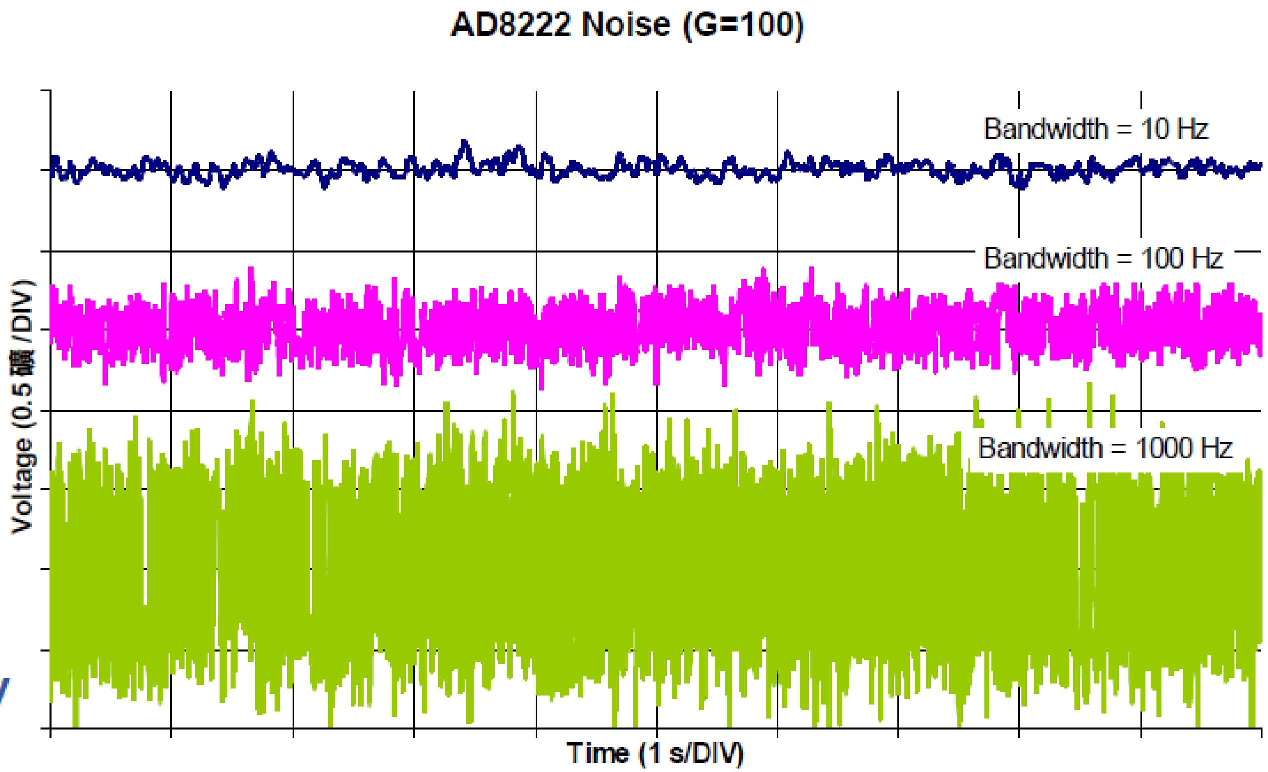
Noise depends on bandwidth

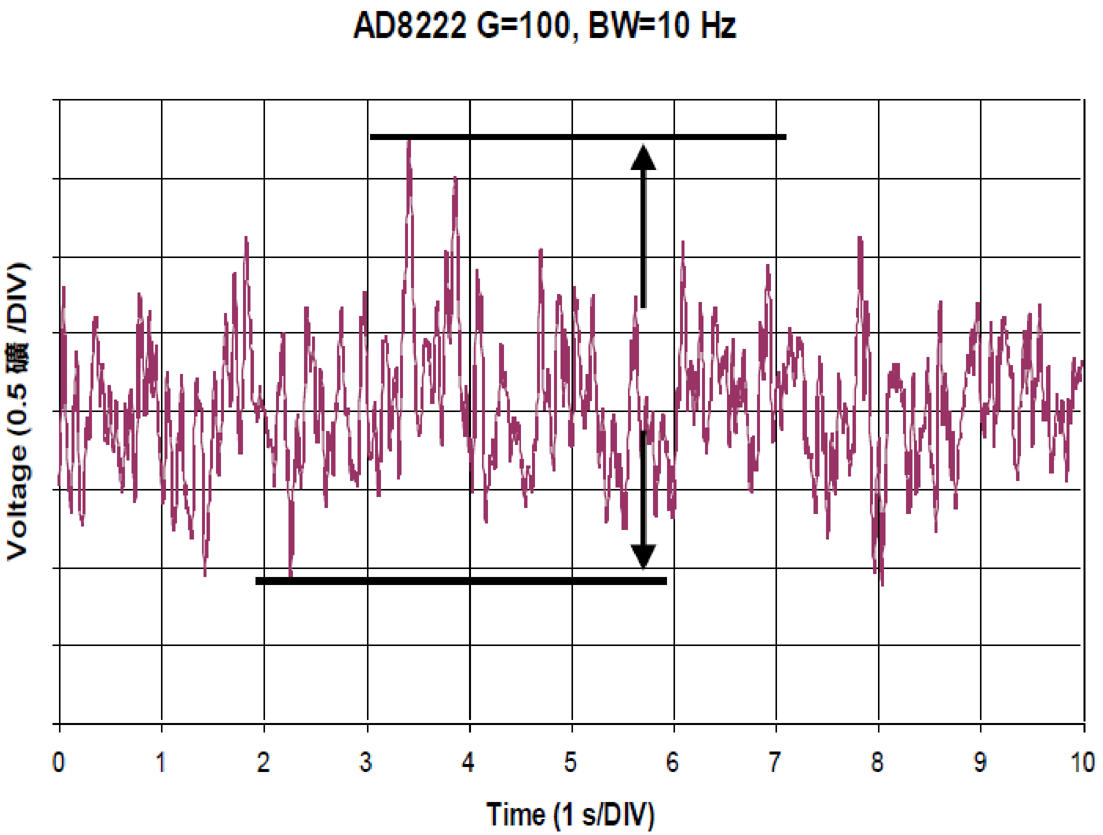
- **Bandwidth Dependent**
  - RMS
  - Peak to Peak



- **Bandwidth Independent**
  - spectral density (nV/√(Hz))

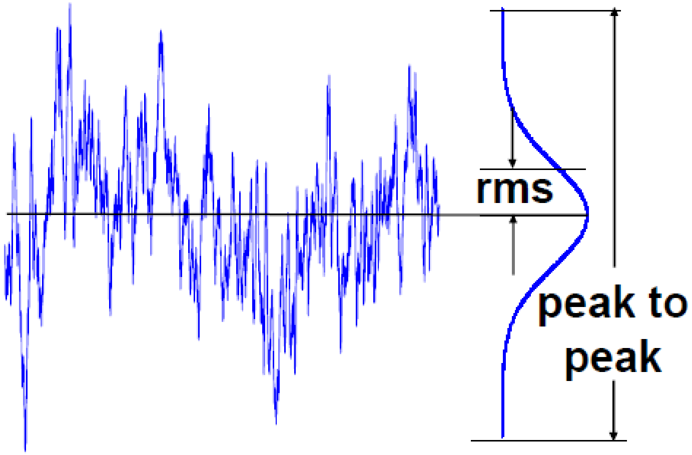
What’s quick to measure?

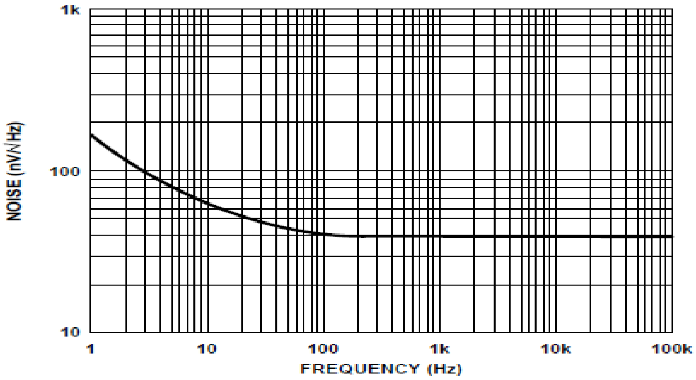
- **Peak to peak noise**
  - Can see on oscilloscope
- **RMS noise**
  - Sometimes with oscilloscope
  - DMM (watch bandwidth)
- **Spectral Density (nV/√Hz)**
  - Spectrum Analyzer



What's accurate?

- **Peak to peak noise**
  - Depends on two points (outliers)
- **RMS noise**
  - Depends on all points in waveform
- **Spectral Density (nV/√Hz)**
  - Depends on all points in waveform
  - Sorts information by frequency band





How to convert

- Conversion process
  - nV/√(Hz) → μVrms
  - μVrms → μVp-p

nV/√(Hz) --> µ Vrms

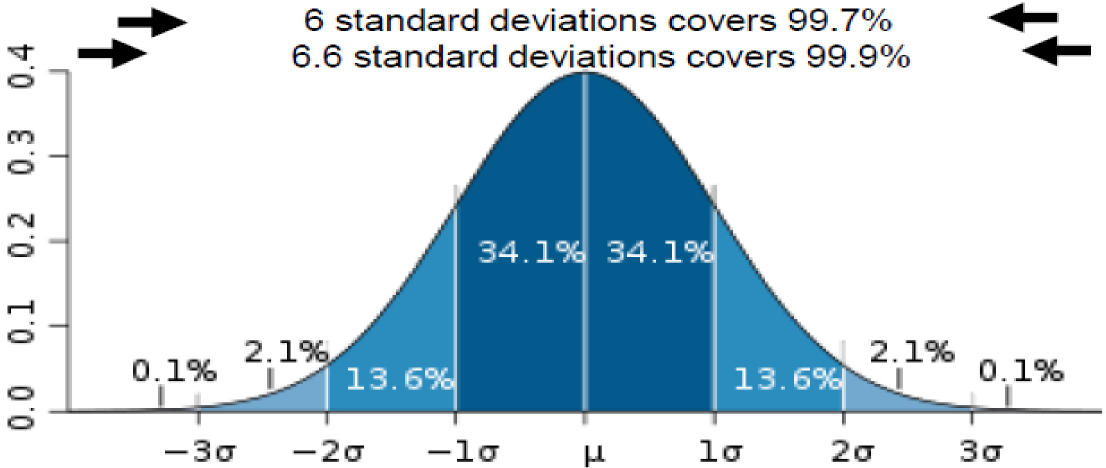
- **Equation**
  - **spectral density * √(bandwidth) = RMS noise**
    - when 1/f corner << bandwidth
- **Note: Use equivalent noise bandwidth of filter**
  - **Noise BW of a filter is always greater than the 3dB BW**
  - **Brick wall: 1**
  - **Equivalent Noise bandwidth for Butterworth filters**
    - 1 pole: ×1.57
    - 2 pole: × 1.11
    - 3 pole: × 1.05

NUMBER OF POLES	NOISE BW / 3dB BW
1	1.57
2	1.11
3	1.05
4	1.03
5	1.02

- **Example:**
  - **Given:**
    - 40 nV/rt(Hz)
    - 1 kHz 1 pole filter
  - **Answer:**
    - 40 nV/rt(Hz) * sqrt(1000 Hz * 1.57) ≈ 1600 nVrms = 1.6 µVrms

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
- Example
  - 1 µVrms * 6 ≈ 6 µVp-p



graph from Wikipedia: original by Jeremy Kemp

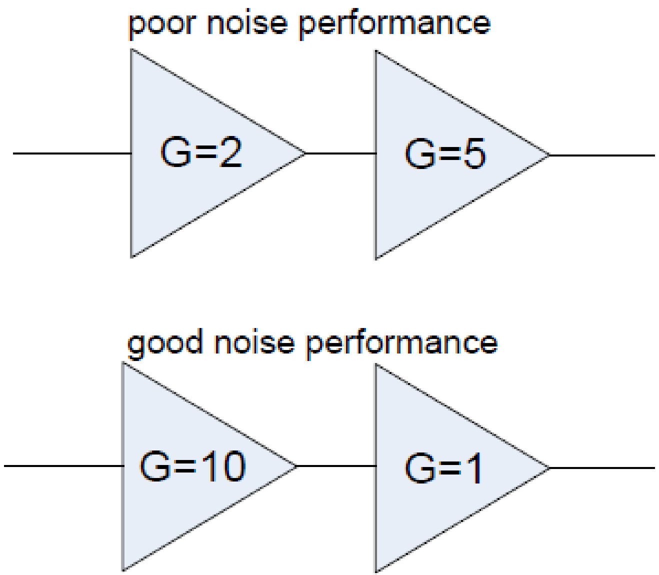
Noise Tip #1: Apply Gain Early

- Noise adds as sum of squares
- Apply all the gain in the 1st stage
- Example: Assuming the noise of amplifier is 1
    - Noise for the circuit above:

$$\sqrt{(1\times 2)^2+1^2}\times 5 = 5\sqrt{5} = 11.180$$

    - Noise for the circuit below:

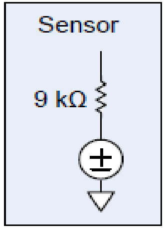
$$\sqrt{(1\times 10)^2+1^2}\times 1 = \sqrt{101} = 10.049$$



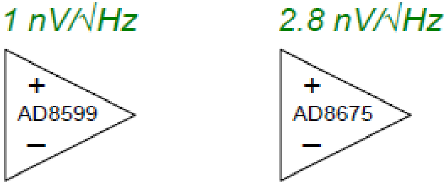
Noise Tip #2: Watch out for source impedance

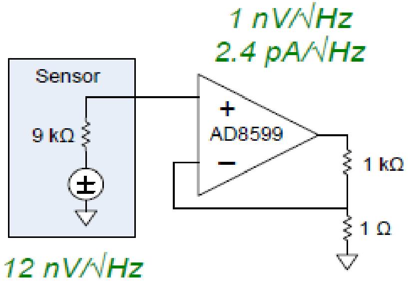
- **Source Resistance adds noise**
- **Current noise calculation**

- **Example**
  - **Given the following sensor**

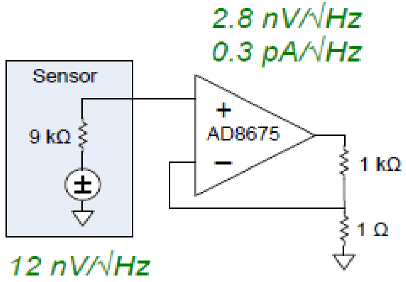


  - **Which op amp is the best?**





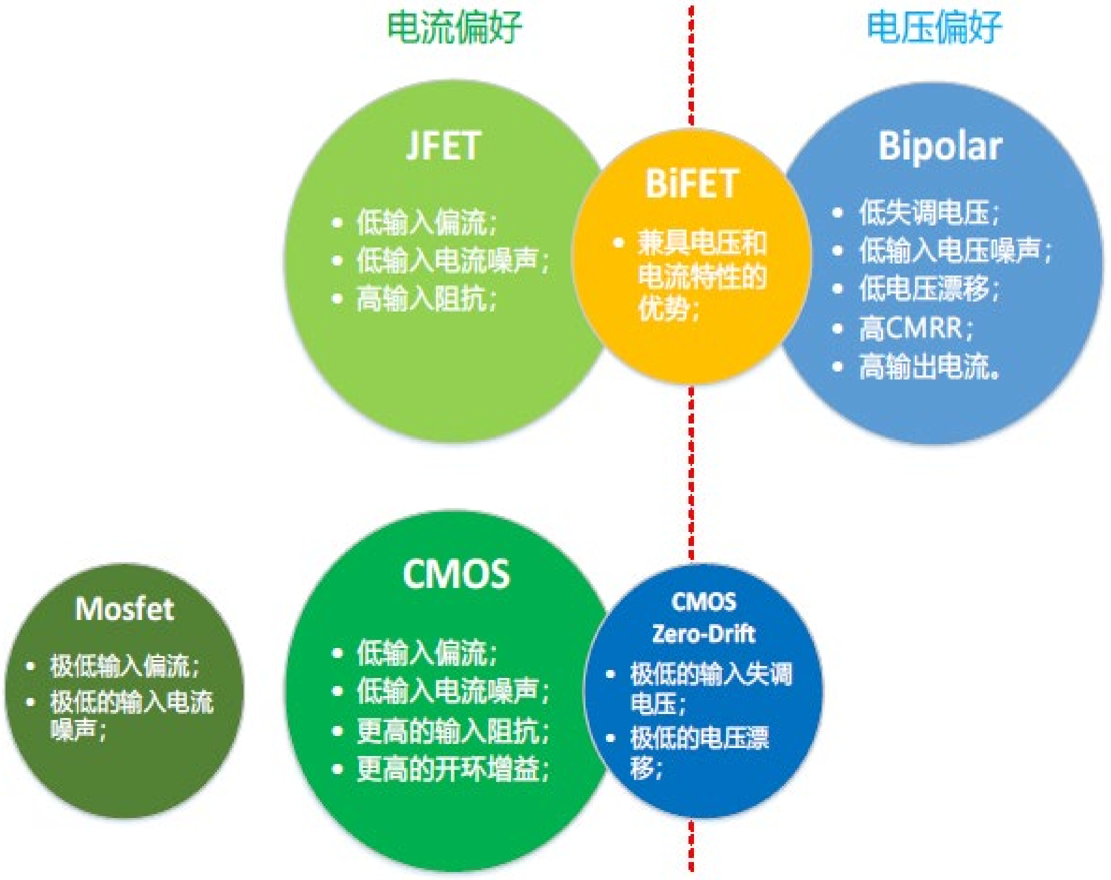
RTI noise
$= \sqrt{(12^2 + 1^2 + (2.4*9)^2)}$
= 25 nV/√Hz



RTI noise
$= \sqrt{(12^2 + 2.8^2 + (0.3 * 9)^2)}$
= 13 nV/√Hz

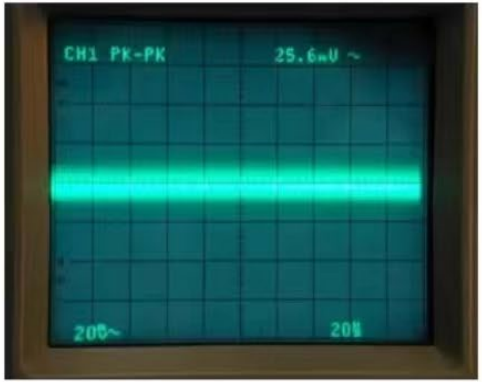
Noise Tip #3:CMOS JFET or Bipolar ?

- Bipolar工艺经典运放:
  早年的 OP27，OP07D，OP177，AD797，
  AD706
  现今的 AD8672，ADA4075，ADA4004
  ADA4077，ADA4177
- JFET工艺经典运放:
  AD549，AD823，AD795
- BiFET是工艺的融合，经典运放:
  早年的 AD712，AD744
  现今的 ADA4610，ADA4622，ADA4625
- CMOS需较低电源供电，经典运放:
  AD8662，AD8602
- COMS型的Zero-Drift 经典运放:
  AD8629，AD8628，AD8639，AD8638
  ADA4522(最大55V供电)，ADA4528
  LTC2057/58HV(最大供电60V)
- MOSFET型经典运放:
  ADA4530-1（Ibias<1fA），LTC6268-10



Noise Tip #4:Noise measurement

- Do not use 10x probes for low noise measurements
- Use direct BNC cable connection (10x better noise floor)
- Use male BNC shorting cap to measure noise floor of oscilloscope
- Use bandwidth limiting (if appropriate)
- Use digital scope in dc coupling mode for 1/f noise measurements (ac coupling has a 60Hz high pass filter)
- Use ac coupling for broadband measurements (if necessary)

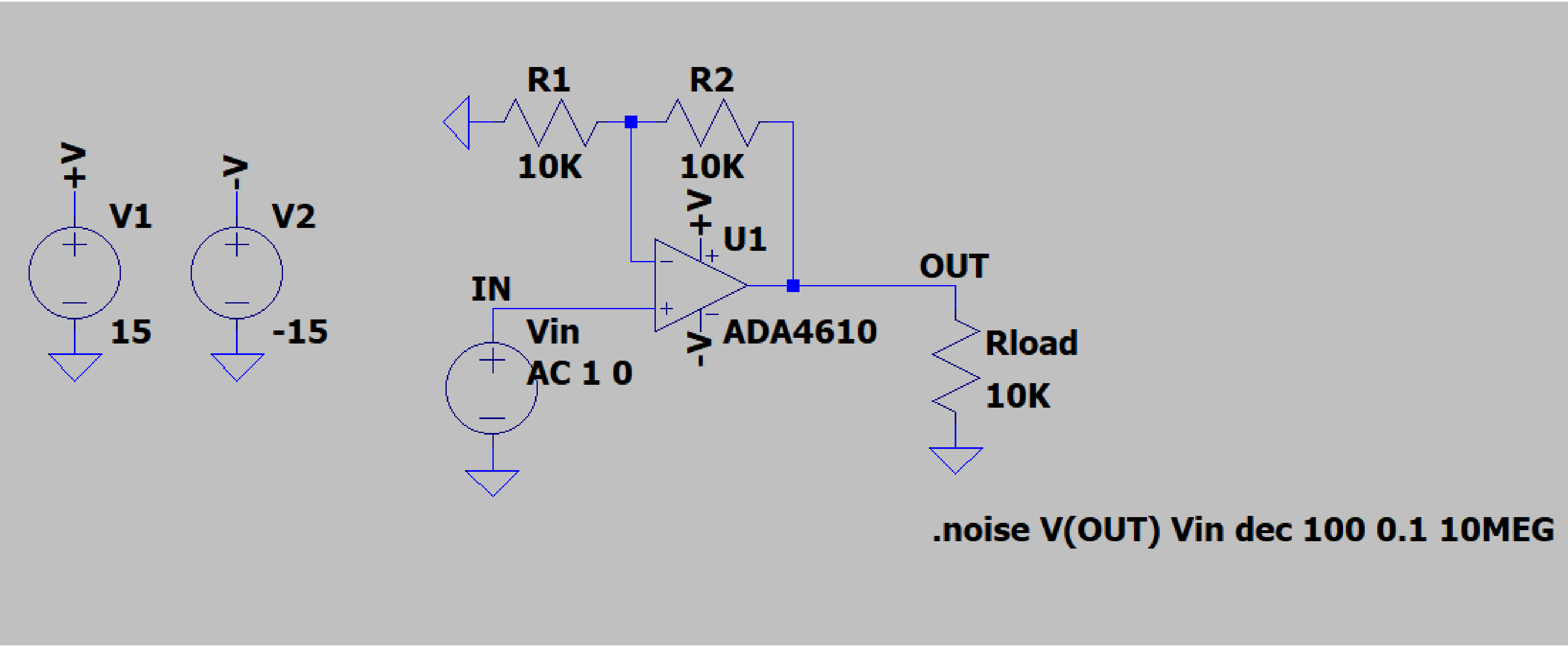


Noise Tip #5:How to Reduce Noise ?

- Select a low noise amplifier
  - Consider both current and voltage noise
  - Consider low and high frequency noise
- Select the appropriate feedback resistors
  - Low resistance for low noise
- Limit the system bandwidth

LTspice

[LTspice Simulator | 亚德诺半导体 (analog.com)](https://www.analog.com)



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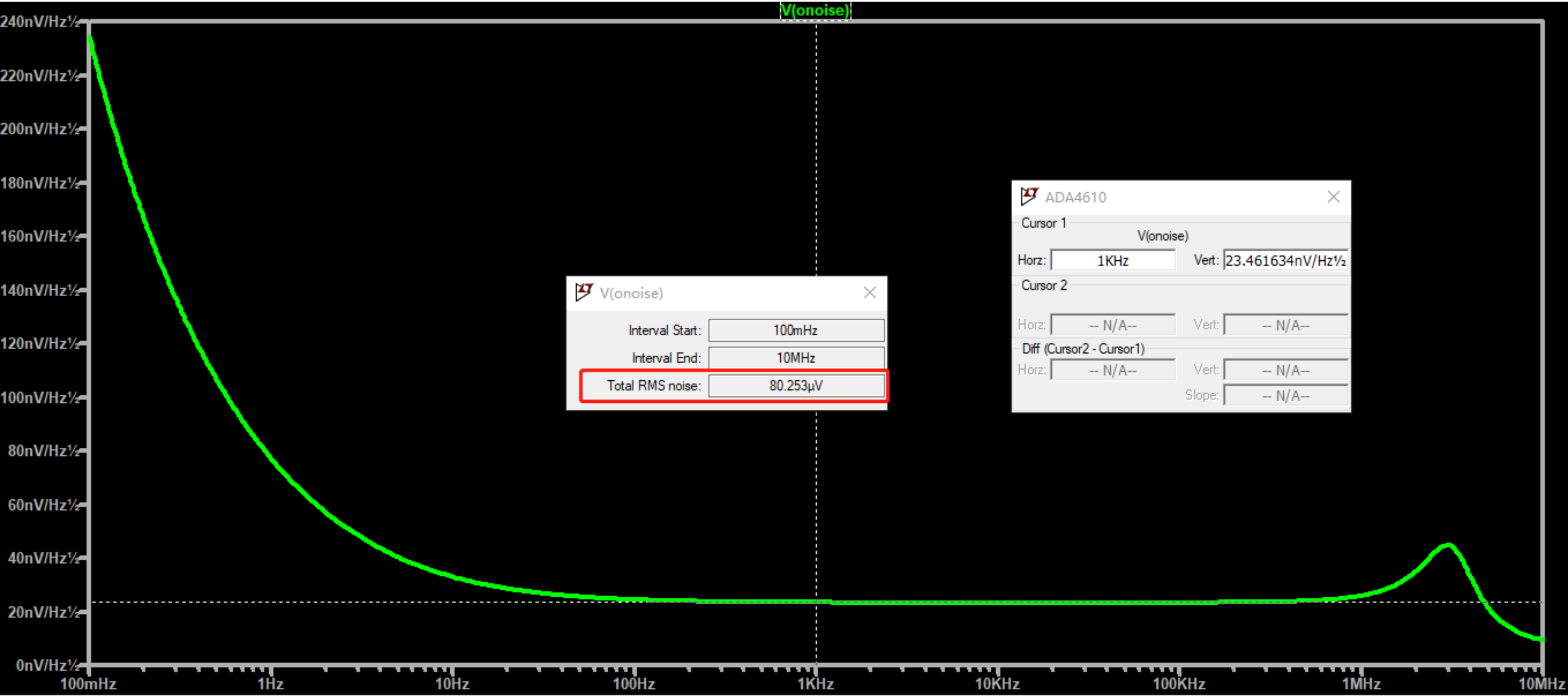


ADI Typical Low Noise Amplifier

ADA4510: 40 V, 70 nV/°C, Low VOS, Low IB, Low Noise RRIO Op Amp

Key Features

- V_{OS} drift (TCV_{OS}): **70 nV/°C** typ., **0.5 µV/°C** max at 0°C to 85°C
- V_{OS}: **±20 µV** max at 25°C
- 1/f noise: **1 µV p-p** typ. from 0.1 Hz to 10 Hz
- Noise density: **5 nV/√Hz** typ. at 1 kHz
- Gain Bandwidth Product (GBP): **10.4 MHz** typ.
- Slew rate: **19 V/µs** typ.
- Input bias current: **10 pA** max 25°C
- Low THD: **-134 dB** at 1 kHz
- Capacitive load drive capability: **1 nF**
- Integrated EMI

Key Applications

- Automated test and measurements
- Data acquisition systems
- Multiplexed-input signal chains
- Electronics test and measurements

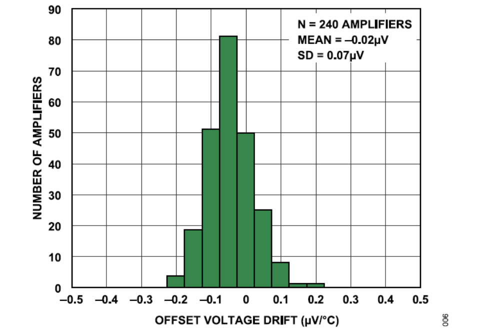


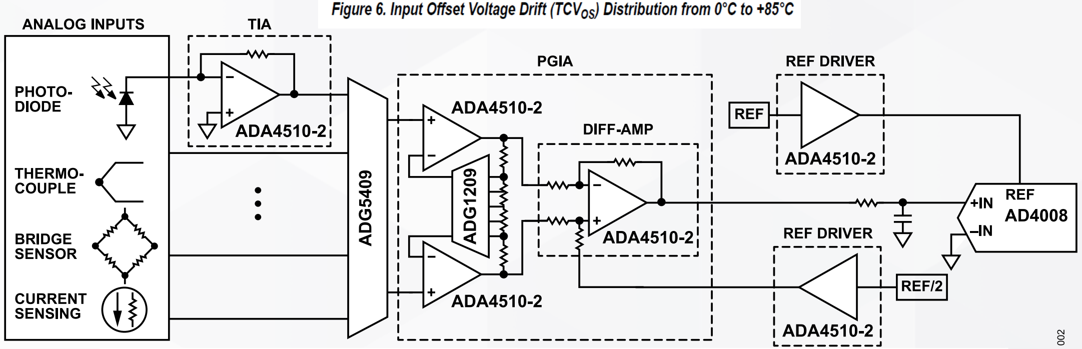
Figure 6. Input Offset Voltage Drift (TCV_{OS}) Distribution from 0°C to +85°C

DEVELOPEMNT

Sample Date: Now (SOIC)

Release Date: Aug 2023 (SOIC)

Feb 2024 (MSOP)



	ADA4510	Competitor
TCV_{OS} (-40°C to +125°C, Max)	0.7 µV/°C	0.8 µV/°C
Offset Voltage (Max)	20 µV	25 µV
1/f Noise	1.0 µV p-p	1.3 µV p-p
Voltage Noise Density	5 nV/√Hz	5.5 nV/√Hz

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ADA4510: Portfolio Positioning

ADA4622

- I_B
- Offset
- Offset drift
- Noise

ADA4610

- I_B
- Offset
- Offset drift

ADA4625

- Noise
- Slew rate and GBW
- I_B
- Quiescent current
- No MSOP package

ADA4522

- Offset/offset drift
- Noise
- Supply voltage range
- Quiescent current
- I_B
- Settling time
- Slew rate and GBW

The ADA4510 is Analog Devices' latest high input swing CMOS op amp part with the best overall precision

ADA4510

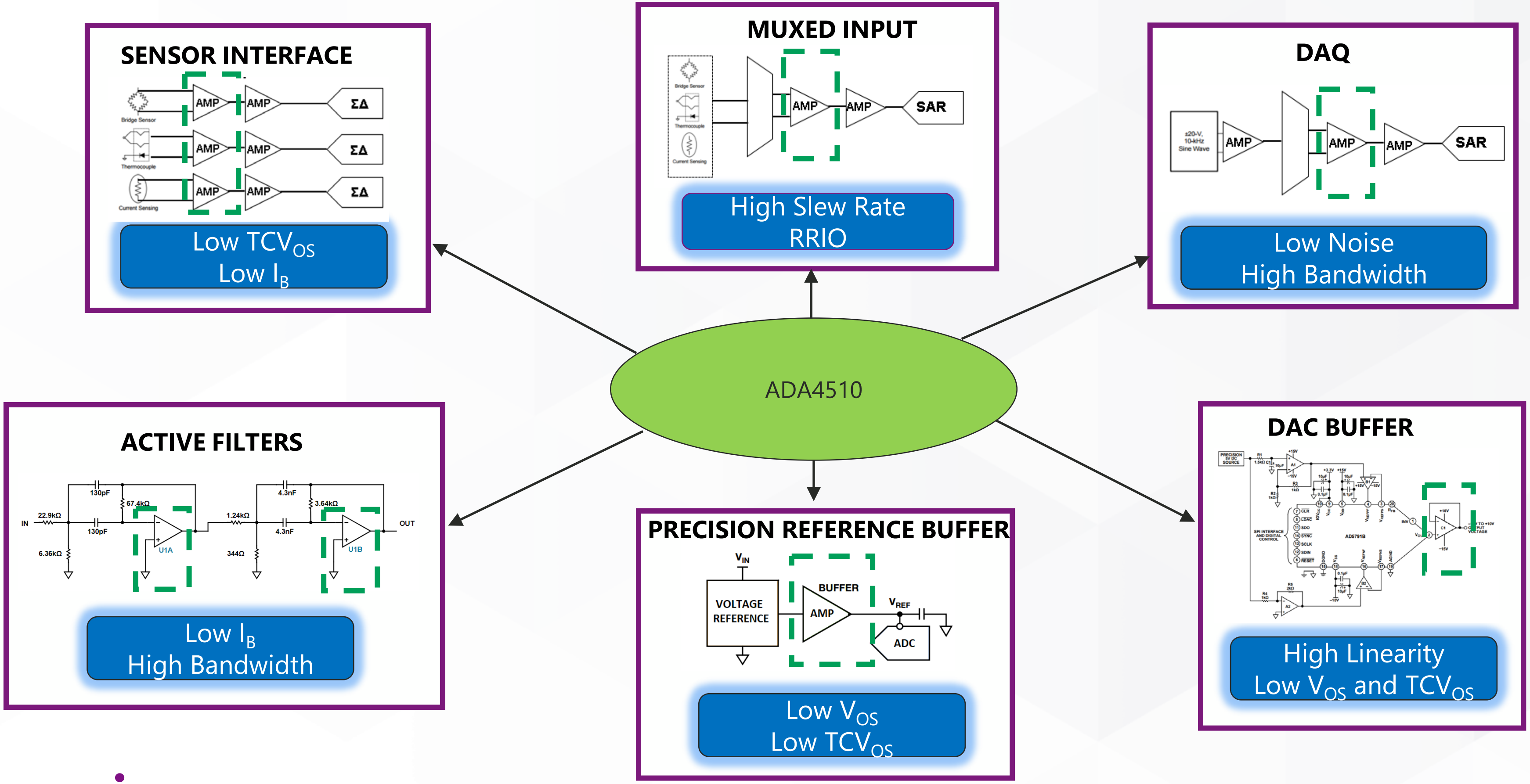
- **Offset**
- **Offset drift**
- **I_B**
- **Small package (on list)**
- **Competitive price**
- **Derivatives**
- Good noise, slew rate, and GBW

- Flagship precision amplifier product
- Stable process and reusable IP for future derivatives
- Latest technology with the top reliability, durability, and accuracy
- Outstanding platform amplifier

ADA4510: 40 V, ±70 nV/°C, Low VOS, Low Noise RRIO Op Amp

Features	Benefits
Excellent DC operational range ▪ Supply voltage range: ±3 V to ±20 V ▪ Rail to rail inputs and outputs ▪ -40°C to +125°C operation	Easily allows user to upgrade performance and accuracy to any system architecture by offering an extensive operating range in supply voltage, input/output voltage, and temperature range Wide applicability
Low offset voltage ▪ 20 µV max at 25°C	Improves system DC accuracy; also improves system dynamic range by allowing smaller signals to be sensed at the input
Low offset voltage drift ▪ 70 nV/°C, typ., 0.5 µV/°C max at 0°C to 85°C	Enables stability and precision at temperature, eliminating need for calibration
Low input bias current ▪ 10 pA max at 25°C	Suitable as a sensor interface amplifier for high impedance sensors such as photodiodes, piezoelectric, pH cell, etc.
Low noise ▪ 1 µV p-p typical at 0.1 Hz to 10 Hz ▪ 5 nV/√Hz typical at f = 1 kHz	Enables high resolution sensor interface solution
High slew rate and fast settling time ▪ 19 V/µs	Dynamic specs enable higher measurement throughput for increased sample rate in data acquisition systems
Low THD, high cap load drive capability, and fast settling	Enable driving the ADC directly without ADC driver Minimized distortion
Integrated EMI filter	Makes the end solution more robust in harsh RF environments by rejecting high frequency signals before they reach the amplifier's sensitive inputs

Typical Applications



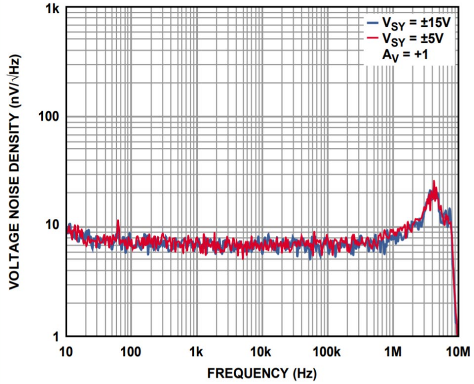
ADA4077-1/ADA4077-2/ADA4077-4: 36 V, 4 MHz, 7 nV/√Hz, Low Offset and Drift, High Precision Amplifier

- 5th generation of the successful OP77 and OPx177 family amplifiers
- Reduced offset and drift with a low noise system provide improved system accuracy as well as bandwidth
- BiPolar® technology to improve power efficiency and increase the system bandwidth for higher speed applications

Part Number	Bandwidth GBP (typ)	Slew Rate (typ)	V_{NOISE} Density (typ)	V_{OS} (max)	V_{OS} Tempco (typ)	V_{OS} Tempco (max)
ADA4077-2 B Grade*	3.9 MHz	1 V/µs	7 nV/rtHz	25 µV	100 nV/°C	250 nV/°C
OP2177	1.3 MHz	0.700 V/µs	7.9 nV/rtHz	75 µV	200 nV/°C	700 nV/°C
B Grade Improvement over OP2177	**200%**	**43%**	**11%**	**67%**	**50%**	**64%**

Key Benefits

- Low noise improves precision in high resolution systems
- Combination of precision specifications eliminates the need for design trade-offs
- Rated for the highest industrial environmental and manufacturing specifications required for demanding applications



Voltage Noise Density vs. Frequency, V_{SY} = ±5 V and V_{SY} = ±15 V

ADA4523-1: 36V Single Op-Amp, The Lowest Noise Zero-Drift Amp

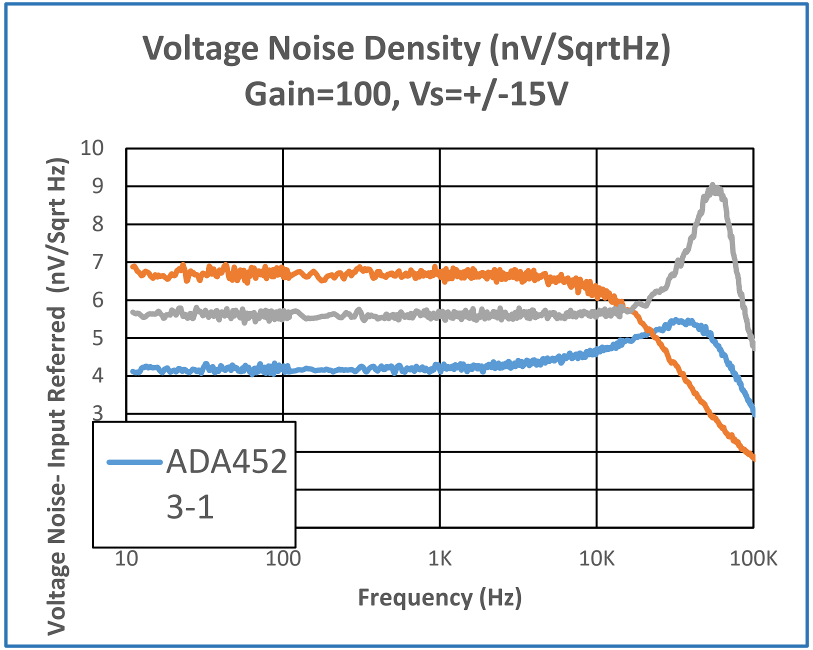
Key Features:

- No other Zero-Drift Amplifier can provide the ultra-low noise performance of the ADA4523-1 at **4.2nV/√Hz** @ 1kHz typ
- Integrated voltage noise over the entire bandwidth is reduced 25%, while still increasing the usable bandwidth

Key Benefits:

- Improves system dynamic range at lower frequencies, allowing smaller signals to be sensed at the input
- Eliminates the need for expensive temperature calibrations by self-correcting offset errors
- Allows lower noise at total power consumption with the shutdown feature

New Product



LTC6226/LTC6227: Single and Dual, Low Noise, High Speed, (420MHz) High Slew Rate Low Distortion Rail-to-Rail Output Op Amps with Shutdown

A Transparent ADC Driver:

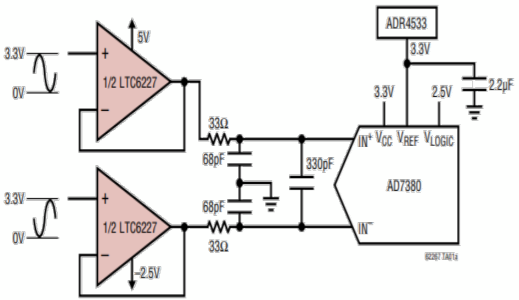
- ADC Drivers should be "transparent" in the signal chain their presence should not influence the signal being digitized
- The LTC6226/6227 are transparent ADC drivers minimizing their footprint within the signal path by offering low noise, low distortion and high speeds complementing the faster LTC6228/6229 offering

Key Specs:

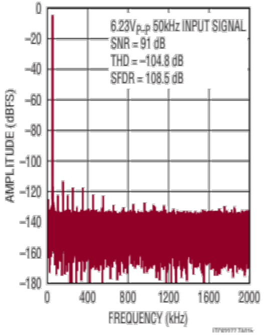
- Ultra Low Voltage Noise: **1.0nV/√Hz**
- Low Distortion at High Speeds:
- HD2/HD3 < −90dBc (Av = +1, 4VP-P, 2MHz, RL = 1kΩ)
- High Speed: 420MHz GBW, 180V/µs Slew Rate
- -3dB Frequency (AV = +1): 330MHz
- Supply Range: 2.8V to 11.75V

TYPICAL APPLICATION

High Performance Transparent LTC6227 Based Driver for the 16-Bit AD7380



16-Bit ADC Driver Performance
Input Signal = −0.5dBFS
f_{SMPL} = 4Msps, f_{IN} = 50kHz



LTC6228/LTC6229: ±5V Low Noise, High Speed, (890MHz) High Slew Rate, Low Distortion, Rail-to-Rail Output Amps

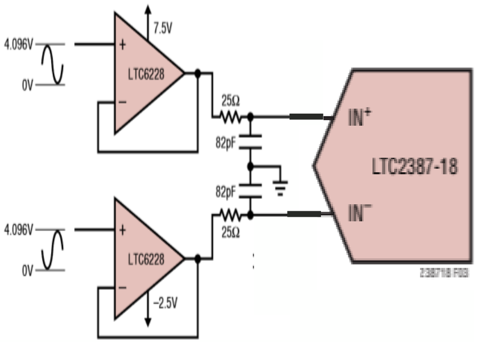
A Transparent ADC Driver:

- ADC Drivers should be "transparent" in the signal chain their presence should not influence the signal being digitized
- The LTC6228/6229 are transparent ADC drivers minimizing their footprint within the signal path by offering low noise, low distortion and high speeds

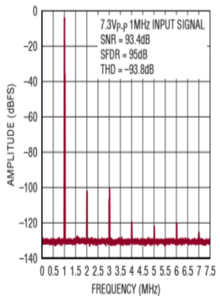
Key Specs:

- Ultra Low Voltage Noise: **0.88nV/√Hz**
- Low Distortion at High Speeds:
  - HD2/HD3 < −100dBc (Av = +1, 4VP-P, 2MHz, RL = 1kΩ)
- High Speed: 890MHz GBW, 500V/µs Slew Rate
- –3dB Frequency (AV = +1): 730MHz

LTC6228 Based Driver for the LTC2387-18 SAR ADC



System Performance: 2 x LTC6228 Driving LTC2387-18
8192 Point FFT, −1dBFS
f_{SMPL} = 15Msps, f_{IN} = 1MHz



ADA4610-1/-2/-4 Low Noise, Precision, Rail-to-Rail Output, JFET Op Amps

Features and specifications

- ADA4610-1: single-channel in SOIC and 5-lead SOT-23
- ADA4610-2: dual-channel in 8-lead MSOP and 8-lead LFCSP
- ADA4610-4: quad-channel in 14-lead SOIC and 16-lead LFCSP
- Low offset voltage
  - B grade: 0.4 mV maximum (ADA4610-2 only)
  - A grade: 1 mV maximum
- Low offset voltage drift
  - B grade: 4 µV/°C maximum (ADA4610-2 only)
  - A grade: 8 µV/°C maximum
- Low input bias current: 5 pA typical
- Dual-supply operation: ±5 V to ±15 V
- Low voltage noise: **0.45 µV p-p at 0.1 Hz to 10 Hz**
- Voltage noise density: **7.3 nV/√Hz at f = 1 kHz**
- Low distortion (THD + noise): 0.00006%
- No phase reversal
- Rail-to-rail output unity-gain stable

Portfolio Positioning

- ADA4610-1 replaces AD8510 pin-compatible
- ADA4610-2 replaces AD8512 pin-compatible
- ADA4610-4 replaces AD8513 pin-compatible
- The ADA4610-x is significantly better in more than seven key specifications, including input bias current, voltage noise, noise density, distortions, rail-to-rail output, and is less expensive

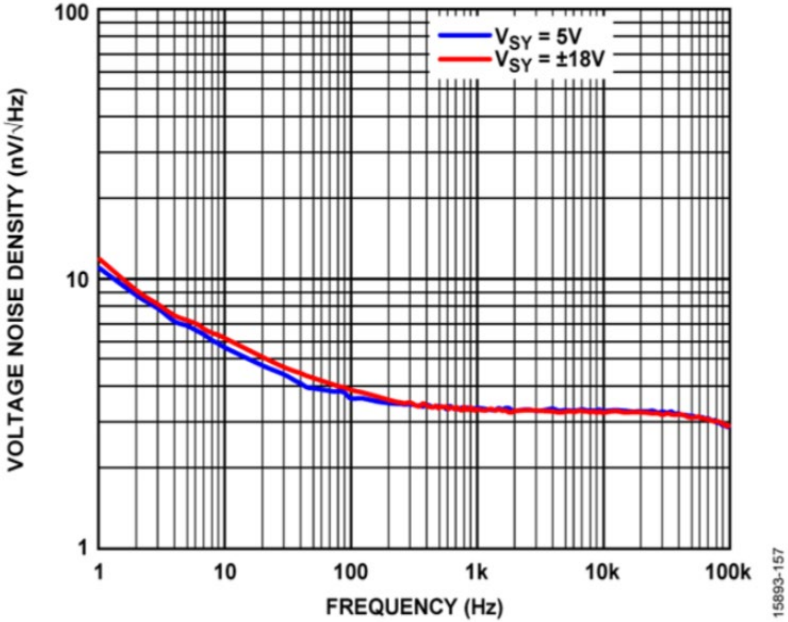
Competitive Positioning

- Provides as much as 2× higher bandwidth and 25% better slew rate than the competition while consuming 2.6× less current

ADA4625: 36 V, 18 MHz, low noise, fast stable single power supply, RRO, JFET operational amplifier

Features and specifications

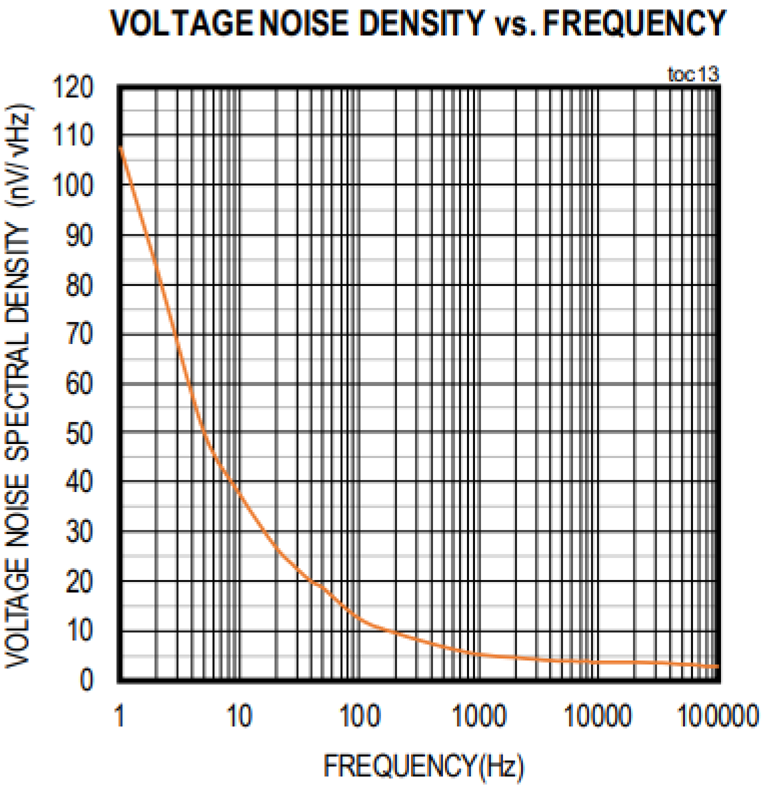
- Wide gain bandwidth product: 18 MHz (typical value)
- High voltage swing rate: 48 V/µs (typical value)
- Low voltage noise density: **3.3nV /√Hz at 1 kHz (typical value)**
- Low peak noise: **0.15 µV p-p, 0.1 Hz to 10 Hz**
- Low input bias current: ±15 pA at TA = 25°C (typical value)
- Low offset voltage: ±80 µV at TA = 25°C (Max)
- Offset voltage drift: ± 1.2µV /°C at TA = −40°C to 85°C (Max)



MAX40078: wide band, low-noise, low-input bias current operational amplifier

Features and specifications

- Low Input Voltage Noise Density: 4.2nV/√Hz at 30KHz
- Low Input Current Noise Density: 0.5fA/√Hz
- Low Input Bias Current: 0.3pA (typ)
- Low Distortion: 0.00035% or -109dB THD+N (1kΩ
- Load)
- Single-Supply Operation from +2.7V to +5.5V
- Input Common-Mode Voltage Range Includes Ground
- Rail-to-Rail Output Swings with a 1kΩ Load



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