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

2 Vpp

Differential Input ADC
ADS8910B

0-5V

0-5V
**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
- Least Significant Bit (LSB) = \(\frac{\text{Full Scale Range}}{2^N} = \frac{2 \times 5V}{2^{18}} = 38.14\) \(\mu\)V

**ADC Driver Requirements**
- The differential range is \(-5V\) to 5 and the range of each input is 0 to 5 gain 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
<table>
<thead>
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<th>Specifications</th>
<th>Units</th>
<th>OPA625</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Channels</td>
<td>#</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Total Supply Voltage min</td>
<td>V</td>
<td>2.7</td>
<td>Ability to maximize dynamic range of the ADC (5V)</td>
</tr>
<tr>
<td>Total Supply Voltage max</td>
<td>V</td>
<td>5.5</td>
<td></td>
</tr>
<tr>
<td>GBW typical</td>
<td>MHz</td>
<td>120</td>
<td>Sufficient Bandwidth</td>
</tr>
<tr>
<td>Voltage Noise typical</td>
<td>nV/√Hz</td>
<td>2.5</td>
<td>Low noise to maintain signal fidelity</td>
</tr>
<tr>
<td>THD typical</td>
<td>dBc</td>
<td>-110</td>
<td>Low distortion to maintain signal fidelity</td>
</tr>
<tr>
<td>Iq per channel (mA)</td>
<td>mA</td>
<td>2</td>
<td>Low power consumption</td>
</tr>
</tbody>
</table>

**Discrete Solution**

**Fully Differential Amplifier Solution**
**Discrete Solution Resistor Values**

**Amplifier 1 - Gain Resistors**

\[ V_{in} = 2V_{pp} \]
\[ V_{out} = 4.6V_{pp} \]
\[ G = \frac{V_{out}}{V_{in}} = 2.3 \]
\[ G_{inverting} = -\frac{R_F}{R_G} = -2.3 \frac{V}{V} \]
\[ R_{F1} = 246 \quad R_{F2} = 107 \quad \text{– Analog engineers calculator} \]

**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

\[ G_{\text{inverting}} = -\frac{R_{F2}}{R_{G2}} = -\frac{V}{V} \]

\[ R_{F2} = R_{G2} = 470 \, \Omega \]

Amplifier 2 - V\text{OCM} Resistors

\[ G_{\text{non inverting}} = 1 + \frac{R_{F2}}{R_{G2}} = 2 \]

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

\[ R_3 = R_4 = 470 \, \Omega \]
FDAs have a $V_{OCM}$ pin

Voltage at 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

Math Behind the R-C Component Selection
Refine the Rfilt and Cfilt Values

Link for free download of Analog Engineer’s Calculator
Noise Theory

TI Precision Labs – Operational Amplifier Noise
1/f Noise is Negligible

If \( \text{BW}_N > 10*\text{f}_{\text{FLICKER}} \)
then 1/f noise will be negligible

If \( \text{BW}_N < 10*\text{f}_{\text{FLICKER}} \)
then 1/f noise will need to be considered

\[
\text{BW}_N = k \times \frac{1}{2\pi \text{RFIL}_{\text{TCFILT}}} = 1.57 \times \frac{1}{2\pi \times 16.25\Omega \times 690pF} = 22\ \text{MHz}
\]
Noise Calculations
Discrete Stage 1

Key Specifications
- GBW = 120 MHz
- \( R_{F1} = 246 \, \Omega \)
- \( R_{G1} = 150 \, \Omega \)
- \( K = 1.38 \times 10^{-23} \, (J/K) \)
- \( k = 1.57 \)
- \( T = 25^\circ C = 293 \, K \)

\( v_{n\text{(OPA625)}} = 2.5 \, nV/\sqrt{Hz} \)
\( i_{n\text{(OPA625)}} = 2.8 \, pA/\sqrt{Hz} \)
\( R_{FILT}/2 = 16.25 \, \Omega \)
\( C_{FILT} = 690 \, pF \)

Voltage Spectral Noise
- \( e_{vn} = vn = 2.5 \, nV/\sqrt{Hz} \)

Current Spectral Noise
- \( e_{in1} = in \ast ReqR_f = 0.209 \, nV/\sqrt{Hz} \)
- \( e_{in2} = in \ast Req_{12} = 0.454 \, nV/\sqrt{Hz} \)

Resistor Spectral Noise
- \( e_{ReqRF} = \sqrt{4KTREQRF} = 1.1 \, nV/\sqrt{Hz} \)
- \( e_{Req_{12}} = \sqrt{4KTREQRF} = 1.62 \, nV/\sqrt{Hz} \)

Stage 1 Spectral Noise
- \( e_1 = 2 \ast GN\sqrt{e_{vn}^2 + e_{in1}^2 + e_{in2}^2 + e_{ReqRF}^2 + e_{Req_{12}}^2} = 21 \, nV/\sqrt{Hz} \)

Key Calculations
- \( G_N = (1 + RF_1/RG_1) = 3.3 \, V/V \)
- \( ReqRF = RF_1||RG_1 = 74.5 \, \Omega \)
- \( Req_{12} = R1||R2 = 162 \, \Omega \)
- \( f_c = \frac{1}{2\pi RFILT_{\text{CFILT}}} = 14.1 \, MHz \)
Noise Calculations
Discrete Stage 2 and \( V_{\text{RMS}} \)

**Key Specifications**
- GBW = 120 MHz
- \( R_{F2} = 246 \Omega \)
- \( R_{G2} = 107 \Omega \)
- \( k = 1.38 \times 10^{-23} (J/K) \)
- \( T = 25^\circ C = 293 K \)
- \( v_n(\text{OPA625}) = 2.5 \text{ nV/\sqrt{Hz}} \)
- \( i_n(\text{OPA625}) = 2.8 \text{ pA/\sqrt{Hz}} \)
- \( R_{FILT}/2 = 16.25 \Omega \)
- \( C_{FILT} = 690 \text{ pF} \)

**Voltage Spectral Noise**
- \( e_{vn} = vn = 2.5 \text{ uV/\sqrt{Hz}} \)

**Current Spectral Noise**
- \( e_{in1} = in \times Req_R_F = 0.658 \text{ nV/\sqrt{Hz}} \)
- \( e_{in2} = in \times Req_{34} = 0.658 \text{ nV/\sqrt{Hz}} \)

**Resistor Spectral Noise**
- \( e_{ReqRF} = \sqrt{4KTR_{ReqRF}} = 1.95 \text{ nV/\sqrt{Hz}} \)
- \( e_{Req34} = \sqrt{4KTR_{Req34}} = 1.95 \text{ nV/\sqrt{Hz}} \)

**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**
- \( e_{TOTAL} = \sqrt{e_1^2 + e_2^2} = 22.5 \text{ nV/\sqrt{Hz}} \)
- \( E_{TOTAL} = e_{TOTAL}\sqrt{k \times f_c} = 106 \mu \text{V}_{\text{RMS}} \)
Noise Simulation
Discrete Solution

\[ E_{\text{TOTAL SIM}} = 104 \, \mu V_{\text{RMS}} \]
\[ E_{\text{TOTAL CALC}} = 106 \, \mu V_{\text{RMS}} \]
Noise Simulation
Discrete Solution with Capacitor

\[ E_{\text{TOTAL SIM}} = 87 \mu V_{\text{RMS}} \]
\[ E_{\text{TOTAL CALC}} = 87.4 \mu V_{\text{RMS}} \]
**Key Specifications**

- $R_F = 493 \, \Omega$
- $R_G = 107 \, \Omega$
- $K = 1.38 \times 10^{-23} \, (J/K)$
- $k = 1.365$
- $T = 25^\circ C = 293 \, K$
- $v_{n(THS4551)} = 3.3 \, nV/\sqrt{Hz}$
- $i_{n(THS4551)} = 0.5 \, pA/\sqrt{Hz}$
- $R_{FILT}/2 = 16.25 \, \Omega$
- $C_{FILT} = 690 \, pF$

**Voltage Spectral Noise**

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

**Current Spectral Noise**

- $e_{in1} = i_{in} \cdot ReqRF = 0.04 \, nV/\sqrt{Hz}$
- $e_{in2} = i_{in} \cdot Req_{12} = 0.04 \, nV/\sqrt{Hz}$

**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**

- $e_{TOTAL} = G_N \sqrt{e_{vn}^2 + e_{in1}^2 + e_{in2}^2 + 2e_{ReqRF}^2}$
  - $= 20.7 \, nV/\sqrt{Hz}$

**Total FDA Solution RMS Noise**

- $E_{TOTAL} = e_{TOTAL} \cdot \sqrt{f_c \cdot k} = 92 \, uVrms$
Noise Simulation
Fully Differential Amplifier Solution

\[ E_{\text{TOTAL SIM}} = 92 \mu V_{\text{RMS}} \]

\[ E_{\text{TOTAL CALC}} = 92 \mu V_{\text{RMS}} \]
## Noise Results

<table>
<thead>
<tr>
<th>Solution</th>
<th>Discrete</th>
<th>Discrete with Cap</th>
<th>Fully Differential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculation</td>
<td>106 $\mu$V\text{RMS}$</td>
<td>89 $\mu$V\text{RMS}$</td>
<td>92 $\mu$V\text{RMS}$</td>
</tr>
<tr>
<td>Simulation</td>
<td>104 $\mu$V\text{RMS}$</td>
<td>87 $\mu$V\text{RMS}$</td>
<td>91 $\mu$V\text{RMS}$</td>
</tr>
</tbody>
</table>
Stability Theory

Stability rule of thumb
If phase margin $> 45^\circ$ then amplifier is considered **optimally stable**
If phase margin $< 45^\circ$ then the amplifier is considered **marginally stable**
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

\[ V_{out_+} = k_1 V_{in} + k_2 V_{in}^2 + k_3 V_{in}^3 + k_4 V_{in}^4 \ldots \]  
\( \text{(1)} \)

\[ V_{out_-} = k_1 (-V_{in}) + k_2 (-V_{in})^2 + k_3 (-V_{in})^3 + k_4 (-V_{in})^4 \ldots \]  
\( \text{(2)} \)

Where \( k_1, k_2 \ldots k_N \) are constants

Taking the differential output:

\[ V_o = V_{OUT_+} - V_{OUT_-} \]
\[ = k_1 V_{in} - (-k_1 V_{in}) + k_2 V_{in}^2 - k_2 (-V_{in})^2 + k_3 V_{in}^3 - (-k_3 V_{in}^3) \ldots \]
\[ = 2k_1 V_{in} + 2k_3 V_{in}^3 + 2k_5 V_{in}^5 \ldots \]  
\( \text{(3)} \)  
No added even-order harmonics
Calculations Total Harmonic Distortion

6.5 Electrical Characteristics: \((V_{S^+}) - (V_{S^-}) = 5\) V THS4551

at \(T_A \approx 25^\circ\text{C}\), VOCM pin = open, \(R_F = 1\) k\(\Omega\), \(R_L = 1\) k\(\Omega\), \(V_{OUT} = 2\) V\(\text{PP}\), 50-\(\Omega\) input match, \(G = 1\) V/V, \(PD = V_{S^+}\), 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

<table>
<thead>
<tr>
<th>HD2</th>
<th>Second-order harmonic distortion</th>
<th>dBc</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(f = 100) kHz, (V_{OUT} = 2) V(\text{PP}), (G = 1), (R_L = 1) k(\Omega)</td>
<td>-128</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>(f = 100) kHz, (V_{OUT} = 8) V(\text{PP}), (G = 1), (R_L = 1) k(\Omega)</td>
<td>-124</td>
<td>C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HD3</th>
<th>Third-order harmonic distortion</th>
<th>dBc</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(f = 100) kHz, (V_{OUT} = 2) V(\text{PP}), (G = 1), (R_L = 1) k(\Omega)</td>
<td>-139</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>(f = 100) kHz, (V_{OUT} = 8) V(\text{PP}), (G = 1), (R_L = 1) k(\Omega)</td>
<td>-131</td>
<td>C</td>
</tr>
</tbody>
</table>

6.5 Electrical Characteristics High-Drive Mode OPA625

at \(T_A = 25^\circ\text{C}\), \(V_+ = 5\) V, \(V_- = 0\) V, MODE pin connected to \(V_-\) pin, \(V_{COM} = V_O = 2.5\) V, gain \((G) = 1\), \(R_F = 1\) k\(\Omega\), \(C_F = 2.7\) pF, \(C_{LOAD} = 20\) pF, and \(R_{LOAD} = 2\) k\(\Omega\) connected to 2.5 V (unless otherwise noted)

<table>
<thead>
<tr>
<th>HD2</th>
<th>Second-order harmonic Distortion</th>
<th>dBc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(V_O = 2) V(\text{PP}), (G = 2) (f = 10) kHz</td>
<td>144</td>
</tr>
<tr>
<td></td>
<td>(f = 100) kHz</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>(f = 1) MHz</td>
<td>80</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HD3</th>
<th>Third-order harmonic Distortion</th>
<th>dBc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(V_O = 2) V(\text{PP}), (G = 2) (f = 10) kHz</td>
<td>155</td>
</tr>
<tr>
<td></td>
<td>(f = 100) kHz</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td>(f = 1) MHz</td>
<td>80</td>
</tr>
</tbody>
</table>
Settling Time Theory

TI Precision Labs - ADCs: Building the SAR ADC Model
Settling Time Simulation
Discrete Amplifiers – $\frac{1}{2}$ 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**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>FDA</th>
<th>Discrete (w/Capacitor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise</td>
<td>91 $\mu$V$_{RMS}$</td>
<td>87 $\mu$V$_{RMS}$</td>
</tr>
<tr>
<td>Stability</td>
<td>Stable</td>
<td>Marginally Stable</td>
</tr>
<tr>
<td>THD (HD2, HD3)</td>
<td>(-128 dBC, -139 dBC)</td>
<td>(-122 dBC, -140 dBC)</td>
</tr>
<tr>
<td>Settling Time</td>
<td>208 ns</td>
<td>141 ns</td>
</tr>
<tr>
<td>Quiescent Current</td>
<td>1.35 mA</td>
<td>4 mA</td>
</tr>
<tr>
<td>Components</td>
<td>9</td>
<td>16</td>
</tr>
</tbody>
</table>
THANKS FOR YOUR TIME!