System Noise Analysis of a Resistive Bridge Pressure Sensor Connected to the PGA900

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ABSTRACT

In this application note we will do a system noise analysis of the PGA900 connected to a resistive bridge pressure sensor. First, we will measure the noise referred to the output for the PGA900. Then, using these measurement results we will calculate the noise-free resolution and effective resolution of the PGA900 for its analog-to-digital converter operating at 64- and 128-µs output data rates and different gain setups. Next, we will summarize the trend between the output resolution and the signal bandwidth when an additional moving average filter is applied. Finally, we will prove that an increase in resolution is minimal for gains set up greater than 80 V/V.

Contents

List of Figures

List of Tables

1 Introduction

When designing mixed signal systems, the most important factor is the accuracy of the output information. Observing the PGA900 connected to a resistive bridge pressure sensor, the excitation signal will create a voltage that will then be gained by the internal instrumentation amplifier (IA) and passed to the internal analog-to-digital converter (ADC). The output of the PGA900 ADC will then be processed by the internal digital filter before it is available at the PGA900 output.

In this signal chain environment, there are many places where the signal can be corrupted and create inaccurate output data. The main problem for this measurement system is that noise can mask the signal.

The user can analyze several sources of noise separately:

- Resistive bridge noise
- IA gain stage noise
- ADC noise
- Reference voltage

Instead of analyzing each single source of noise, this application note examines total noise that is present at the system output and uses this information to determine the best achievable resolution of the input signal.

2 PGA and ADC System Noise

Delta-sigma (ΔΣ) analog-to-digital converters (ADCs) are based on the principle of oversampling. The input signal of a ΔΣ ADC is sampled at a high frequency (modulator frequency) and subsequently filtered and decimated in the digital domain to yield a conversion result at the respective output data rate (DR). The ratio between modulator frequency and output data rate is called oversampling ratio (OSR). By increasing the OSR, and thus reducing the output data rate, the noise performance of the ADC can be optimized. In other words, the input referred noise drops when reducing the output data rate because more samples of the internal modulator are averaged to yield one conversion result. The delta-sigma modulator of the PGA900 is second order with the output word size of 4 bits and a sampling frequency of 1 MHz. The output of the modulator passes through a third-order digital low-pass Sinc filter that has an adjustable decimation ratio or OSR of 64 or 128. Output DR is 15.6 kSPS and 7.8 kSPS respectively.

To measure the amount of noise at the output of the PADC, the inputs VINPP and VINPN of the PGA900 are short circuited and connected to a heavily-decoupled, common mode voltage source. We used internal reference voltage as the voltage source to keep measurements ratiometric. Figure 1 shows the measurement setup.

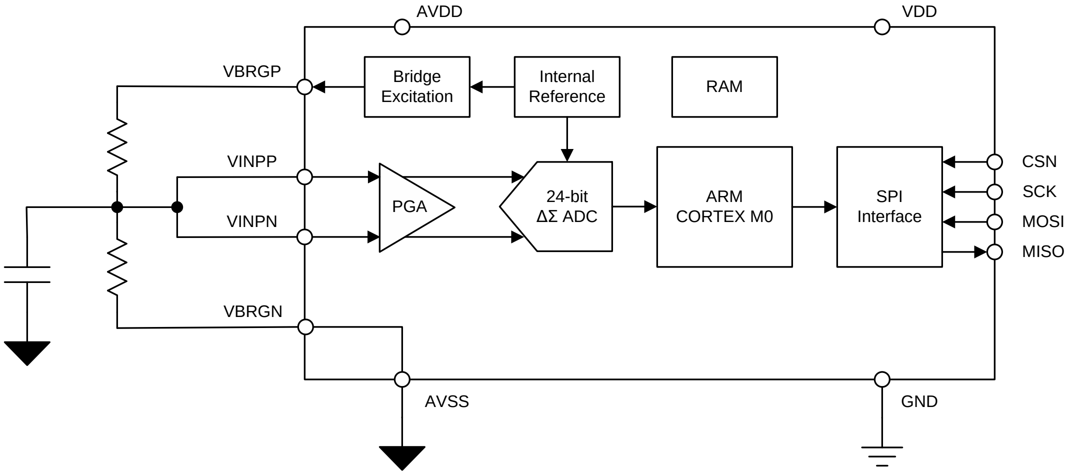


Figure 1. PGA900 Noise Measurement Test Circuit

In most cases the conversion result is directly proportional to the stability of the reference sources. Any noise and drift of the voltage reference is reflected in the conversion result. Using internal voltage reference for ADC and bridge excitation allows the implementation of ratiometric measurements. In a ratiometric measurement the same excitation voltage source that is used to excite the sensor is also used to establish the reference for the ADC. The circuit in Figure 1 employs a ratiometric measurement approach. In other words, the sensor signal (that is, the voltage across the resistive bridge in this case) and the reference voltage for the ADC are derived from the same excitation source. Therefore, errors resulting from temperature drift or noise of the excitation source cancel out because these errors are common to both the sensor signal and the reference.

Then, 2048 output samples are collected that are representative of typical noise performance at T_A = 25°C using the internal 2.5-V reference. Data are the result of averaging readings from a single device over a time period of approximately 0.26 and 0.13 seconds depending on OSR selection. These samples are then plotted as a histogram and analyzed. Example of histogram for OSR of 128 and the gain setting of 80 V/V is shown in Figure 2. Bin with is 57.3 codes, standard deviation σ is 157.3 codes and range is 1146 codes.

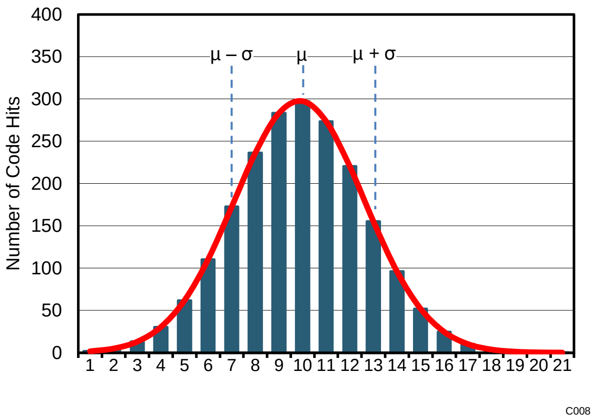


Figure 2. Histogram of the Measurement Codes for Gain of 80 V/V

Device noise is approximately Gaussian in its distribution, the standard deviation of the histogram, σ, corresponds to the effective output's rms noise. This rms noise is expressed in terms of LSBs. The corresponding rms input voltage and rms output noise are referenced to the ADC full-scale input range (FSR), which is ±2.5 V for the PGA900.

Knowing the peak-to-peak noise, the noise-free code resolution of the PGA900 ADC can be defined as the number of bits of resolution beyond which it is impossible to distinctly resolve individual codes, Equation 2. The ratio of the full-scale range to the rms input noise (rather than peak-to-peak noise) is sometimes used to calculate resolution, Equation 1. In this case, the term effective resolution was used. Note that under identical conditions, effective resolution is larger than noise-free code resolution by log2(6.6), or approximately 2.7 bits.

Because of the similarity of the terms, effective number of bits (ENOB) and effective resolution are often assumed to be equal. This assumption is not correct. ENOB is derived from a FFT analysis of the ADC output when the ADC is stimulated with a full-scale sine-wave input signal. SINAD and ENOB are used to measure the dynamic performance of an ADC, while effective resolution and noise-free code resolution are used to measure the noise of the ADC under essentially dc input conditions, where quantization noise and distortion are not a problem.

Noise measurements with shorted inputs are repeated for different gain settings. Table 1 and Table 2 summarize the device noise performance. Table 1 list the effective resolution calculated from σ, rms noise codes from histogram, using Equation 1. Note that noise-free resolution is calculated from peak-to-peak noise values, also from histogram analysis, using Equation 2 as shown in parenthesis.

$$\text{Effective resolution} = \log_2 \frac{2^{24}}{\text{rms noise (LSBs)}} \qquad (1)$$

$$\text{Noise-free resolution} = \log_2 \frac{2^{24}}{\text{peak-to-peak noise (LSBs)}} \quad (2)$$

Table 2 lists the corresponding input-referred noise in units of μV_{RMS} for the conditions shown previously. Note that μV_{PP} values are shown in parenthesis. RMS noise voltage is calculated from effective resolution where there relationship is shown in Equation 3. Peak-to-pea noise voltage and its relationship to noise-free resolution is shown in Equation 4.

$$\text{Effective resolution} = \log_2 \frac{\text{Full-scale range}}{e_n\ (V_{RMS})} \quad (3)$$

$$\text{Noise-free resolution} = \log_2 \frac{\text{Full-scale range}}{e_n\ (V_{PP})} \quad (4)$$

$$\text{Full-scale range} = \frac{2 \times V_{REF}}{\text{GAIN}} \quad (5)$$

Table 1. Effective Resolution from RMS Noise (Noise-Free Bits from Peak-to-Peak Noise)

DR (SPS)	GAIN (V/V)							
	5	9.09	14.29	22.22	40	80	133.3	400
7813	18.0 (15.1)	18.0 (15.2)	17.9 (14.9)	17.7 (15.0)	17.3 (14.4)	16.7 (13.8)	16.0 (13.2)	14.4 (11.6)
15625	17.2 (14.6)	17.2 (14.4)	17.2 (14.1)	17.0 (14.2)	16.7 (13.8)	16.1 (13.3)	15.5 (12.6)	14.0 (11.2)

Table 2. RTI Noise in μV_{RMS} (μV_{PP})

DR (SPS)	GAIN (V/V)							
	5	9.09	14.29	22.22	40	80	133.3	400
7813	3.85 (27.60)	2.16 (14.59)	1.44 (11.28)	1.03 (6.95)	0.76 (5.60)	0.59 (4.27)	0.57 (3.89)	0.57 (3.94)
15625	6.54 (41.13)	3.67 (26.23)	2.36 (19.60)	1.67 (12.34)	1.14 (8.72)	0.89 (6.03)	0.82 (6.04)	0.76 (5.29)

The IA of the PGA900 that is interfacing the resistive bridge can provide a signal gain from 5 V/V up to 400 V/V.

This IA is performing function of programmable gain amplifier (PGA) in the signal chain of PGA900. Unfortunately, any noise present at the input of the IA will also be gained along with the signal. This means the total noise on the output of IA will be dominated by the broadband noise on the input, and its magnitude will be dependent on the measurement bandwidth. The higher the gain, the higher output-referred noise (RTO) will be. On the other hand, increasing the gain at the same time will reduces the input-referred noise, which is particularly useful when measuring low-level signals. From Table 2 and Figure 3 we can see how RTI noise changes for different gains.

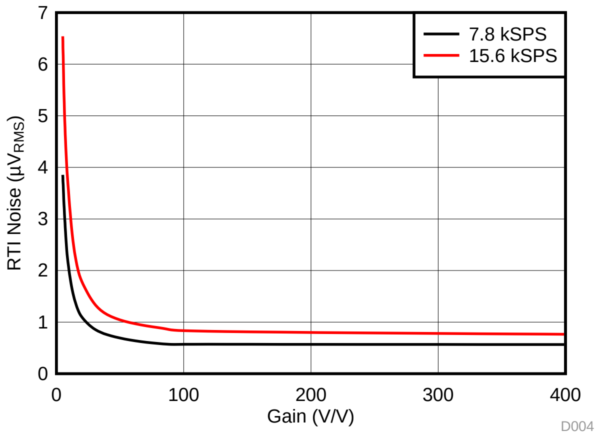


Figure 3. PGA900 RTI Noise vs Gain

3 Applying Additional Digital Filter

The device uses a linear-phase finite impulse response (FIR) digital filter that performs both filtering and decimation of the digital data stream coming from the modulator. Output data rate is selectable between 15.6 kSPS and 7.8 kSPS. The frequency responses of the digital filter are shown in Figure 4 and Figure 5 for two different output data rates.

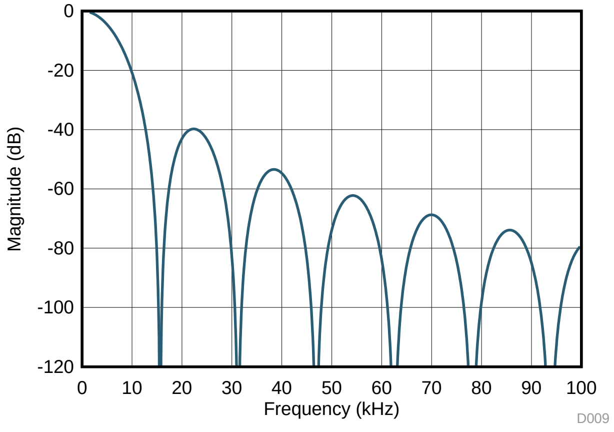


Figure 4. ADC Filter Response (DR = 15.6 kSPS)

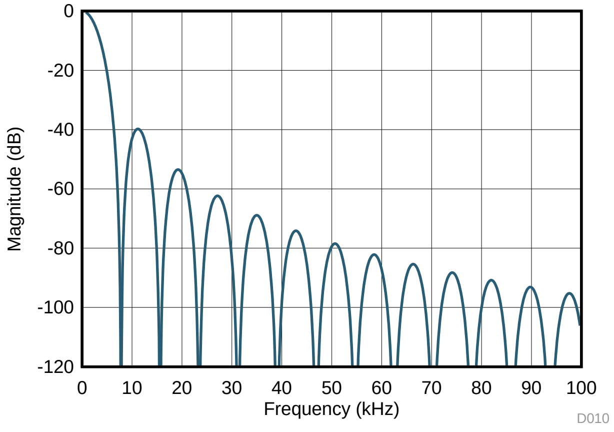


Figure 5. ADC Filter Response (DR = 7.8 kSPS)

It is common for the ADCs used in this application to have data rates that are much higher than the required system bandwidth. Therefore, additional digital filtering can be applied to further reduce the ADC noise and therefore increase the noise-free resolution at the expense of the output data rate.

Adding a simple averaging filter creates a low-pass filter that will lower the in-band noise by 3 dB and increase the measurement resolution by a half-bit for each two consecutive samples that are averaged.

$$W = \frac{1}{2}\log_2 M$$

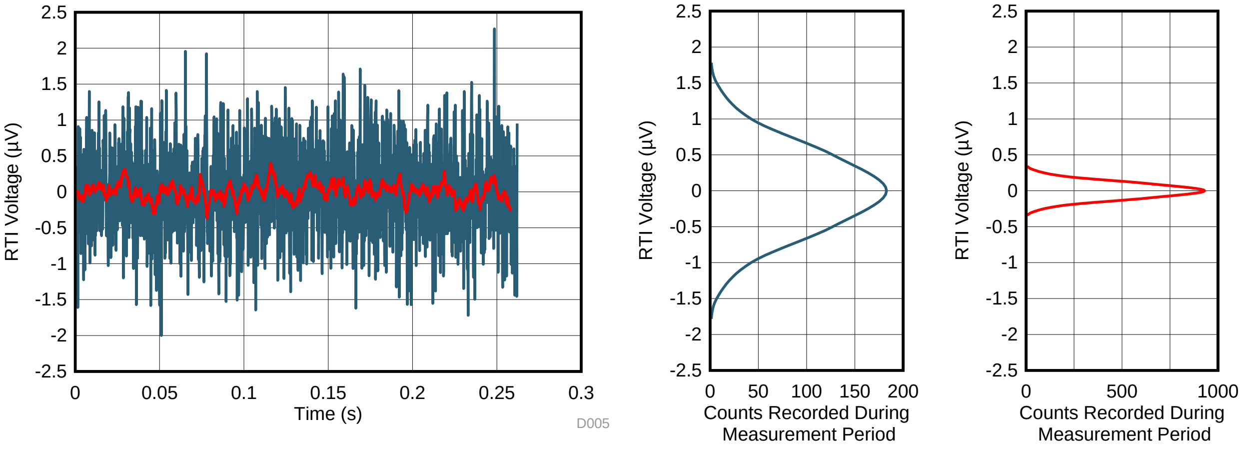
where

- M is the number of consecutive samples averaged.
- W is the increase in output signal resolution. (6)

Frequency response of an M point moving average filter is shown in Equation 7. Example of its effect on the signal noise can be seen in Figure 6. Averaging 32 samples, RTI noise can be reduced from 0.59 μV_{RMS} (4.27 μV_{PP}) to 0.12 μV_{RMS} (0.76 μV_{PP}). Effective resolution will increase from 16.7 bit to 19.1 bit and noise-free resolution from 13.8 bit to 16.3 bit. Output DR from the filter will decrease from 7.8 kSPS to 244 SPS as described by Equation 8.

$$H(f) = \frac{1}{M}\frac{\sin\left(M\pi\frac{f}{f_S}\right)}{\sin\left(\pi\frac{f}{f_S}\right)} \tag{7}$$

$$DR_{FILTER} = \frac{DR_{ADC}}{M} \tag{8}$$



Thermal Noise Measured in Time Domain

ADC Output Distribution of Noise

Moving Average Filter Distribution of Noise

Figure 6. ADC and Filter Output With Decimation Ratio by a Factor of M = 32

Table 3 shows dynamic performances of PGA900 with added moving average filter for different number of averaged samples. Nyquist frequency is half of the DR, where –3-dB bandwidth is calculated using Equation 7. Sinc filter that is implemented inside of the ADC is third order, so the step response of the output signal can be calculated by following formula.

$$\text{Step response} = \frac{2 + M}{DR_{ADC}} \quad (9)$$

Table 3. Dynamic Performances of PGA900 With Added Moving Average Filter

M (samples)	DR (SPS)	NYQUIST FREQUENCY (Hz)	–3-dB BANDWIDTH (Hz)	STEP RESPONSE (ms)
64	122	61	54	8.45
32	244	122	108	4.35
16	488	244	216.3	2.30
8	977	488	434.8	1.28
4	1953	977	888	0.77
2	3906	1953	1950.2	0.51
1	7813	3906	3455.1	0.38

Now data from previous noise measurements with shorted inputs for different gain settings are pass through added moving average filter operating over different number of averaged samples. Table 4 and Table 5 summarize the device new noise performance. Table 4 lists the effective resolution calculated from σ, rms noise codes from histogram when signal is pass through added moving average filter. Note that noise-free resolution is calculated from peak-to-peak noise values, also from the same histogram analysis, are shown in parenthesis.

Table 5 lists the corresponding new input-referred noise in units of μV_{RMS} for the conditions shown previously. Note that new μV_{PP} values are shown in parenthesis.

Table 4. Effective Resolution from RMS Noise (Noise-Free Bits from Peak-to-Peak Noise) With Added Moving Average Filter

DR (SPS)	GAIN (V/V)							
	5	**9.09**	**14.29**	**22.22**	**40**	**80**	**133.3**	**400**
61	21.4 (19.0)	21.5 (19.0)	21.1 (18.9)	20.8 (18.4)	20.3 (18.1)	20.2 (17.8)	19.0 (16.6)	17.5 (15.1)
122	20.8 (18.4)	20.7 (18.1)	20.6 (18.2)	20.3 (17.9)	19.9 (17.7)	19.6 (17.1)	18.6 (16.1)	17.0 (14.6)
244	20.2 (17.6)	20.2 (17.6)	20.1 (17.2)	19.8 (17.3)	19.3 (16.7)	19.1 (16.3)	18.1 (15.5)	16.6 (14.1)
488	19.7 (17.0)	19.6 (17.0)	19.5 (16.9)	19.4 (17.1)	18.8 (16.2)	18.4 (15.8)	17.6 (15.0)	16.1 (13.6)
977	19.2 (16.6)	19.1 (16.4)	19.0 (16.4)	18.9 (16.2)	18.4 (15.7)	17.9 (15.2)	17.1 (14.5)	15.6 (12.9)
1953	18.7 (16.0)	18.6 (16.0)	18.5 (15.8)	18.4 (15.5)	18.0 (15.2)	17.4 (14.9)	16.6 (14.0)	15.1 (12.4)
3906	18.3 (15.5)	18.2 (15.6)	18.2 (15.4)	18.0 (15.2)	17.6 (14.7)	17.0 (14.3)	16.3 (13.5)	14.7 (12.0)
ADC OUTPUT								
7813	18.0 (15.1)	18.0 (15.2)	17.9 (14.9)	17.7 (15.0)	17.3 (14.4)	16.7 (13.8)	16.0 (13.2)	14.4 (11.6)

Table 5. RTI Noise in μV_{RMS} (μV_{PP}) With Added Moving Average Filter

DR (SPS)	GAIN (V/V)							
	5	**9.09**	**14.29**	**22.22**	**40**	**80**	**133.3**	**400**
61	0.36 (1.87)	0.19 (1.02)	0.15 (0.73)	0.12 (0.63)	0.10 (0.44)	0.05 (0.28)	0.07 (0.37)	0.07 (0.36)
122	0.54 (2.84)	0.32 (1.95)	0.22 (1.19)	0.18 (0.94)	0.13 (0.60)	0.08 (0.44)	0.10 (0.53)	0.09 (0.49)
244	0.83 (4.94)	0.47 (2.77)	0.32 (2.25)	0.24 (1.36)	0.19 (1.13)	0.12 (0.76)	0.13 (0.82)	0.12 (0.69)
488	1.15 (7.65)	0.68 (4.10)	0.48 (2.95)	0.33 (1.65)	0.27 (1.62)	0.18 (1.08)	0.19 (1.16)	0.18 (1.01)
977	1.66 (9.99)	0.98 (6.44)	0.67 (3.99)	0.47 (3.07)	0.37 (2.27)	0.26 (1.71)	0.27 (1.66)	0.26 (1.66)
1953	2.35 (15.48)	1.35 (8.65)	0.92 (5.97)	0.66 (4.72)	0.49 (3.30)	0.36 (2.11)	0.37 (2.35)	0.36 (2.31)
3906	3.15 (21.90)	1.79 (11.23)	1.20 (8.18)	0.86 (5.93)	0.63 (4.55)	0.48 (3.08)	0.48 (3.15)	0.48 (3.02)
ADC OUTPUT								
7813	3.85 (27.60)	2.16 (14.59)	1.44 (11.28)	1.03 (6.95)	0.76 (5.60)	0.59 (4.27)	0.57 (3.89)	0.57 (3.94)

4 Conclusion

In this application note, we measured ADC output noise with shorted PGA inputs. Significant RTI noise improvement is seen for gain increase up to 80 V/V. For gain from 80 V/V up to 400 V/V there is insignificant decrease in RTI noise. We also show how noise-free resolution and effective resolution change for different gain settings. At the end we summarized the trend between the output resolution and the signal bandwidth when an additional moving average filter is applied. For different number of averaged samples we show how dynamic performance of the system change and how resolution increase.

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