Designing a Front-End Circuit for Driving a Differential Input ADC

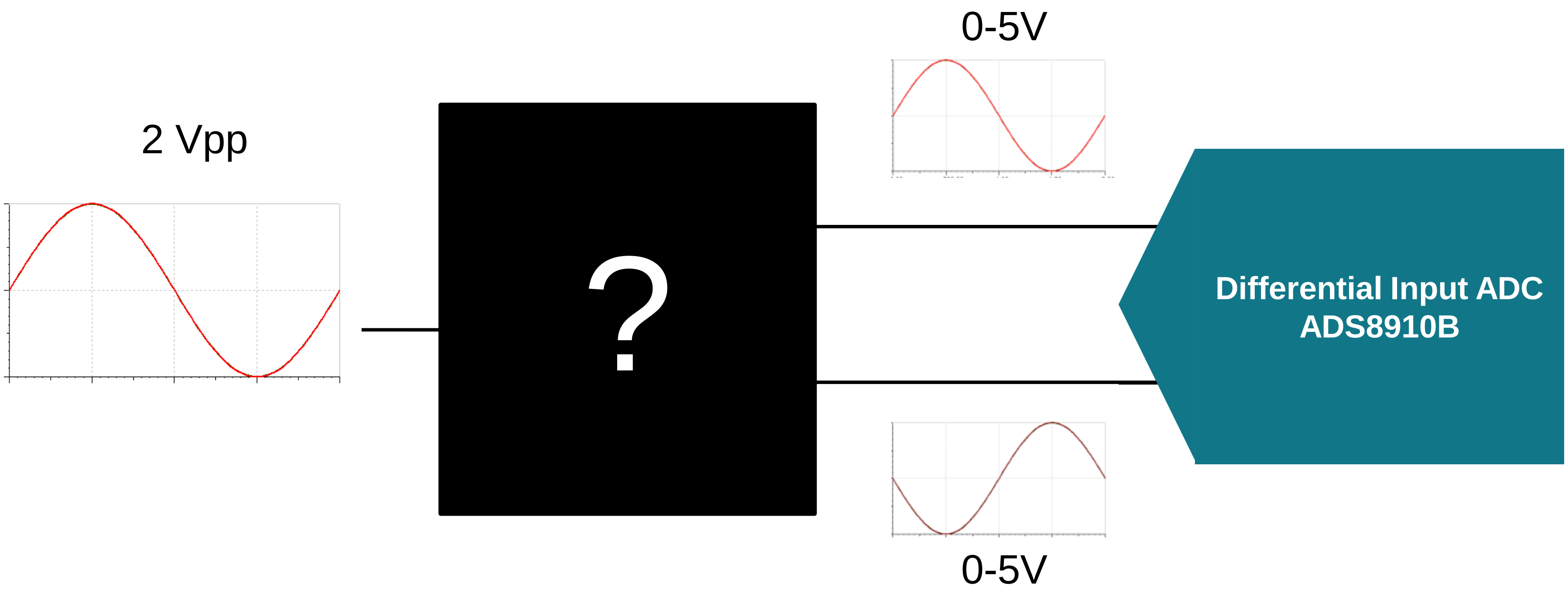
TI Precision Labs – Op Amps

Presented and prepared by Morgan Haggerty

Topics to review before continuing

- Fully Differential Amplifiers
  - TI Precision Labs – Op Amps: Fully Differential Amplifiers – Introduction to FDAs and Differential Signaling
- Noise
  - TI Precision Labs – Op Amps: Noise 1
  - TI Precision Labs – Op Amps: Fully Differential Amplifiers – Noise Analysis, Advanced Compensation Techniques, and Variable Gain FDAs
- Stability
  - TI Precision Labs – Op Amps: Stability 1
  - TI Precision Labs – Op Amps: Fully Differential Amplifiers – FDA stability and Simulating Phase Margin
- Total Harmonic Distortion
  - Application Note: Maximizing Signal Chain Distortion Performance Using High Speed Amplifiers
- Settling Time
  - TI Precision Labs – ADCs: Building a SAR ADC Model
  - TI Precision Labs – ADCs: Refine the Rfilt and Cfilt Values

Converting a single-ended signal to differential



ADC Driver Requirements

Input Signal

- Single ended signal
- 2 V_{pp} amplitude
- 500 kHz frequency

ADS8910B Specifications

- Differential Input
- ADC input voltage: -V_{REF} to V_{REF}
- 1 MSPS
- THD f_{in} = 100 kHz is -110 dB
- 18 bit resolution
- $\text{Least Significant Bit (LSB)} = \frac{\text{Full Scale Range}}{2^{\text{N}}} = \frac{2*5V}{2^{18}} = 38.14\ uV$

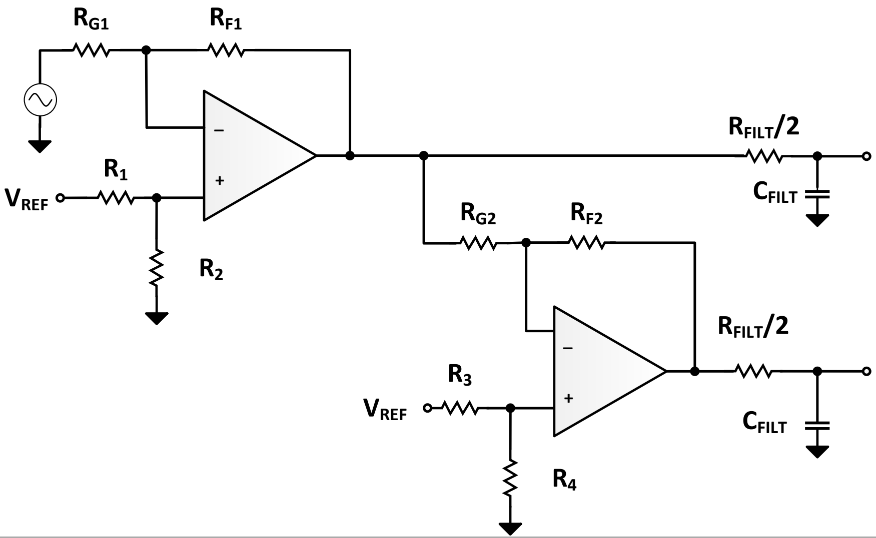
PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
ANALOG INPUT						
FSR	Full-scale input range (AINP – AINM)		$-V_{REF}$		V_{REF}	V
V_{IN}	Absolute input voltage (AINP and AINM to REFM)		0		V_{REF}	V

ADC driver requirements

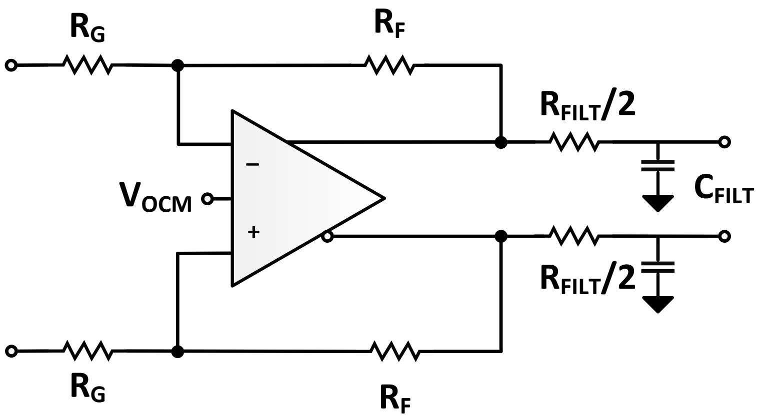
- The differential range is -5V to 5 and the range of each input is 0 to 5gain of 4.6 to allow for dynamic range and for some room
- Amplifier supply voltage of 5.2V
- Bandwidth > 500 kHz
- Better or equal distortion performance to maintain signal fidelity
- Good noise performance to maintain signal fidelity
- Minimize the power consumption

Specifications	Units	OPA625	Comment	THS4551
Number of Channels	#	2		1
Total Supply Voltage min	V	2.7		2.7
Total Supply Voltage max	V	5.5	Ability to maximize dynamic range of the ADC (5V)	5.4
GBW typical	MHz	120	Sufficient Bandwidth	135
Voltage Noise typical	nV/√Hz	2.5	Low noise to maintain signal fidelity	3.3
THD typical	dBc	-110	Low distortion to maintain signal fidelity	-138
Iq per channel (mA)	mA	2	Low power consumption	1.35

Discrete Solution



Fully Differential Amplifier Solution



Discrete Solution Resistor Values

Amplifier 1 - Gain Resistors

$V_{in} = 2V_{pp}$

$V_{out} = 4.6V_{pp}$

$G = V_{out}/V_{in} = 2.3$

$$G_{inverting} = -\frac{R_F}{R_G} = -2.3\ \frac{V}{V}$$

RF1 = 246 RF2 = 107 – Analog engineers calculator

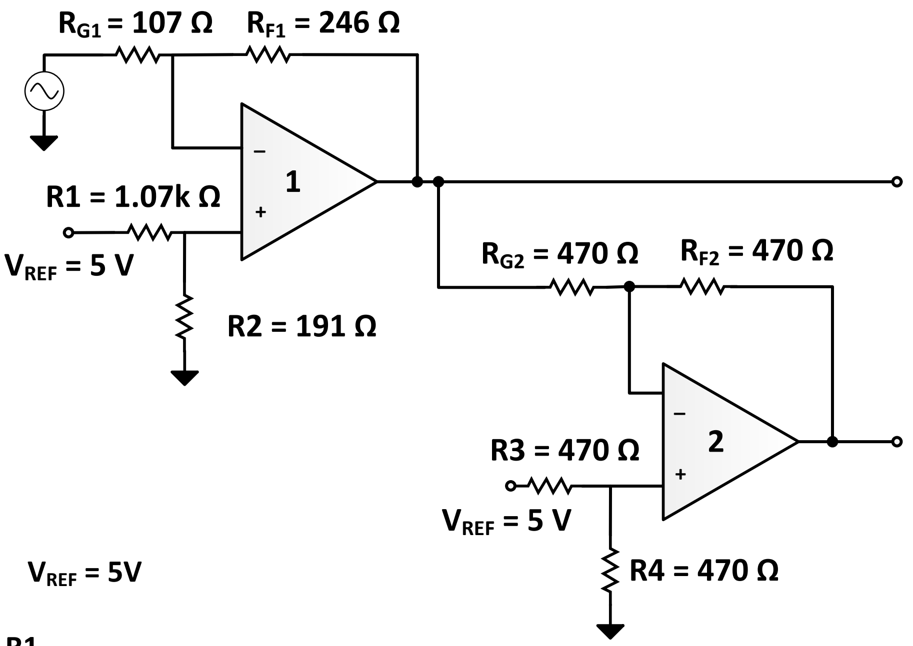
Amplifier 1 - V_{SHIFT} Resistors

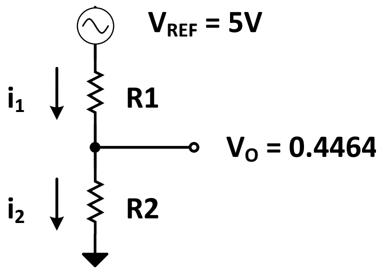
$$G_{non\ inverting} = 1 + \frac{R_F}{R_G} = 3.3\ \frac{V}{V}$$

$V_{OCM} = 2.5\ V$

$$V_o = \frac{V_{OCM}}{G} = \frac{2.5V}{3.3} = 0.7575V$$

$i_1 = i_2$





Discrete Solution Resistor Values

Amplifier 2 - Gain Resistors

$$G_{inverting} = -\frac{R_{F2}}{R_{G2}} = -1\ \frac{V}{V}$$

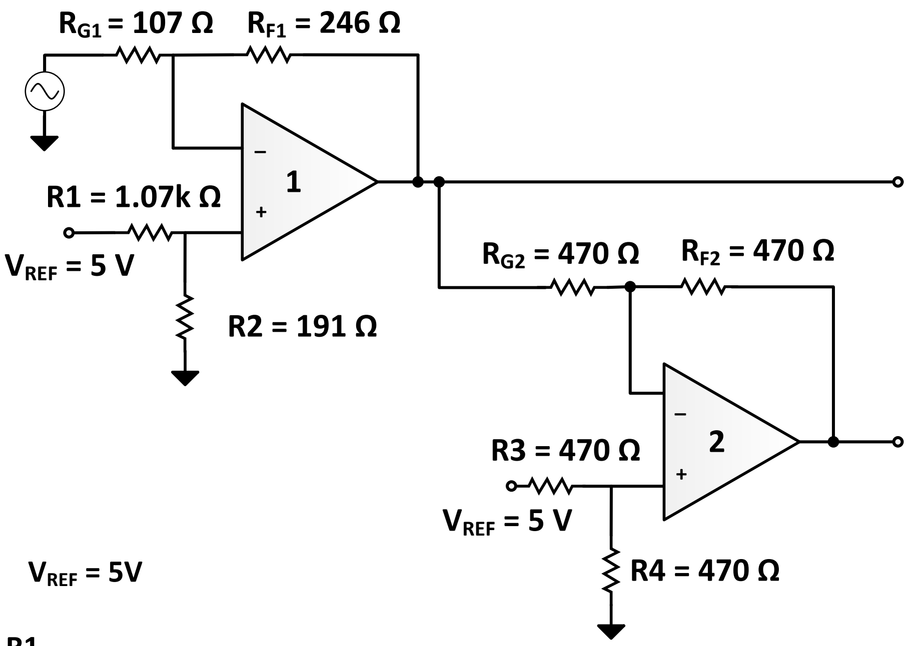
$$R_{F2} = RG_2 = 470\ \Omega$$

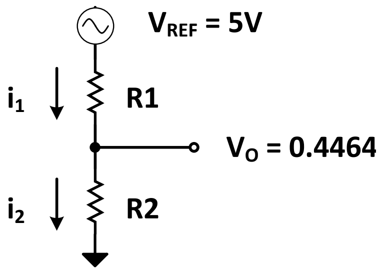
Amplifier 2 - V_{OCM} Resistors

$$G_{non\ inverting} = 1 + \frac{R_{F2}}{R_{G2}} = 2$$

In a voltage divider, when the resistors are the same value the input voltage will be divided in half.

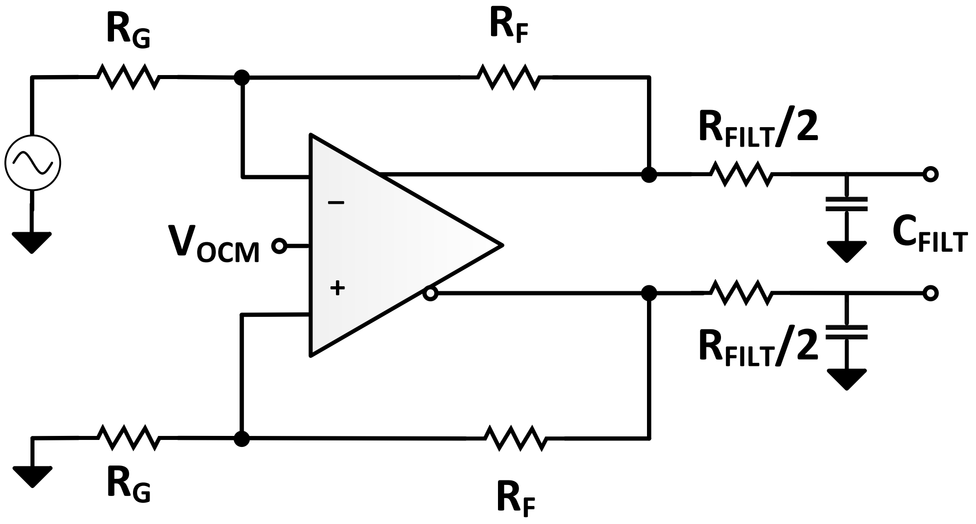
$$R_3 = R_4 = 470\ \Omega$$





FDA Solution Resistor Values

Output Common Mode Voltage



FDAs have a V_{OCM} pin

Voltage a the V_{OCM} pin sees a G = 1
No resistors are required

To maximize the dynamic range of the input of our ADC:

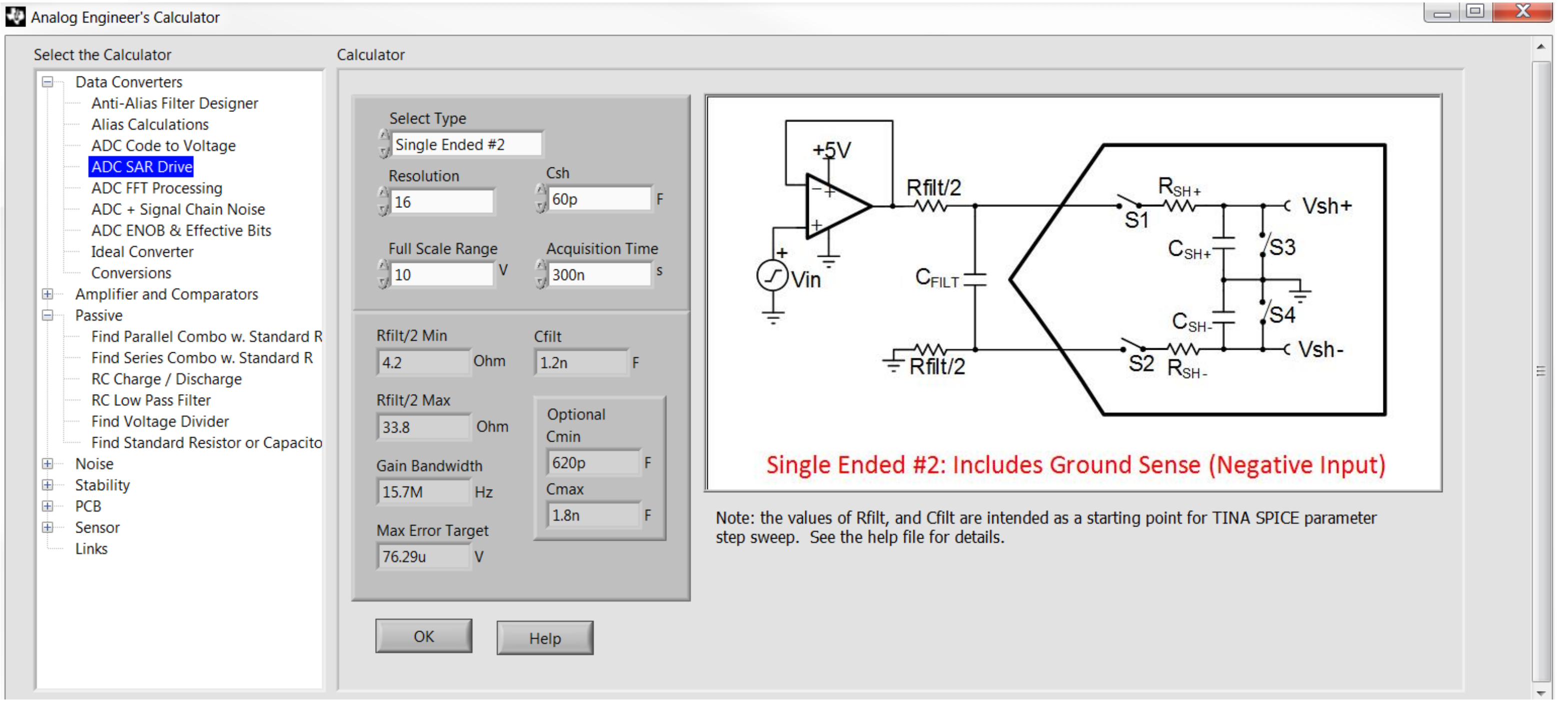
$R_F = 493$

$R_G = 107$

$$G = -\frac{RF}{RG} = -\frac{493}{107} = -4.6$$

Both Solutions Resistor Values

Charge Bucket Filter

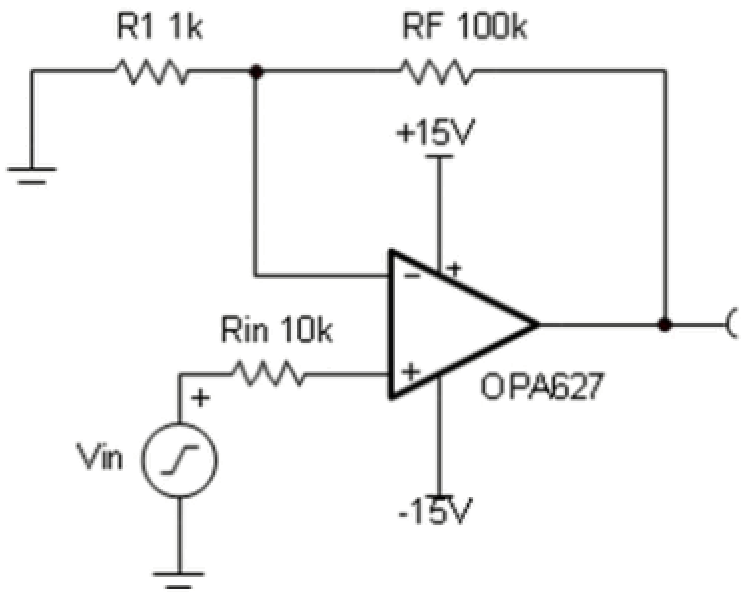


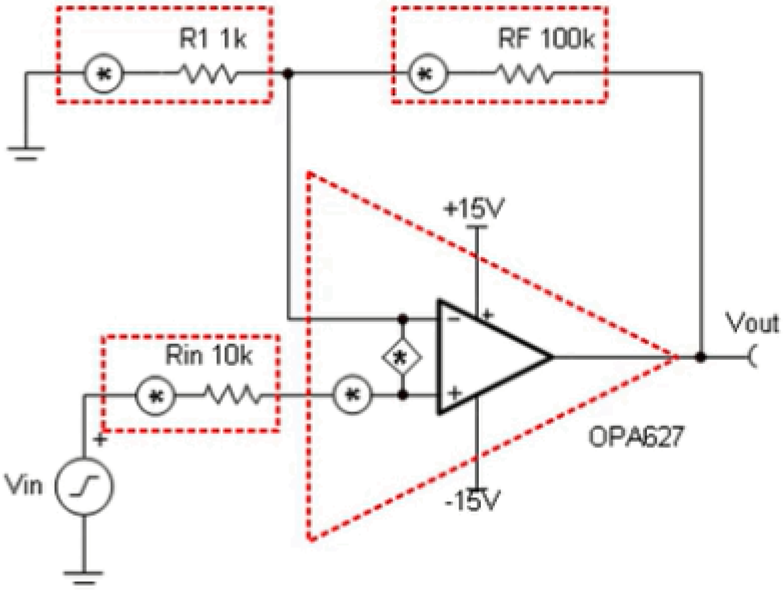
Link for free download of Analog Engineer's Calculator

Math Behind the R-C Component Selection

Refine the Rfilt and Cfilt Values

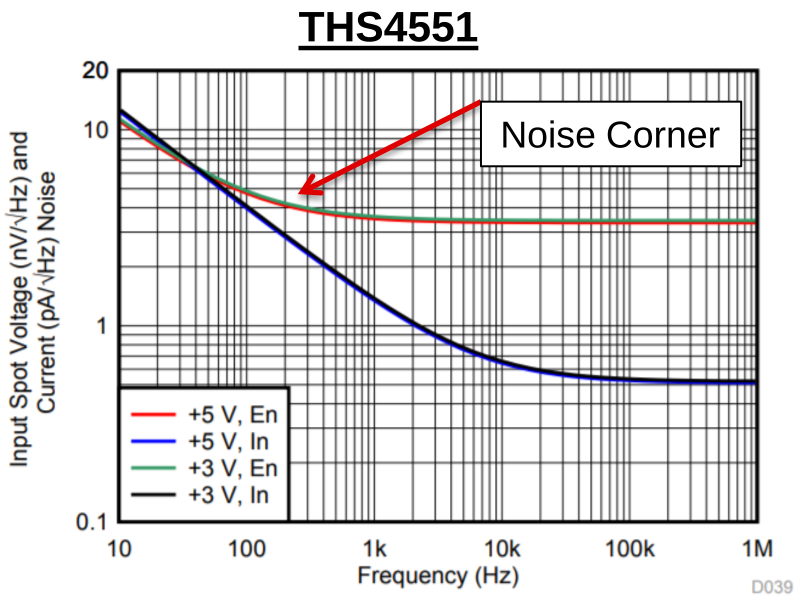
Noise Theory

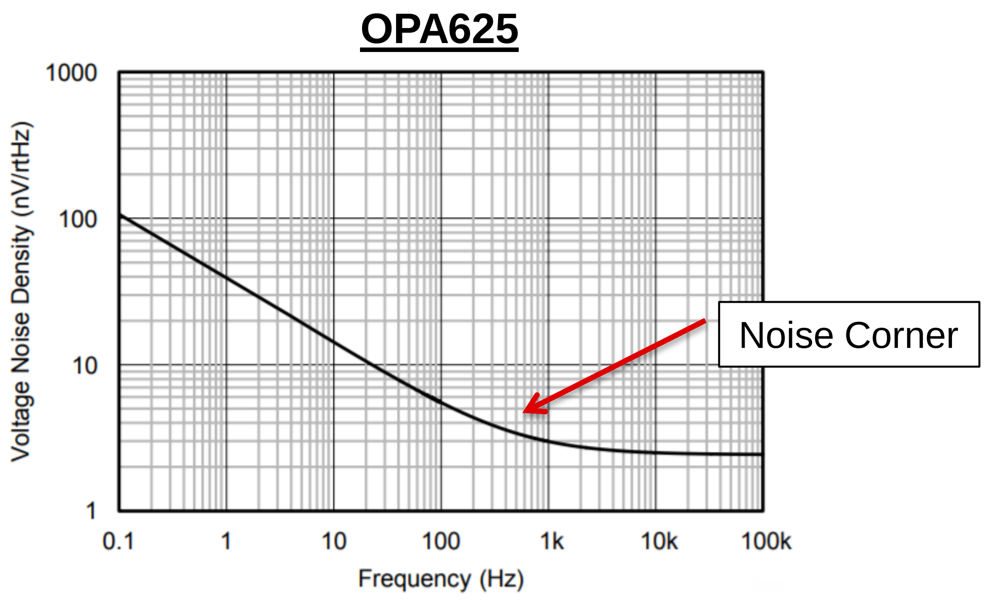




TI Precision Labs – Operational Amplifier Noise

1/f Noise is Negligible



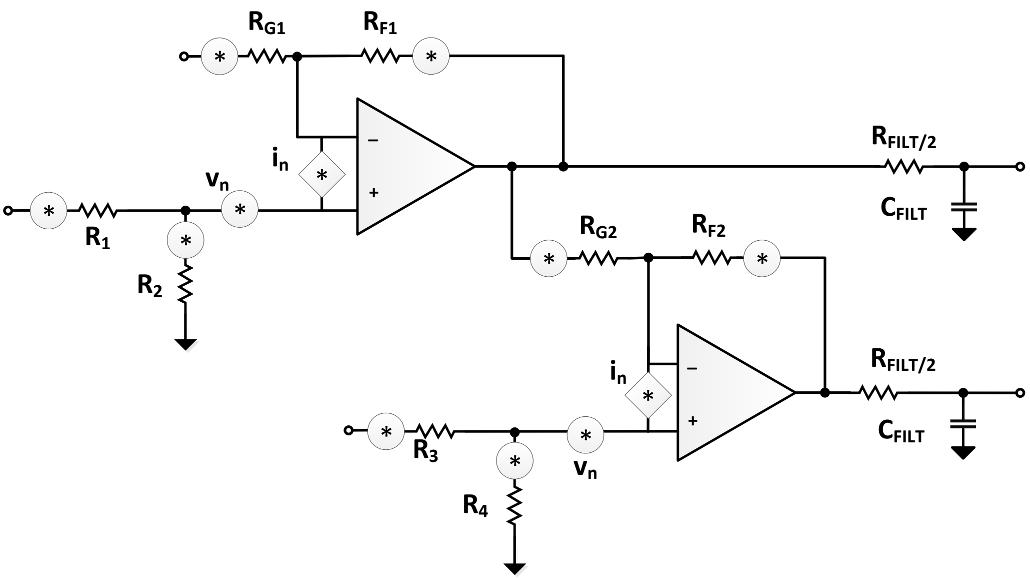


If $BW_N > 10*f_{FLICKER}$ then 1/f noise will be negligible

If $BW_N < 10*f_{FLICKER}$ then 1/f noise will need to be considered

$$BWN = k * \frac{1}{2\pi RFIL_{TCFILT}} = 1.57 * \frac{1}{2\pi * 16.25\Omega * 690pF} = 22\ MHz$$

Noise Calculations
Discrete Stage 1



Key Specifications

GBW = 120 MHz

$R_{F1} = 246\ \Omega$

$R_{G1} = 150\ \Omega$

$K = 1.38x10^{-23}\ (J/K)$

$k = 1.57$

$T = 25°C = 293\ K$

$v_{n(OPA625)} = 2.5\ nV/\sqrt{Hz}$

$i_{n(OPA625)} = 2.8\ pA/\sqrt{Hz}$

$R_{FILT}/2 = 16.25\ \Omega$

$C_{FILT} = 690\ pF$

Key Calculations

$G_N = (1 + RF_1/RG_1) = 3.3\ V/V$

$Req_{RF} = RF_1 || RG_1 = 74.5\Omega$

$Req_{12} = R1||R2 = 162\Omega$

$fc = \dfrac{1}{2\pi RFIL_{TCFILT}} = 14.1\ MHz$

Voltage Spectral Noise

$e_{vn} = vn = 2.5\ nV/\sqrt{Hz}$

Current Spectral Noise

$e_{in1} = in * ReqR_F = 0.209\ \text{nV}/\sqrt{Hz}$

$e_{in2} = in * Req_{12} = 0.454\ \text{nV}/\sqrt{Hz}$

Resistor Spectral Noise

$e_{ReqRF} = \sqrt{4KTR_{eqRF}} = 1.1\ nV\sqrt{Hz}$

$e_{Req12} = \sqrt{4KTR_{eqRF}} = 1.62\ nV/\sqrt{Hz}$

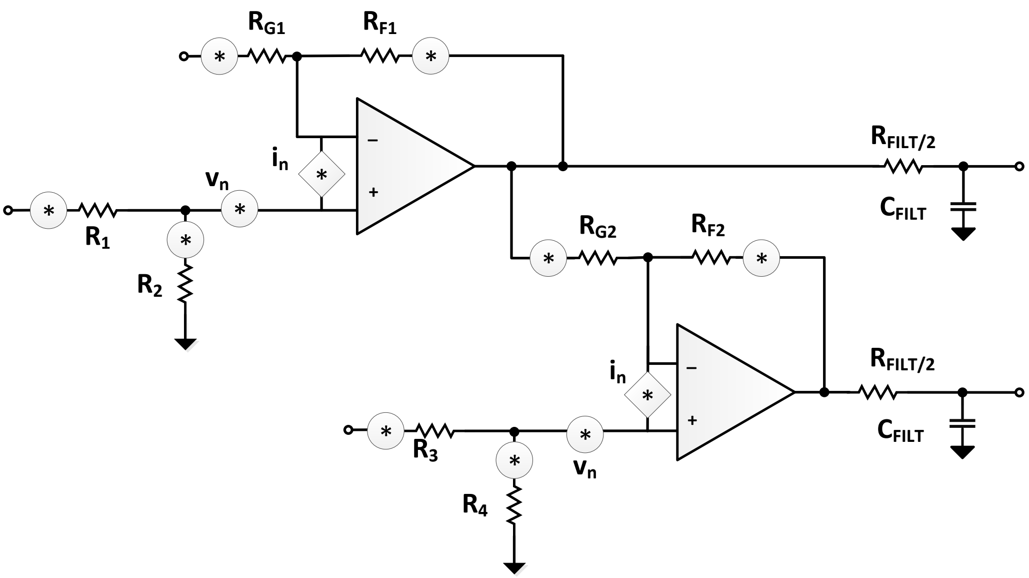
Stage 1 Spectral Noise

$e_1 = 2 * GN\sqrt{e_{vn}{}^2 + e_{in1}{}^2 + e_{in2}{}^2 + e_{ReqRF}{}^2 + eR_{eq12}{}^2}$

$= 21\ \text{nV}/\sqrt{Hz}$

Noise Calculations

Discrete Stage 2 and V_{RMS}



Key Specifications

GBW = 120 MHz

$R_{F2} = 246\ \Omega$

$R_{G2} = 107\ \Omega$

$K = 1.38x10^{-23}\ (J/K)$

$k = 1.57$

$T = 25°C = 293\ K$

$v_{n(OPA625)} = 2.5\ nV/\sqrt{Hz}$

$i_{n(OPA625)} = 2.8\ pA/\sqrt{Hz}$

$R_{FILT}/2 = 16.25\ \Omega$

$C_{FILT} = 690\ pF$

Key Calculations

$G_N = (1 + RF/RG) = 2\ V/V$

$Req_{RF} = RF_2||RG_2 = 235\Omega$

$$fc = \frac{1}{2\pi RFIL_{TCFILT}} = 14.1\ MHz$$

Voltage Spectral Noise

$e_{vn} = vn = 2.5\ uV/\sqrt{Hz}$

Current Spectral Noise

$e_{in1} = in * ReqR_F = 0.658\ \text{nV}/\sqrt{Hz}$

$e_{in2} = in * Req_{34} = 0.658\ \text{nV}/\sqrt{Hz}$

Resistor Spectral Noise

$e_{ReqRF} = \sqrt{4KTReq_{RF}} = 1.95\ nV\sqrt{Hz}$

$e_{Req34} = \sqrt{4KTReq_{34}} = 1.95\ nV/\sqrt{Hz}$

Stage 2 Spectral Noise

$$e_2 = G_N\sqrt{{e_{vn}}^2 + {e_{in1}}^2 + {e_{in2}}^2 + {e_{ReqRF}}^2 + {e_{Req34}}^2}$$

$$= 7.67\ \text{nV}/\sqrt{Hz}$$

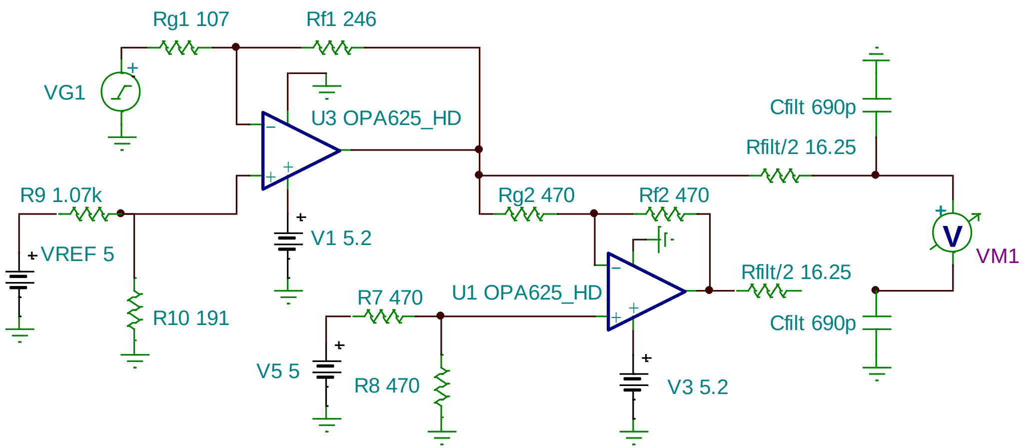
Total RMS Noise

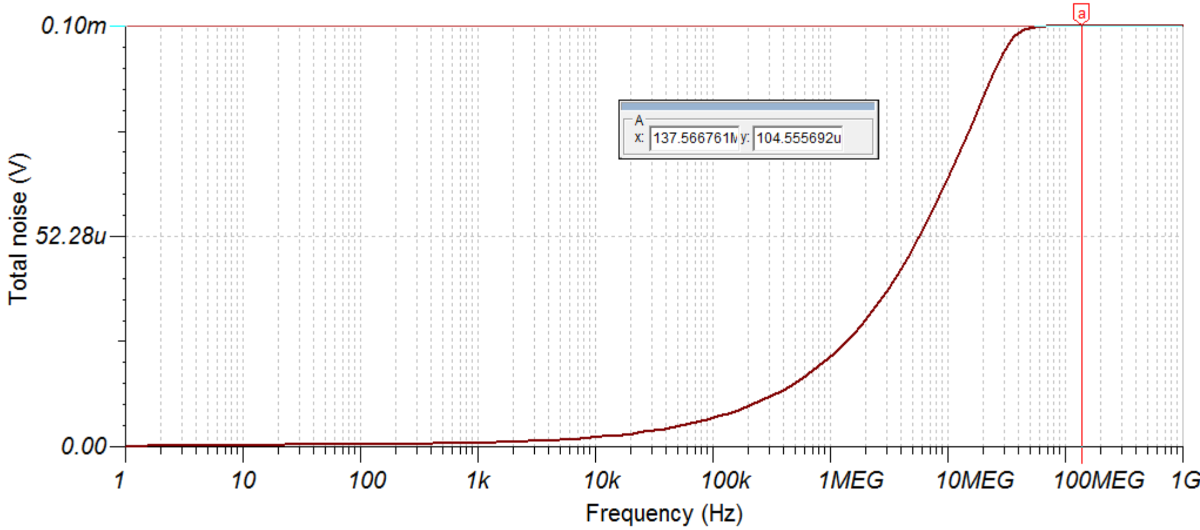
$e_{TOTAL} = \sqrt{{e_1}^2 + {e_2}^2} = 22.5\ \text{nV}/\sqrt{Hz}$

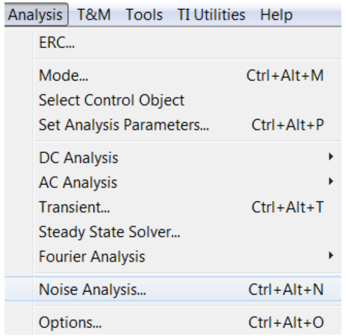
$E_{TOTAL} = e_{TOTAL}\sqrt{k * fc} = 106\ \mu V_{RMS}$

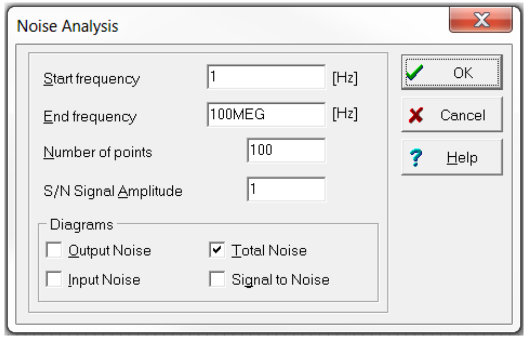
Noise Simulation

Discrete Solution





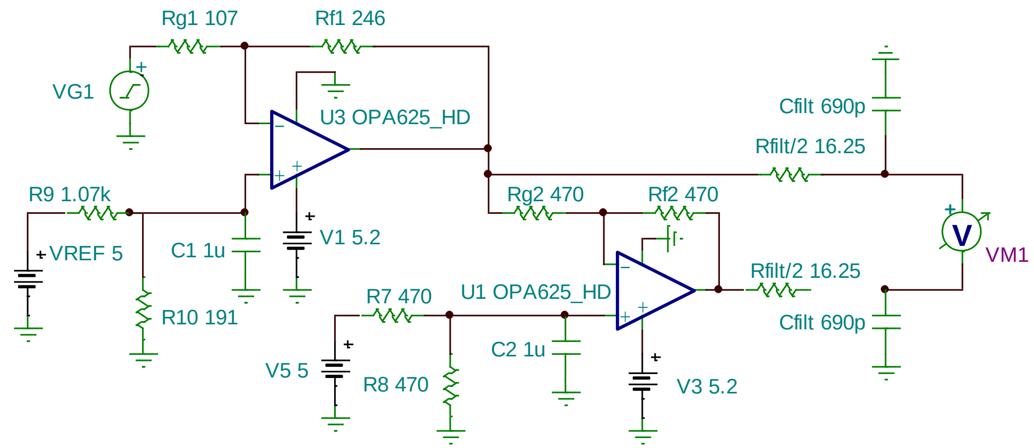


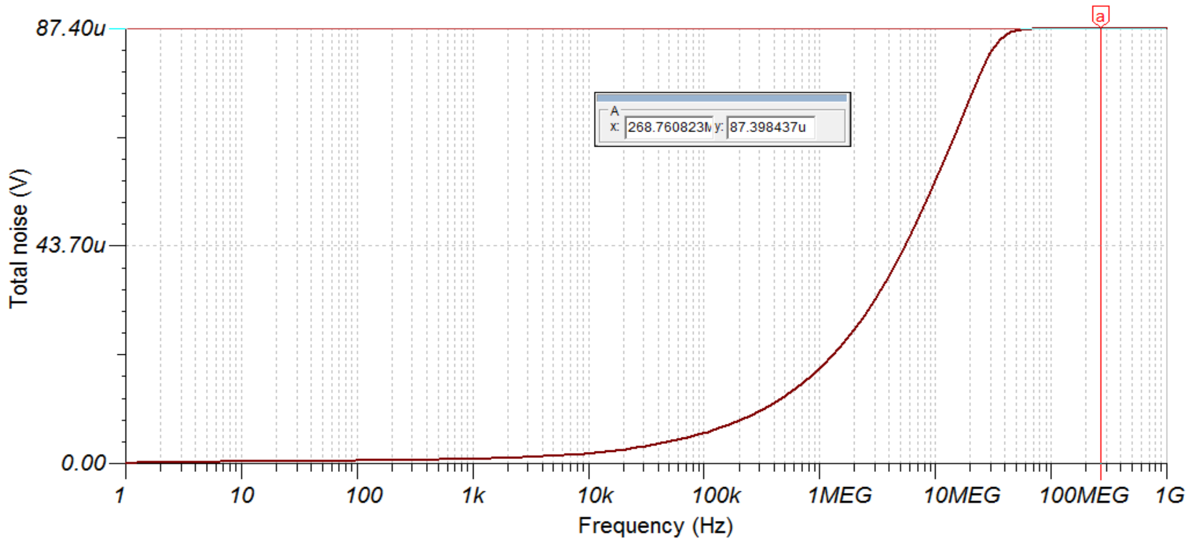


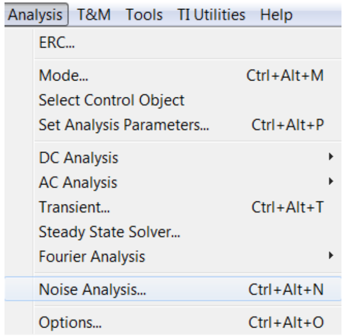
$E_{TOTAL\ SIM} = 104\ \mu V_{RMS}$

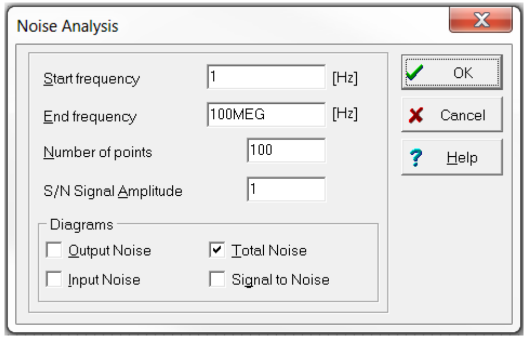
$E_{TOTAL\ CALC} = 106\ \mu V_{RMS}$

Noise Simulation
Discrete Solution with Capacitor





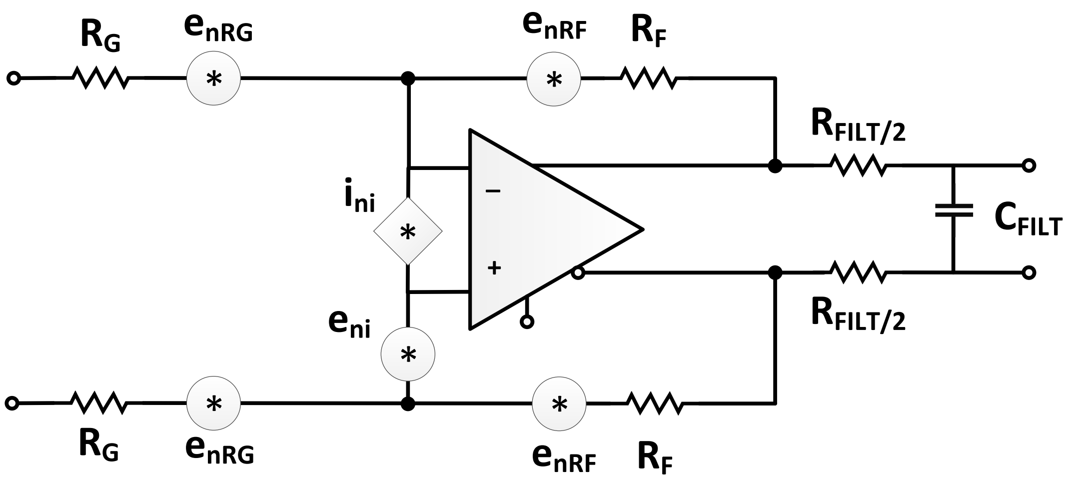




$E_{TOTAL\ SIM} = 87\ \mu V_{RMS}$

$E_{TOTAL\ CALC} = 87.4\ \mu V_{RMS}$

Noise Calculations
Fully Differential Amplifier



Key Specifications

$R_F = 493\ \Omega$

$R_G = 107\ \Omega$

$K = 1.38x10^{-23}\ (J/K)$

$k = 1.365$

$T = 25°C = 293\ K$

$v_{n(THS4551)} = 3.3\ nV/\sqrt{Hz}$

$i_{n(THS4551)} = 0.5\ pA/\sqrt{Hz}$

$R_{FILT}/2 = 16.25\ \Omega$

$C_{FILT} = 690\ pF$

Key Calculations

$G_N = (1 + RF/RG) = 5.6\ V/V$

$Req_{RF} = RF||RG = 87.9\Omega$

$$fc = \frac{1}{2\pi RFILTCFILT} = 14\ MHz$$

$BW_N = \sqrt{\mathrm{k} * \mathrm{fc}} = 4.4\ kHz$

Voltage Spectral Noise

$e_{vn} = vn = 3.3\ nV/\sqrt{Hz}$

Current Spectral Noise

$e_{in1} = in * ReqRF = 0.04\ \mathrm{nV}/\sqrt{Hz}$

$e_{in2} = in * Req_{12} = 0.04\ \mathrm{nV}/\sqrt{Hz}$

Resistor Spectral Noise

$e_{ReqRF} = \sqrt{4KTR_{eqRF}} = 1.19\ nV\sqrt{Hz}$

$e_{ReqRF} = \sqrt{4KTR_{eqRF}} = 1.19\ nV/\sqrt{Hz}$

Total Stage 1 Spectral Noise

$$e_{TOTAL} = G_N\sqrt{{e_{vn}}^2 + {e_{in1}}^2 + {e_{in2}}^2 + 2eReq{R_F}^2}$$

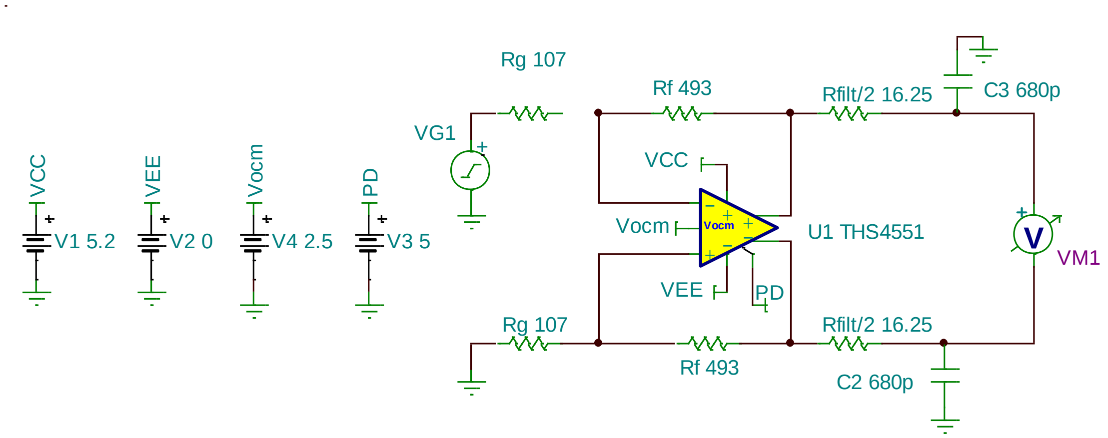
$$= 20.7\ \mathrm{nV}/\sqrt{Hz}$$

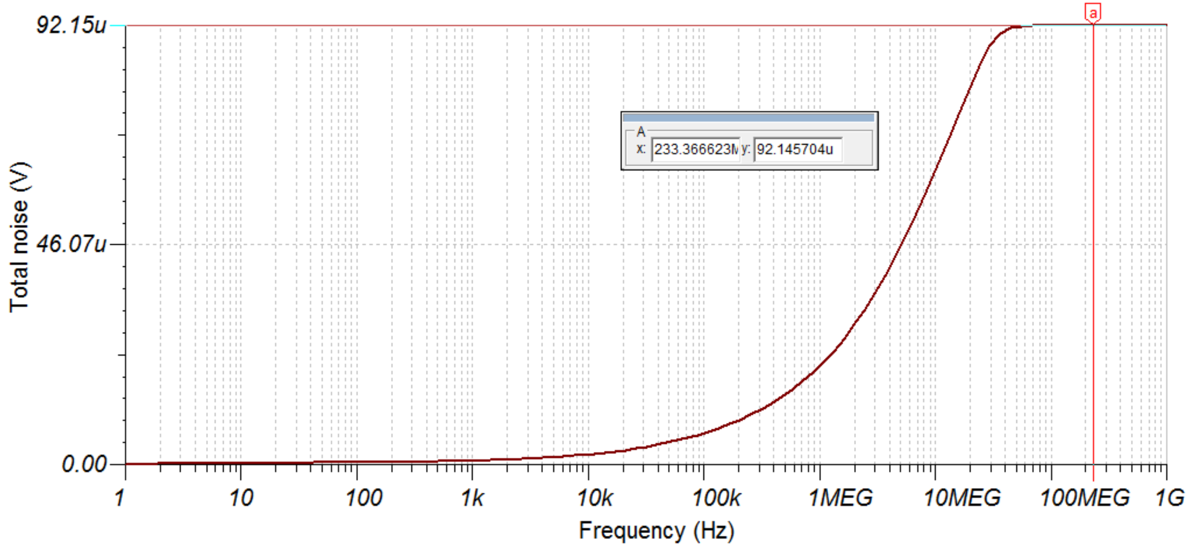
Total FDA Solution RMS Noise

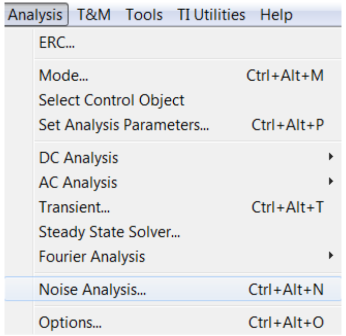
$E_{TOTAL} = eTOTA_L\sqrt{fc * k} = 92\ uVrms$

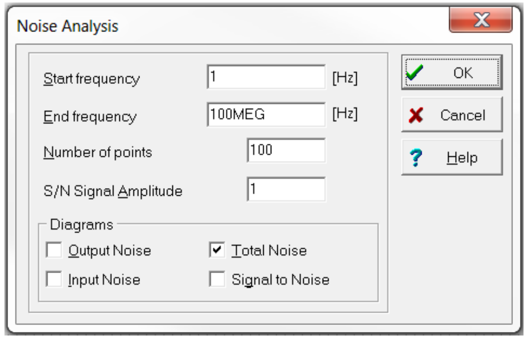
Noise Simulation

Fully Differential Amplifier Solution









$E_{TOTAL\ SIM} = 92\ \mu V_{RMS}$

$E_{TOTAL\ CALC} = 92\ \mu V_{RMS}$

Noise Results

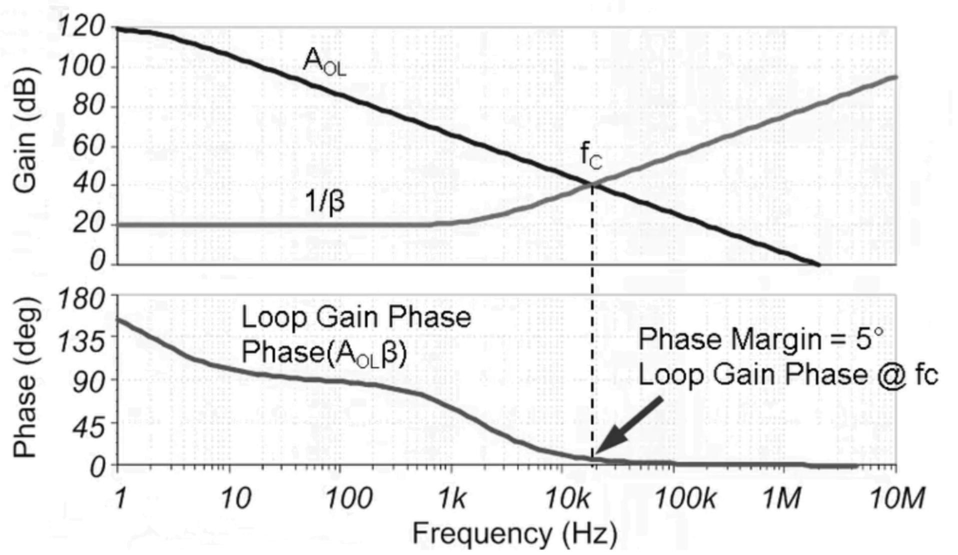
Solution	Discrete	Discrete with Cap	Fully Differential
Calculation	106 μV_{RMS}	89 μV_{RMS}	92 μV_{RMS}
Simulation	104 μV_{RMS}	87 μV_{RMS}	91 μV_{RMS}

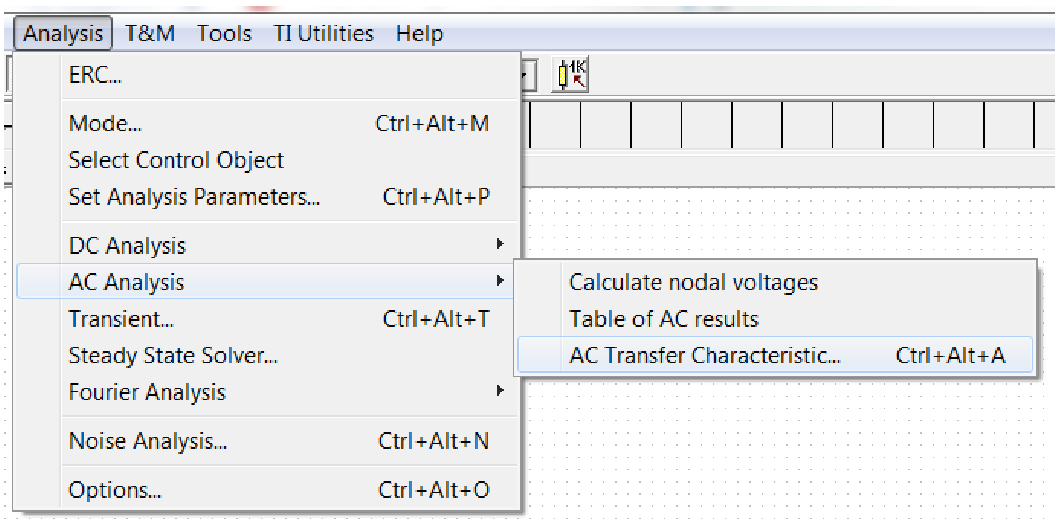
Stability **Theory**

Stability rule of thumb

If phase margin **> 45°** then amplifier is considered **optimally stable**

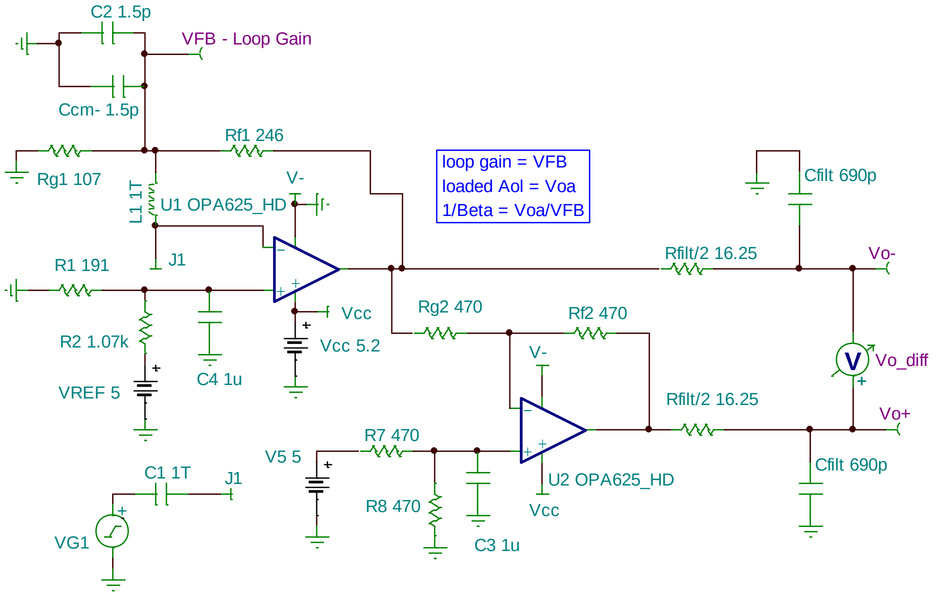
If phase margin **< 45°** then the amplifier is considered **marginally stable**

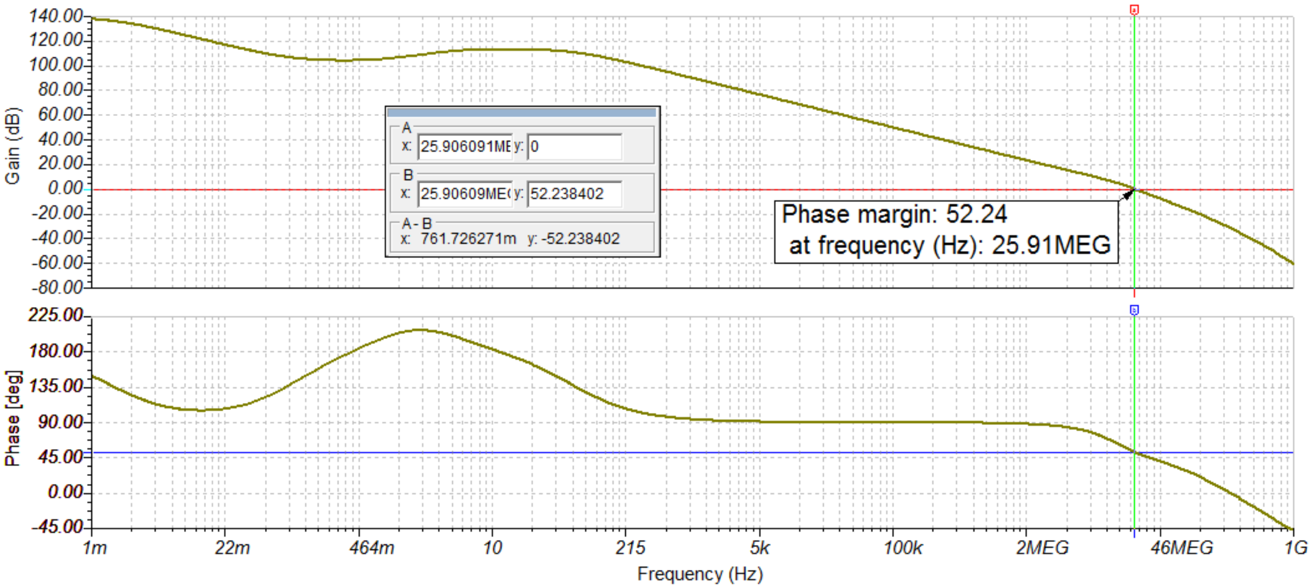




TI Precision Labs – Op Amp: Stability

Stability Simulation
Discrete Amplifier 1

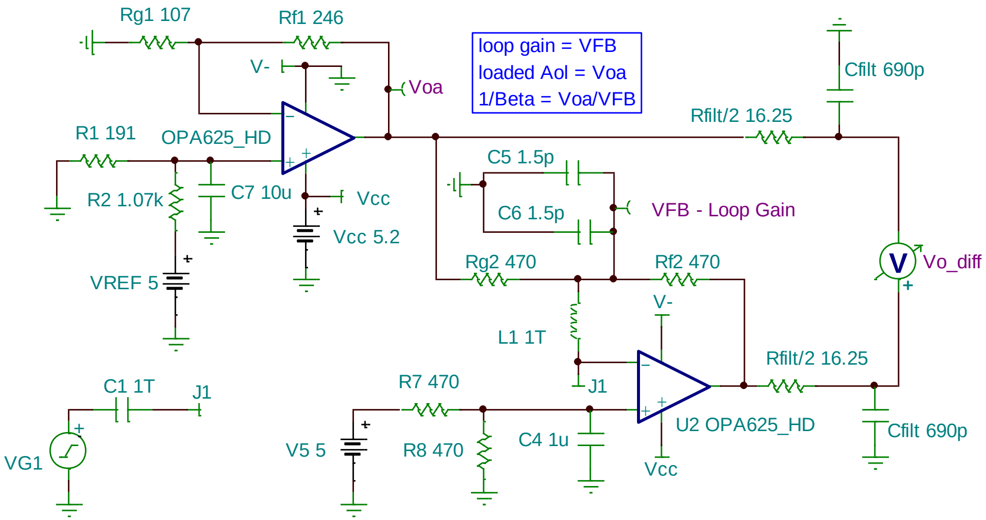


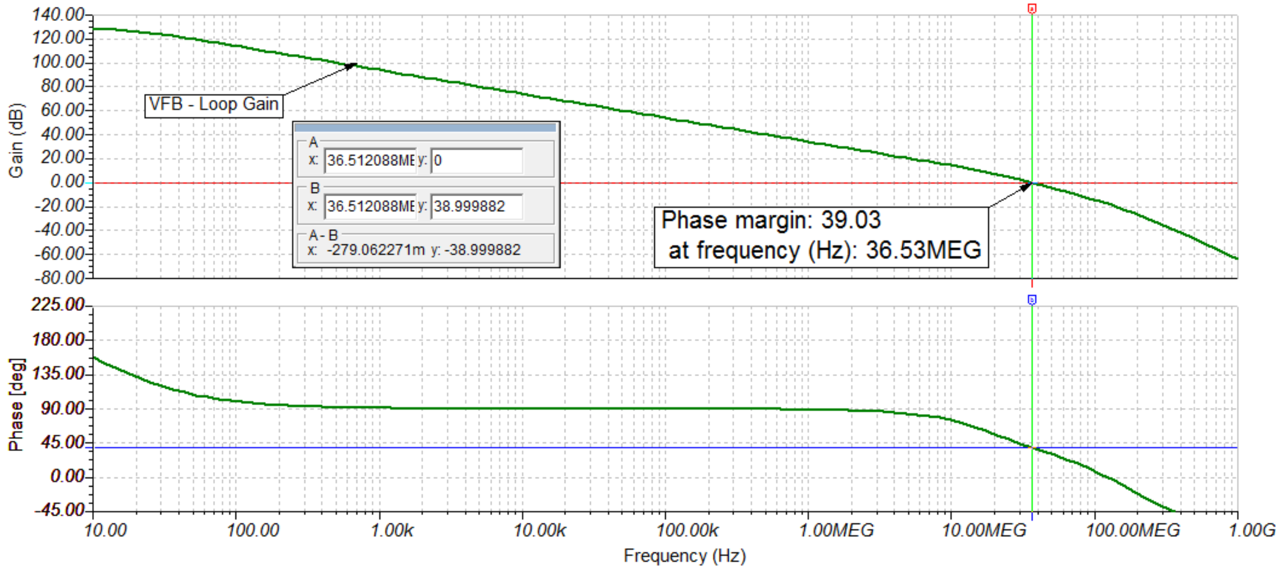


Marginally Stable!

Stability Simulation

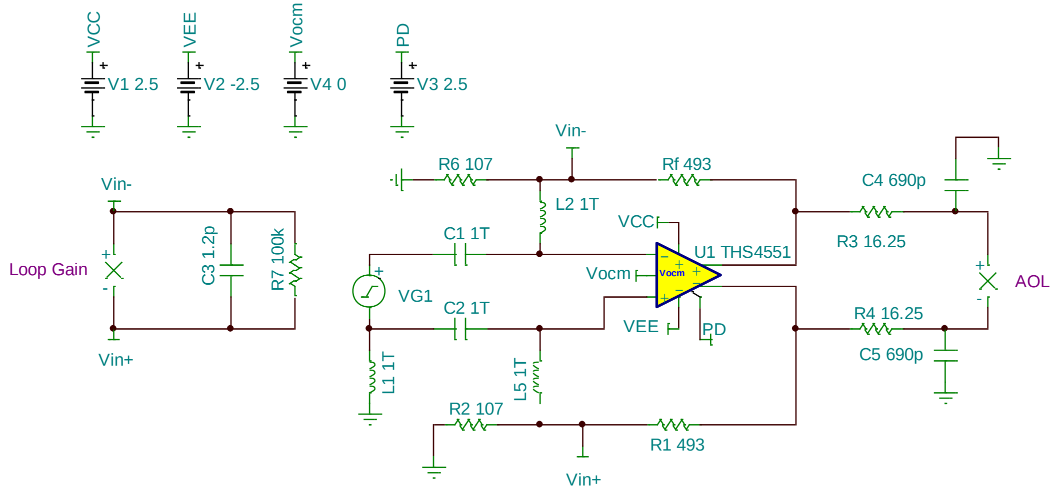
Discrete Amplifier 2

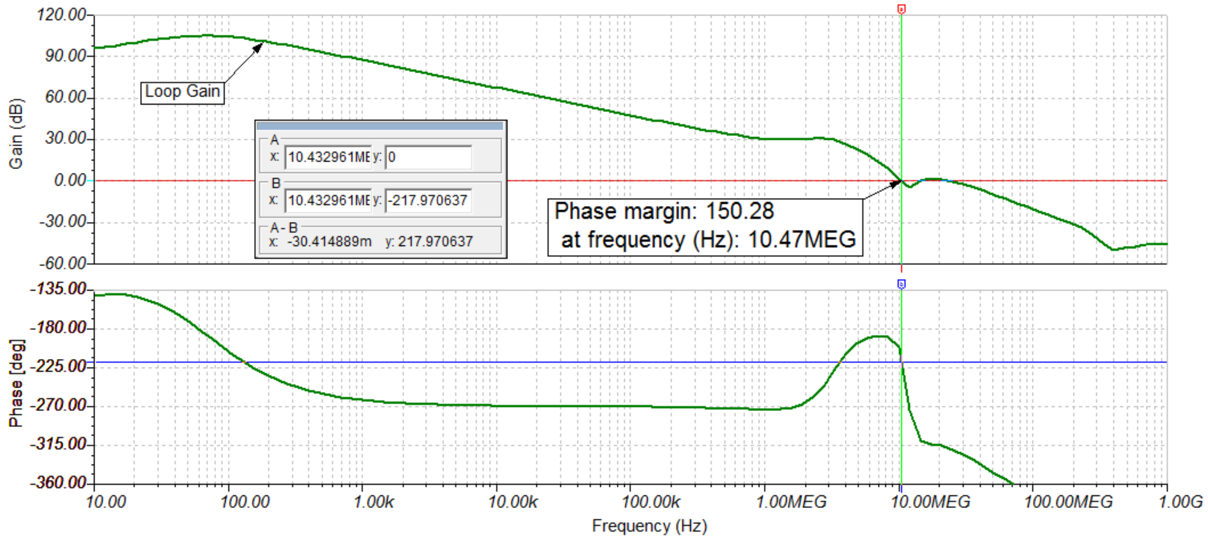




Marginally Stable/Potentially Unstable

Stability Simulation
Fully Differential Amplifier





STABLE!

Total Harmonic Distortion Theory

FDAs Even Order Harmonic Distortion

$$V_{out_+} = k_1 Vin + k_2 Vin^2 + k_3 Vin^3 + k_4 Vin^4 \ldots \quad (1)$$

$$V_{out_-} = k_1(-Vin) + k_2(-Vin)^2 + k_3(-Vin)^3 + k_4(-Vin)^4 \ldots. \quad (2)$$

Where k_1, k_2… k_N are constants

Taking the differential output:

$$V_o = VOUT_{+} - V_{OUT\,-}$$

$$= k_1 V_{in} - (-k_1 V_{in}) + k_2 V_{i_n{}^2} - k_2(-Vi_n)^2 + k_3 V_{in}{}^3 - (-k_3 V_{in}{}^3) \ldots$$

$$= 2k_1 V_{in} + 2k_3 V_{in}{}^3 + 2k_5 V_{in}{}^5 \ldots. \quad (3)$$

→ No added even-order harmonics

Calculations Total Harmonic Distortion

6.5 Electrical Characteristics: $(V_{S+}) – (V_{S–}) = 5$ V THS4551

at $T_A \approx 25°C$, VOCM pin = open, $R_F = 1$ kΩ, $R_L = 1$ kΩ, $V_{OUT} = 2\ V_{PP}$, 50-Ω input match, G = 1 V/V, $\overline{PD} = V_{S+}$, single-ended input, differential output, and input and output referenced to default midsupply for ac-coupled tests (unless otherwise noted); see Figure 61 for a gain of 1-V/V test circuit

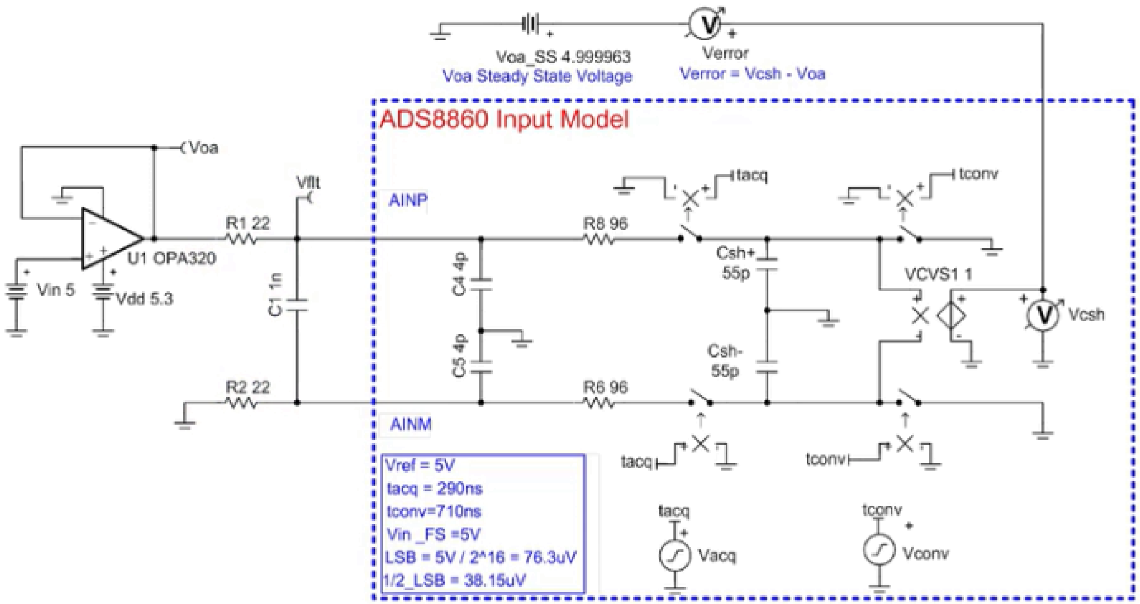
HD2	Second-order harmonic distortion	f = 100 kHz, $V_{OUT} = 2\ V_{PP}$, G = 1, $R_L = 1$ kΩ	–128	dBc	C
		f = 100 kHz, $V_{OUT} = 8\ V_{PP}$, G = 1, $R_L = 1$ kΩ	–124		C
HD3	Third-order harmonic distortion	f = 100 kHz, $V_{OUT} = 2\ V_{PP}$, G = 1, $R_L = 1$ kΩ	–139	dBc	C
		f = 100 kHz, $V_{OUT} = 8\ V_{PP}$, G = 1, $R_L = 1$ kΩ	–131		C

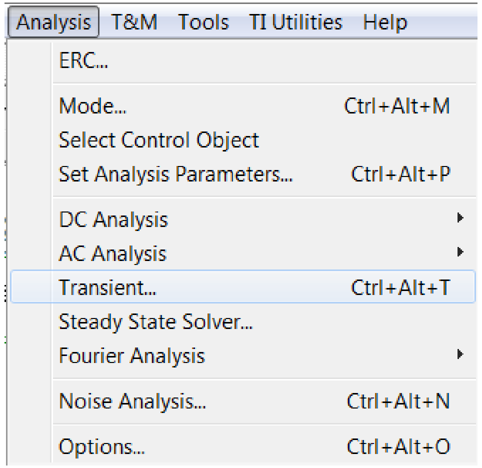
6.5 Electrical Characteristics High-Drive Mode OPA625

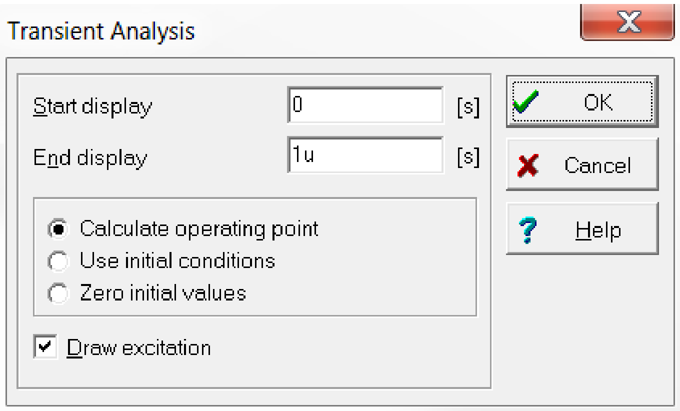
at $T_A = 25°C$, V+ = 5 V, V– = 0 V, MODE pin connected to V– pin, $V_{COM} = V_O = 2.5$ V, gain (G) = 1, $R_F = 1$ kΩ, $C_F = 2.7$ pF, $C_{LOAD} = 20$ pF, and $R_{LOAD} = 2$ kΩ connected to 2.5 V (unless otherwise noted)

HD2	Second-order harmonic Distortion	$V_O = 2\ V_{PP}$, G = 2	f = 10 kHz	144	dBc
			f = 100 kHz	122	
			f = 1 MHz	80	
HD3	Third-order harmonic Distortion	$V_O = 2\ V_{PP}$, G = 2	f = 10 kHz	155	dBc
			f = 100 kHz	140	
			f = 1 MHz	80	

Settling Time Theory

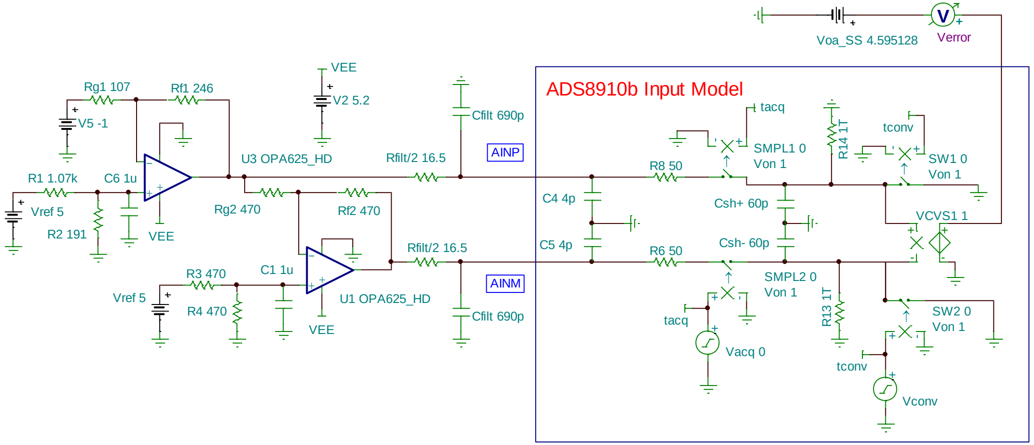


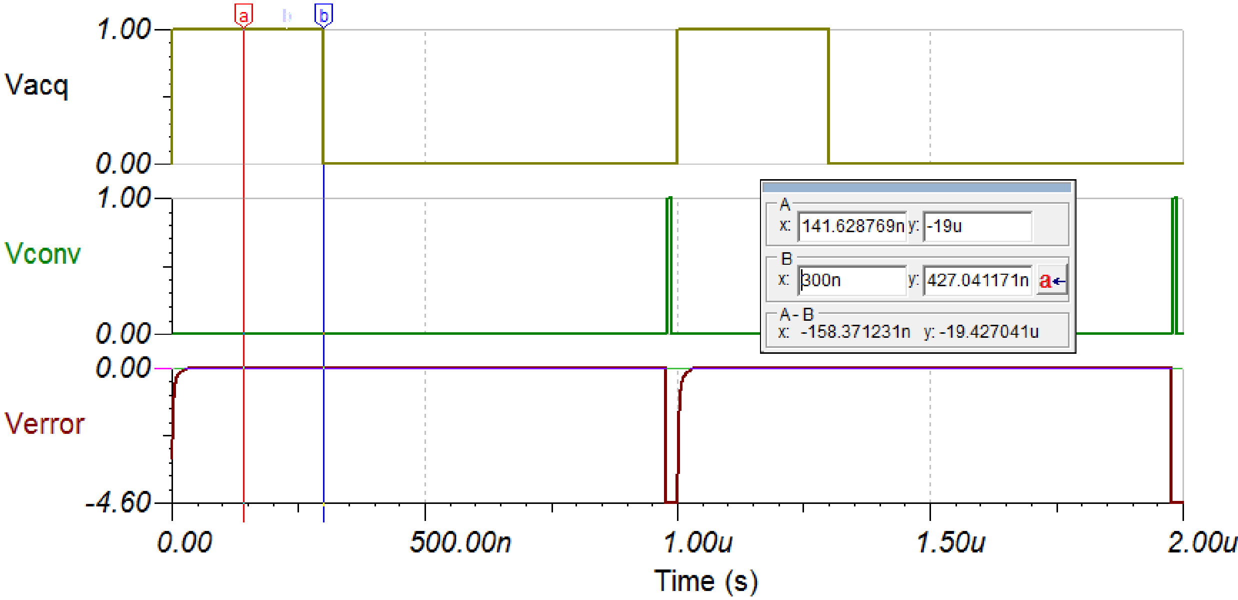




TI Precision Labs - ADCs: Building the SAR ADC Model

Settling Time Simulation
Discrete Amplifiers – ½ LSB

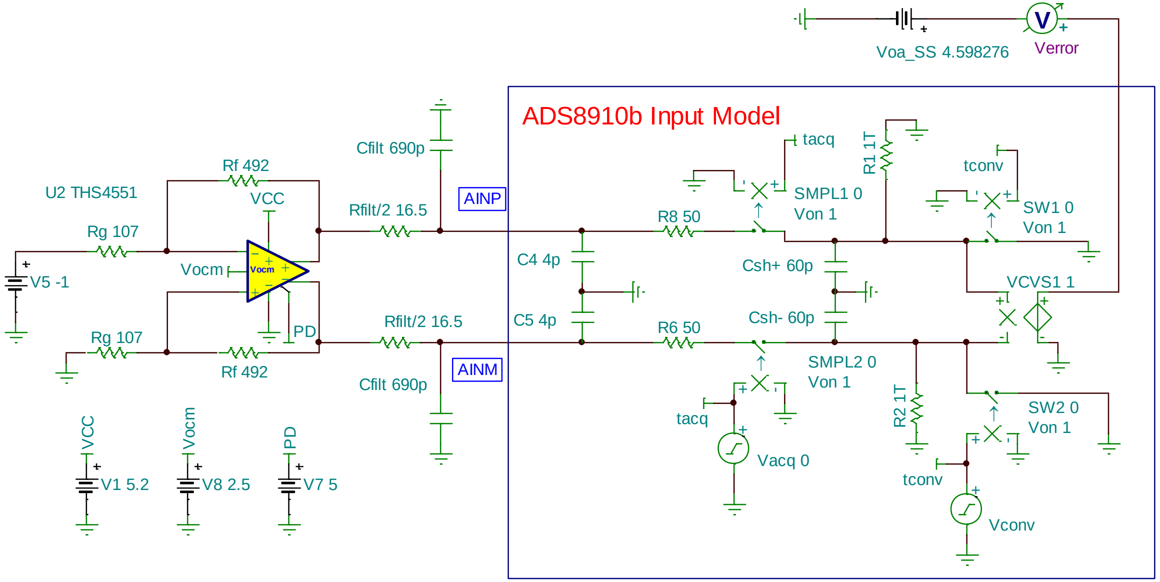


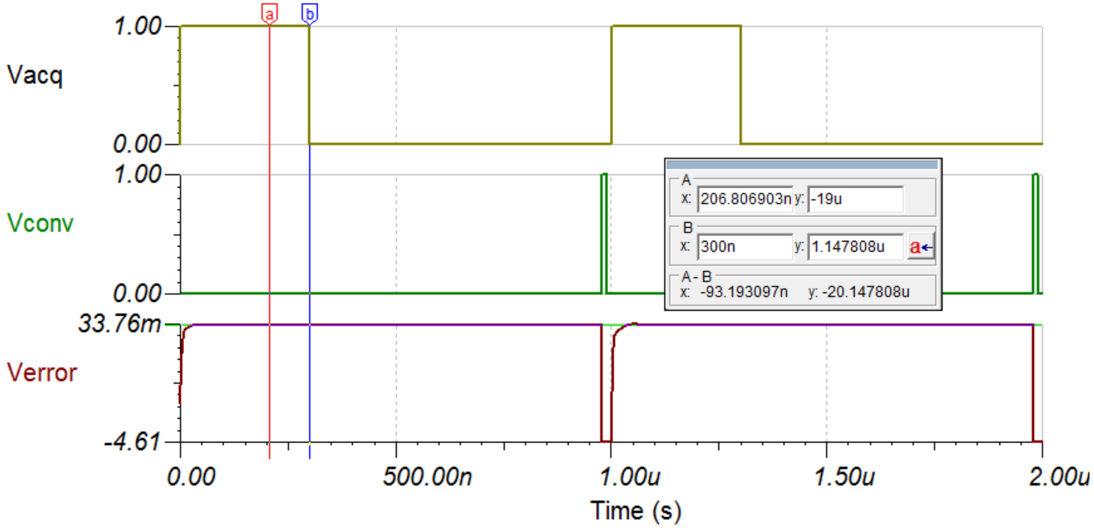


Settling time = 141 ns
Final Error Voltage = 427 nV

Settling Time Simulation

Fully Differential Amplifier – ½ LSB

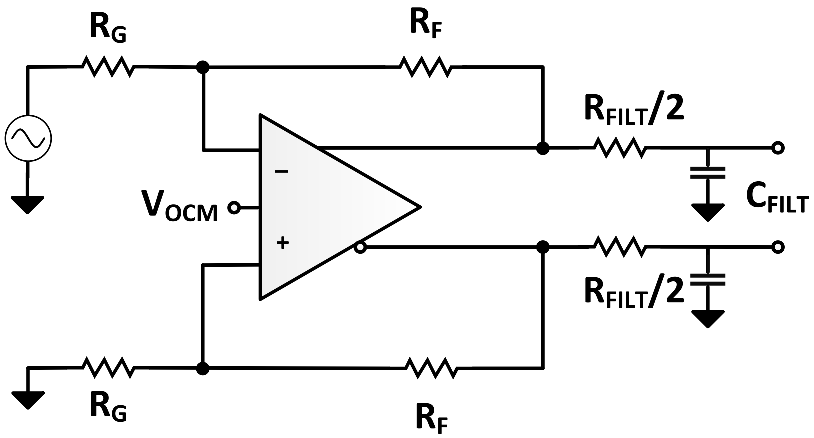


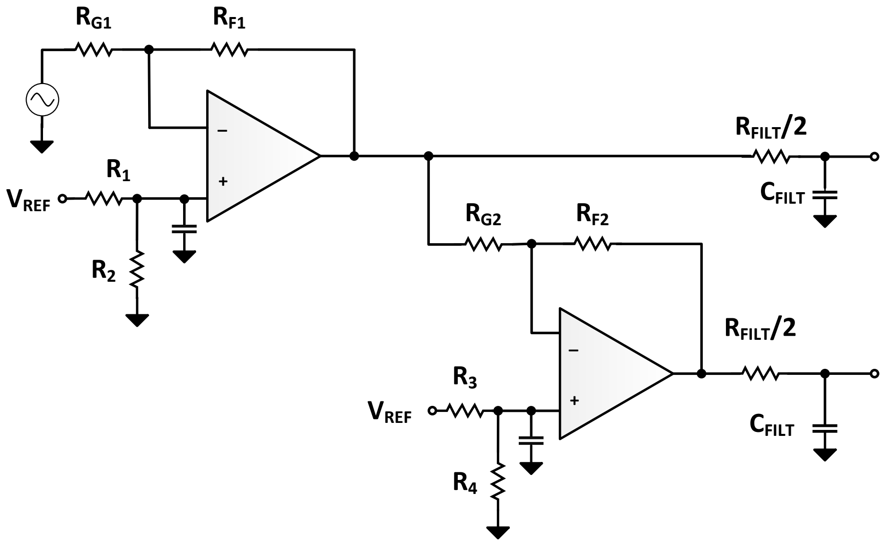


Settling time = 206 ns

Final Error Voltage = 1.147 µV

Fully Differential Amplifier vs Discrete Solutions





Specifications	FDA	Discrete (w/Capacitor)
Noise	91 μV_{RMS}	87 μV_{RMS}
Stability	Stable	Marginally Stable
THD (HD2, HD3)	(-128 dBc, -139 dBc)	(-122 dBc, -140 dBc)
Settling Time	208 ns	141 ns
Quiescent Current	1.35 mA	4 mA
Components	9	16

THANKS FOR YOUR TIME!