Circuit for driving a switched-capacitor SAR ADC with an instrumentation amplifier

Art Kay, Bryan McKay

<table>
<thead>
<tr>
<th>Input</th>
<th>ADC Input</th>
<th>Digital Output ADS8660</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5mV</td>
<td>Out = 0.2V</td>
<td>0A3Dₜₖ or 2621ₜₖ</td>
</tr>
<tr>
<td>15mV</td>
<td>Out = 4.8V</td>
<td>F5C3ₜₖ or 62915ₜₖ</td>
</tr>
</tbody>
</table>

### Power Supplies

<table>
<thead>
<tr>
<th></th>
<th>AVDD</th>
<th>DVDD</th>
<th>V_ref,INA</th>
<th>V_ref</th>
<th>V_cc</th>
<th>V_ve</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0V</td>
<td>3.0V</td>
<td>3.277V</td>
<td>5.0V</td>
<td>+15V</td>
<td>-15V</td>
<td></td>
</tr>
</tbody>
</table>

### Design Description

Instrumentation amplifiers are a common way of translating low level sensor outputs to high level signals to drive an ADC. Typically, instrumentation amplifiers are optimized for low noise, low offset, and low drift. Unfortunately, the bandwidth of many instrumentation amplifiers may not be sufficient to achieve good settling to ADC charge kickback at maximum sampling rates. This document shows how sampling rate can be adjusted to achieve good settling. Furthermore, many instrumentation amplifiers are optimized for high-voltage supplies and it may be required to interface the high-voltage output (that is, ±15V) to a lower voltage ADC (for example, 5V). This design shows how to use Schottki diodes and a series resistor to protect the ADC input from an overvoltage condition. Note that the following circuit shows a bridge sensor, but this method could be used for a wide range of different sensors. A modified version of this circuit, Driving a Switched-Capacitor SAR With a Buffered Instrumentation Amplifier shows how a wide bandwidth buffer can be used to achieve higher sampling rate.

This circuit implementation is applicable to all Bridge Transducers in PLC’s and Analog Input Modules that require Precision Signal-Processing and Data-Conversion.
Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Calculated</th>
<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling rate</td>
<td>200ksps</td>
<td>200ksps, settling to −6µV</td>
</tr>
<tr>
<td>Offset (ADC Input)</td>
<td>40µV · 306.7 = 12.27mV</td>
<td>16mV</td>
</tr>
<tr>
<td>Offset Drift</td>
<td>(0.4µV/ºC) · 306.7 = 123µV/ºC</td>
<td>NA</td>
</tr>
<tr>
<td>Noise</td>
<td>978µV</td>
<td>874µV</td>
</tr>
</tbody>
</table>

Design Notes

1. Select the gain to achieve an input swing that matches the input range of the ADC. Use the instrumentation amplifier reference pin to shift the signal offset to match the input range. This is covered in the component selection section.

2. The input Schottky diode configuration is used to prevent driving the input voltage outside of the absolute maximum specifications. The BAT54S Schottky is a good option for design as this device integrates both diodes into one package and the diodes are low leakage and have a low forward voltage. This is covered in the component selection section.

3. The buffer amplifier following the voltage divider is required for driving the reference input of most instrumentation amplifiers. Choose precision resistors and a precision low-offset amplifier as the buffer. Refer to Selecting the right op amp for more details on this subject.

4. Check the common-mode range of the amplifier using the Common-Mode Input Range Calculator for Instrumentation Amplifiers software tool.

5. Select C0G capacitors for $C_{CM1}$, $C_{CM2}$, $C_{DFI}$, and $C_{filt}$ to minimize distortion.

6. Use 0.1% 20ppm/ºC film resistors or better for the gain set resistor $R_g$. The error and drift of this resistor will directly translate into gain error and gain drift.

7. The TI Precision Labs – ADCs training video series covers methods for selecting the charge bucket circuit $R_{filt}$ and $C_{filt}$. Although this method was designed for op amps, it can be modified for instrumentation amplifiers. Refer to Introduction to SAR ADC Front-End Component Selection for details on this subject.
Component Selection

1. Find the gain set resistor for the instrumentation amplifier to set the output swing to 0.2V to 4.8V.

\[
\text{Gain} = \frac{V_{\text{out\_max}} - V_{\text{out\_min}}}{V_{\text{in\_max}} - V_{\text{in\_min}}} = \frac{4.9V - 0.2V}{5mV - (-10mV)} = 306.7
\]

\[
\text{Gain} = 1 + \frac{49.4k\Omega}{R_g}
\]

\[
R_g = \frac{49.4k\Omega}{\text{Gain} - 1.0} = \frac{49.4k\Omega}{(306.7) - 1.0} = 151.6\Omega \text{ or } 162\Omega \text{ for standard 0.1\% resistor}
\]

2. Find the INA826 reference voltage \((V_{\text{ref}})\) to shift the output swing to the proper voltage level.

\[
V_{\text{out}} = \text{Gain} \cdot V_{\text{in}} + V_{\text{ref\_INA}}
\]

\[
V_{\text{ref\_INA}} = V_{\text{out}} - \text{Gain} \cdot V_{\text{in}} = 4.8V - \left(1 + \frac{49.4k\Omega}{162\Omega}\right)(5mV) = 3.27V
\]

3. Select standard value resistors to set the INA826 reference voltage \((V_{\text{ref}} = 3.27V)\). Use Analog Engineer's Calculator \("Passive\Find Voltage Divider\" section) to find standard values for the voltage divider.

\[
V_{\text{ref\_INA}} = \frac{R_2}{R_1 + R_2} V_{\text{in\_div}} = \frac{21.5k\Omega}{11.3k\Omega + 21.5k\Omega}(5V) = 3.277V
\]

4. Use the Common-Mode Input Range Calculator for Instrumentation Amplifiers to determine if the INA826 is violating the common-mode range.
**DC Transfer Characteristics**

The following graph shows a linear output response for inputs from –5mV to +15mV. Refer to *Determining a SAR ADC’s Linear Range when using Instrumentation Amplifiers* for detailed theory on this subject. Note that the output range is intentionally limited to –0.12V to 5.12V using Schottky diodes to protect the ADS8860. Note that Schottky diodes are used because the low forward voltage drop (typically less than 0.3V) keeps the output limit very near the ADC supply voltages. The absolute maximum rating for the ADS8860 is –0.3V < Vin < REF +0.3V.

![DC Transfer Characteristic Graph](image)

**AC Transfer Characteristics**

The bandwidth is simulated to be 20.1kHz, and the gain is 49.7dB which is a linear gain of 305.8. See the video series on *Op Amps: Bandwidth 1* for more details on this subject.

![AC Transfer Characteristic Graph](image)
**Transient ADC Input Settling Simulation**

The following simulation shows settling to a +15mV dc input signal. This type of simulation shows that the sample and hold kickback circuit is properly selected. Refer to *Introduction to SAR ADC Front-End Component Selection* for detailed theory on this subject.

**Noise Simulation**

The following simplified noise calculation is provided for a rough estimate. We neglect noise from the OPA192 as the instrumentation amplifier is in high gain, so its noise is dominant.

\[
E_n = \text{Gain} \cdot \sqrt{\frac{\text{ENOB}^2 + \text{ENOB}^2}{\text{Gain}}} \cdot \sqrt{\frac{\text{f}}{\text{C}}}
\]

\[
E_n = (305.8) \cdot \sqrt{\left(18 \text{nV} / \sqrt{\text{Hz}} \right)^2 + \left(\frac{110 \text{nV} / \sqrt{\text{Hz}}}{305.8} \right)^2} \cdot \sqrt{\frac{1.57 (20 \text{kHz})}{\text{C}}} = 978 \text{uV} / \sqrt{\text{Hz}}
\]

Note that calculated and simulated match well. Refer to *TI Precision Labs - Op Amps: Noise 4* for detailed theory on amplifier noise calculations, and *Calculating the Total Noise for ADC Systems* for data converter noise.
Optional Input Filter

The following figure shows a commonly used instrumentation amplifier input filter. The differential noise is filtered with $C_{\text{dif}}$, and the common-mode noise is filtered with $C_{\text{cm}1}$ and $C_{\text{cm}2}$. Note that it is recommended that $C_{\text{dif}} \geq 10C_{\text{cm}}$. This prevents conversion of common-mode noise to differential noise due to component tolerances. The following filter was designed for a differential cutoff frequency of 15kHz.

Let $C_{\text{dif}} = 1\text{nF}$ and $f_{\text{dif}} = 15\text{kHz}$

$$R_{\text{in}} = \frac{1}{\frac{1}{4\pi f_{\text{dif}} C_{\text{dif}}}} = \frac{1}{4\pi \cdot (15\text{kHz}) \cdot (1\text{nF})} = 5.305\text{k}\Omega \text{ or } 5.23\text{k}\Omega \text{ for 1\% standard value}$$

$$C_{\text{cm}} = \frac{1}{10}C_{\text{dif}} = 100\text{pF}$$

$$f_{\text{cm}} = \frac{1}{2\pi R_{\text{in}} C_{\text{cm}}} = \frac{1}{2\pi \cdot (5.23\text{k}\Omega) \cdot (100\text{pF})} = 304\text{kHz}$$

$$f_{\text{dif}} = \frac{1}{4\pi R_{\text{in}} \left( C_{\text{dif}} + \frac{1}{2}C_{\text{cm}} \right)} = \frac{1}{4\pi \cdot (5.23\text{k}\Omega) \left( 1\text{nF} + \frac{1}{2} \cdot 100\text{pF} \right)} = 14.5\text{kHz}$$
Design Featured Devices

<table>
<thead>
<tr>
<th>Device</th>
<th>Key Features</th>
<th>Link</th>
<th>Similar Devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADS8860</td>
<td>16-bit resolution, SPI, 1Msps sample rate, single-ended input, Vref input range 2.5 V to 5.0 V.</td>
<td><a href="http://www.ti.com/product/ADS8860">www.ti.com/product/ADS8860</a></td>
<td><a href="http://www.ti.com/adcs">www.ti.com/adcs</a></td>
</tr>
<tr>
<td>OPA192</td>
<td>Bandwidth 10MHz, Rail-to-Rail input and output, low noise 5.5nV/rtHz, low offset ±5µV, low offset drift ±0.2µV/°C. (Typical values)</td>
<td><a href="http://www.ti.com/product/OPA192">www.ti.com/product/OPA192</a></td>
<td><a href="http://www.ti.com/opamp">www.ti.com/opamp</a></td>
</tr>
<tr>
<td>INA826</td>
<td>Bandwidth 1MHz (G = 1), low noise 18nV/rtHz, low offset ±40µV, low offset drift ±0.4µV/°C, low gain drift 0.1ppm/°C. (Typical values)</td>
<td><a href="http://www.ti.com/product/INA826">www.ti.com/product/INA826</a></td>
<td><a href="http://www.ti.com/inas">www.ti.com/inas</a></td>
</tr>
</tbody>
</table>

Design References

See Analog Engineer's Circuit Cookbooks for TI's comprehensive circuit library.

Link to Key Files


Revision History

<table>
<thead>
<tr>
<th>Revision</th>
<th>Date</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>March 2019</td>
<td>Downstyle the title and changed title role to 'Data Converters'. Added link to circuit cookbook landing page.</td>
</tr>
</tbody>
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