Reducing effects of external RC filter circuit on gain and drift error for integrated analog front ends (AFEs): ±10V

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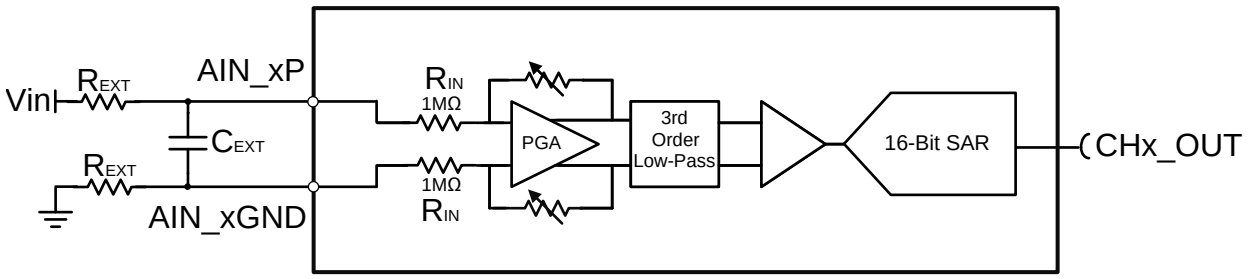
Input	ADC Input	Digital Output
VinMin = –10V	AIN-xP = –10V, AIN-xGND = 0V	-32768_{10}, 8000_{H}
VinMax = 10V	AIN-xP = 10V AIN-xGND = 0V	32767_{10}, $7FFF_{H}$

Power Supplies	
AVDD	**DVDD**
5V	5V

Design Description

This cookbook design describes how to select filter component values and how to minimize the gain error and drift introduced by this filter on a fully-integrated analog front end (AFE) SAR ADC. The design uses the input impedance drift at the full scale range of ±10V of the ADS8588S. This external RC filter minimizes external noise and provides protection from electrical overstress. Minimizing gain error and drift are important to end equipment such as: *Multi-Function Relays*, *AC Analog Input Modules*, and *Terminal Units*. This design describes two correction methods, a no-calibration correction factor and a 2-point calibration. Implementing calibration can minimize both the gain error introduced by the external resistor and the internal device gain error to negligible levels.



Specifications

Specification	Calculated	Measured
Introduced Gain Error (25°C)	0.9901%	0.9894%
Introduced Gain Error (125°C)	0.995%	–1.1388%
Introduced Gain Error Drift	0.49ppm/°C	–0.8031ppm/°C

Design Notes

1. Use low drift R_{EXT} resistors to maintain low drift and minimize gain error. This design uses resistors with a temperature coefficient of 25ppm/°C and ±0.1% tolerance.
2. The internal programmable gain amplifier (PGA) presents a constant resistive impedance of 1MΩ
3. The R_{EXT} value introduced is directly proportional to its introduced error
4. Calibration can also be used to eliminate system offset gain error
5. The *TI Precision Labs – ADCs* training video series covers methods for calculating gain and offset error and eliminating these errors through calibration, see *Understanding and Calibrating the Offset and Gain for ADC Systems*. *Using SPICE Monte Carlo Tool for Statistical Error Analysis* explains how to use *Monte Carlo Analysis* for statistical error analysis.

Component Selection

External anti-aliasing RC filters reduce noise and protect from electrical overstress; if a large resistor value is used, this will further limit the input current. A large external resistive value will also provide a low cutoff frequency, which is desired for relay protection applications as the input frequencies are usually 50 or 60 Hz. Furthermore, a balanced RC filter configuration is required for better common-mode noise rejection; matching external resistors are present on both the negative and positive input paths. To minimize the introduced drift error, the external resistors should be low drift; 25ppm/°C resistors.

1. Choose a high-value R_{EXT} based on the desired cutoff frequency. A cutoff frequency of 320Hz was used to eliminate harmonics from a 50- or 60-Hz input signal.

   R_{EXT} = 10kΩ
2. Choose C_{EXT}

$$C_{EXT} = \frac{1}{2 \cdot \pi \cdot f_C \cdot 2 \cdot R_{EXT}} = \frac{1}{2 \cdot \pi \cdot 320\ Hz \cdot 2 \cdot 10\ k\Omega} = 24.8\ nF$$

   Nearest standard capacitor value available, C_{EXT} = 24nF

Calculate Gain Error Drift

This section demonstrates how to calculate the introduced gain error drift. The additional drift from the external filter resistor is small compared to the internal device drift.

R_{IN} = 1MΩ, R_{EXT} = 10kΩ, C_{EXT} = 24nF

1. Calculate effective internal impedance due to maximum negative drift (–25ppm/°C)

$$R_{IN(-25\,ppm/°C)} = R_{IN} \cdot [Drift\ (ppm/°C) \cdot \delta T(°C) + 1]$$

$$R_{IN(-25\,ppm/°C)} = 1M\Omega \cdot [-25\ ppm/°C \cdot (125\,°C - 25\,°C) + 1]$$

$$R_{IN(-25\,ppm/°C)} = 0.9975\ M\Omega$$

2. Calculate effective external resistance due to maximum positive drift (25ppm/°C)

$$R_{EXT\ (+25\,ppm/°C)} = R_{EXT} \cdot [Drift\ (ppm/°C) \cdot \delta T(°C) + 1]$$

$$R_{EXT\ (+25\,ppm/°C)} = 10\,k\Omega \cdot [25\ ppm/°C \cdot (125\,°C - 25\,°C) + 1]$$

$$R_{EXT\ (+25\,ppm/°C)} = 10.025\ k\Omega$$

3. Calculate nominal gain error introduced by the external resistor at room temperature

$$\text{GainError}\,(R_{EXT})_{RoomTemp} = \frac{1}{1+\frac{R_{IN}}{R_{EXT}}}$$

$$\text{GainError}\,(R_{EXT})_{RoomTemp} = \frac{1}{1+\frac{1\text{M}\Omega}{10\,\text{k}\Omega}}$$

$$\text{GainError}\,(R_{EXT})_{RoomTemp} = 0.009901 \text{ or } 0.9901\%$$

4. Calculate nominal gain error introduced by the external resistor at highest rated temperature

$$\text{GainError}\,(R_{EXT})_{125°C} = \frac{1}{1+\frac{0.9975\,\text{M}\Omega}{10.025\,\text{k}\Omega}}$$

$$\text{GainError}\,(R_{EXT})_{125°C} = 0.009950 \text{ or } 0.995\%$$

5. Calculate gain error drift introduced by the external resistor

$$\text{GainError\_Drift}(R_{EXT}) = \frac{\text{GainError}(R_{EXT})_{RoomTemp} - \text{GainError}(R_{EXT})_{125°C}}{\delta T} \cdot 10^6$$

$$\text{GainError\_Drift}(R_{EXT}) = \frac{0.009901 - 0.00950}{(125°C - 25°C)} \cdot 10^6$$

$$\text{GainError\_Drift}(R_{EXT}) = -0.49\text{ppm}/°C$$

The maximum gain error temperature drift of the ADS8588S is ±14ppm/°C, which is orders of magnitude larger than the calculated drift error introduced, making the introduced error negligible. The minimal drift error introduced by the external resistors has greatly to do with the low drift coefficient of the input impedance (±25ppm/ºC).

To measure the introduced gain error drift, two test signals are sampled and applied at 0.5V from the full scale input range within the linear range of the ADC. The signals are applied and sampled with and without the external RC filter present. These measurements are performed at both temperatures, 25°C and 125°C. The percent gain errors are solved for by finding the percent error of the ideal slope and the measured slope for each of the four distinctive test conditions, resulting in four distinct percent gain error measurements. The drift (ppm/°C) with and without the RC present is then calculated by converting the percent gain errors to decimal format then following step 5 shown above. The introduced gain error drift is then solved for by subtracting the drift of the RC and no RC present.

Uncalibrated Correction

An uncalibrated correction targets to solve the input voltage before any losses occur due to the RC filter by working backwards from the ADC measured samples using a voltage divider.

1. Apply known test signal and measure equivalent code

V_{in}	Measured Code	Equivalent Measured Input
9.5V	30841	9.412

2. Calculate the input voltage before RC losses

$$V_{IN\_NoLoss} = V_{IN\_Equivalent} \cdot \frac{R_{EXT} + R_{IN}}{R_{IN}}$$

$$V_{IN\_NoLoss} = 9.412 \cdot \frac{1M\Omega + 10k\Omega}{1M\Omega}$$

$$V_{IN\_NoLoss} = 9.50612\,V$$

Uncalibrated Correction Measurements

Using a voltage correction can be beneficial, but not the most comprehensive. The correction factor can have a worst-case error of 0.2456% at room temperature due to change in internal impedance.

Room Temperature (25°C) Measurements				
V_{in}	Code	Reading	Correction	Error %
9.5	30841	9.412	9.506120	0.0644
8.5	27594	8.421	8.505210	0.0613
5	16232	4.954	5.003540	0.0708
0	1	0	0.000000	–
–5	–16230	–4.953	–5.002530	0.0506
–8.5	–27593	–8.421	–8.505210	0.0613
–9.5	–30839	–9.411	–9.505110	0.0538

2-Point Calibration Method

A two point calibration applies and samples two test signals at 0.5V from the full scale input range within the linear range of the ADC. These sample measurements are then used to calculate the slope and offset of the linear transfer function. Calibration will eliminate both the gain error introduced by the external resistor and the internal device gain error.

1. Apply test signal at 2.5% of input linear range

Vmin	Measured Code
–9.5V	–30839

2. Apply test signal at 97.5% of input linear range

Vmax	Measured Code
9.5V	30841

3. Calculate slope and offset calibration coefficients

$$m = \frac{Code_{max} - Code_{min}}{V_{max} - V_{min}}$$

$$m = \frac{30841 - (-30839)}{9.5 - (-9.5)} = 3246.3158$$

$$b = Code_{min} - m \cdot V_{min}$$

$$b = (-30839) - 3246.3 \cdot (-9.5\,V) = 1.0001$$

4. Apply calibration coefficient to all subsequent measurements

$$Vin_{Calibrate} = \frac{Code - b}{m}$$

$$Vin_{Calibrate} = \frac{30841 - 1.0001}{3246.3158} = 9.5000$$

2-Point Calibration Method Measurements

Calibration Coefficients

m = 3246.3158; *b* = 1.0001

At room temperature without calibration, a gain error is present. Once calibration is applied to the measured results from the ADC, the gain error is minimized to nearly zero.

Room Temperature (25°C) Measurements					
V_{IN}	Code	Uncalibrated V_{IN}	Calibrated V_{IN}	Voltage Error Without Calibration %	Voltage Error With Calibration %
9.5	30841	9.412	9.500000	–0.926316	–0.000001
8.5	27594	8.421	8.499789	–0.929412	–0.002480
5	16232	16232	4.999822	–0.920000	–0.003568
0	1	0	0.000000	–	–
–5	–16230	–4.953	–4.999822	–0.0940000	–0.003567
–8.5	–27593	–8.421	–8.500097	–0.929412	0.001144
–9.5	–30839	–9.411	–9.500000	–0.936842	0.000000

When exposed to high temperatures, the gain error increases, as expected. Once calibration is applied, the voltage error is decreased but not eliminated; the error still present is the drift error.

High Temperature (125°C) Measurements					
V_{IN}	Code	Uncalibrated V_{IN}	Calibrated V_{IN}	Relative Voltage Error Without Calibration %	Relative Voltage Error With Calibration %
9.5	30826	9.407	9.495379	–0.978947	–0.048639
8.5	27582	8.417	8.496093	–0.976471	–0.045968
5	16224	4.951	4.997357	–0.980000	–0.052854
0	0	0	–0.000308	0	–
–5	–16224	–4.951	–4.997973	–0.980000	–0.040531
–8.5	–27581	–8.417	–8.496401	–0.976471	–0.042344
–9.5	–30826	–9.407	–9.495995	–0.978947	–0.042153

Design References

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

Design Featured Devices

Device	Key Features	Link	Similar Devices
ADS8588S	16-bit, high-speed 8-channel simultaneous-sampling ADC with bipolar inputs on a single supply	www.ti.com/product/ADS8588S	www.ti.com/adcs

Revision History

Revision	Date	Change
A	January 2019	Downscale title, updated header on first page.

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