Application Report
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ADC Performance Parameters - Convert the Units Correctly!

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ABSTRACT

All semiconductor manufacturers define operation and performance of Analog-to-Digital Converters (ADC) using common specifications. Typically, different manufacturers use different units to define the same ADC specification. This inconsistent use of units may result in misinterpretation of performance while comparing various ADCs, possibly leading to improper selection of the ADC. This application report explains how to convert the specification numbers between various units.

Contents

List of Figures

1 Introduction

The important ADC parameters are usually divided in two broad categories: DC (or Static) Input Specifications and AC (or Dynamic) Input Specifications. This report covers the following specifications in detail.

1. DC (or Static) Input Specifications:
   (a) Offset Error and drift
   (b) Gain Error and drift
   (c) Differential Non Linearity (DNL)
   (d) Integral Non Linearity (INL)
   (e) Total Unadjusted Error (TUE)
2. AC (or Dynamic) Input Specifications:
   (a) Total Harmonic Distortion (THD)
   (b) Signal to Noise Ratio (SNR)
   (c) Signal to Noise and Distortion (SINAD)
   (d) Spurious Free Dynamic Range (SFDR)

For all the calculations shown throughout this document, the following typical specifications are used for the ADC:

- Resolution = 16 bit
- Unipolar Single-ended configuration
- Vref = 5 V
- Full scale input = 5 V

The calculation methodology can be applied to Differential and Bipolar ADCs as well.

2 DC/Static Specifications

The DC specifications for an ADC provide an understanding of the device behavior for dc or a very-low-frequency input signal. Important DC specifications are explored in the following sections.

2.1 Offset Error

Offset Error is also referred to as *zero scale error*. It is defined as the difference between Ideal offset point (0.5 LSB) to actual offset and it can be a positive or negative value (as shown in Figure 1 and Figure 2).

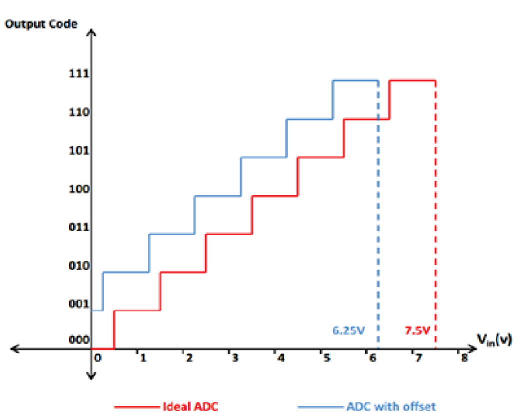

Figure 1. Positive Offset Error

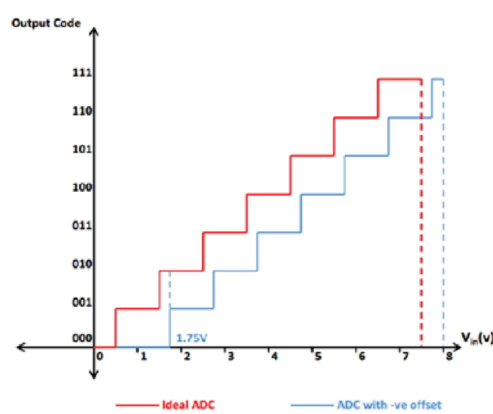

Figure 2. Negative Offset Error

Offset Error value is usually specified using one of the following units: Volts, Least Significant Bits (LSB), %Full Scale Value (%FSV), and parts per million (ppm). FSV is sometimes also referred to as FSR (Full Scale Range). Parts per million (ppm) is usually associated with the actual unit, for example, 1 ppm of 1 V = 1 µV.

Each of these can be converted to another form by using equations and formulas.

For the above example, you can convert between different units as shown in the following example.

Calculate a 3 LSB offset error conversion to Volts:

Offset Error (V) = Error in LSB × Maximum Input / ($2^{\text{number of bits}}$)

Offset Error (V) = 3 × 5 V / (2^{16})

Offset Error (V) = 0.000229, that is, 229 µV

Offset Error (%FSV) = Offset Error (V) × 100 / Full scale value

Offset Error (%FSV) = 0.00458%

ppm, with regard to full scale voltage, is Offset Error (ppm FSV) = 46 ppm, in the example above.

Though the offset error is usually specified at 25°C in the data sheets, the offset does vary with temperature. The variation in offset is specified as *Offset Drift* and denoted as ppm/°C. The actual offset at any temperature can be calculated by adding the drift to offset value calculated for room temperature.

For the above example if the drift is specified as 1 ppm/°C of REF V.

Offset at 85°C = 229 µV + [(85 – 25) × 5 µV] = 529 µV.

2.2 Gain Error

Gain Error is also referred to as *Full Scale Error*. It represents the difference between ideal voltage which provides Full scale output code (in our example 0xFFFF) versus the actual voltage for which the converter provides full scale output code. This measurement is done after calibrating the ADC readings for the offset error. The error represents the difference in the ideal and actual slopes; therefore, the percentage error is same across all the ADC steps (Figure 3).

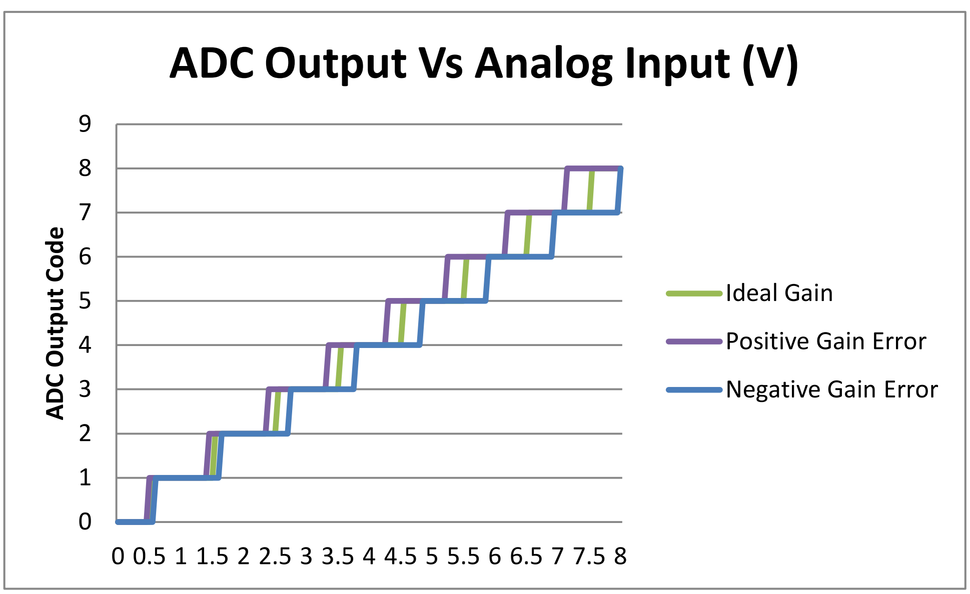

Figure 3. Gain Error

Gain Error value is usually specified using one of the following units: %FSV or LSB or Volts.

For the above ADC, if the gain error is 4 LSB, then it can be converted to Volts as follows:

- Gain Error (Volts) = Error in LSB × Maximum Input / ($2^{\text{number of bits}}$)
- Gain Error (Volts) = 4 × 5 / (2^{16}) = 0.000305 V, that is, 305 µV

This means the ADC will reach 0xFFFF code for input voltage of 4.999656 V.

If the gain error is –4 LSB, then the device will reach 0xFFFF code for input voltage 5.000267 V.

- Gain Error (%FSV) = Gain Error (V) × 100 / Full scale value
- Gain Error (%FSV) = 0.0061%

Similar to offset error, the gain error is usually specified at 25°C in the data sheets and the gain also varies with temperature. The variation in gain is specified as *Gain Drift* and denoted as ppm/°C. The actual gain error at any temperature can be calculated by adding the drift to gain error value calculated for room temperature.

For the above example, if the drift is specified as 1 ppm/°C of REF V.

Gain Error at 85°C = 305 µV + [(85 – 25) × 5 µV] = 605 µV.

2.3 Differential Non Linearity (DNL)

Differential Non Linearity, also referred as Differential Linearity Error, describes deviation between ideal step-size to actual step-size observed for each ADC code. The ideal step-size is 1 LSB. A typical DNL curve is as shown in Figure 4.

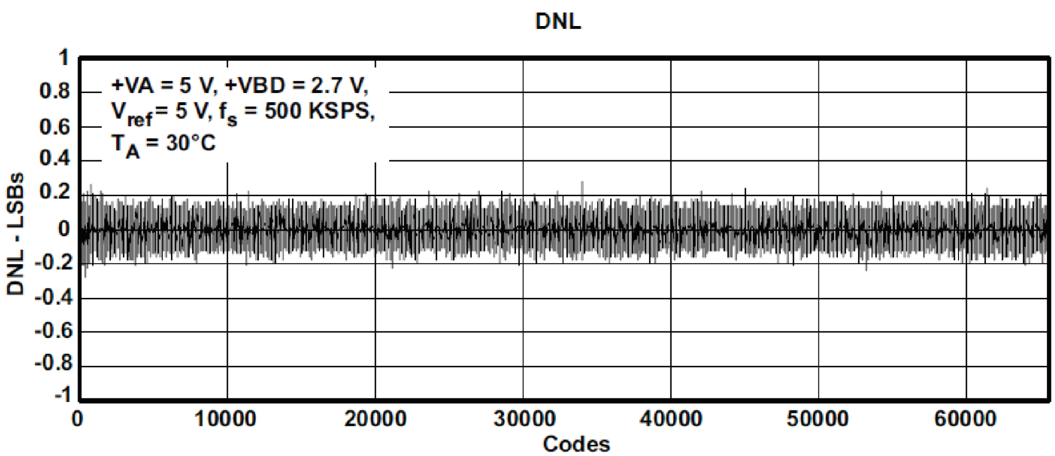

Figure 4. DNL

DNL value is usually specified using one of the following units: LSB or %FSV

We can use the same equations explained in Offset and Gain Error sections to convert from LSB to %FSV.

For the above ADC, 3 LSB error = 0.0046% FSV

2.4 Integral Non Linearity (INL)

Integral Non Linearity, also referred as Integral Linearity Error, describes the deviation of the actual transfer function with respect to ideal transfer function for an ADC. By definition, INL for a particular code is the summation of DNL array till that code. A typical INL curve is as shown in Figure 5.

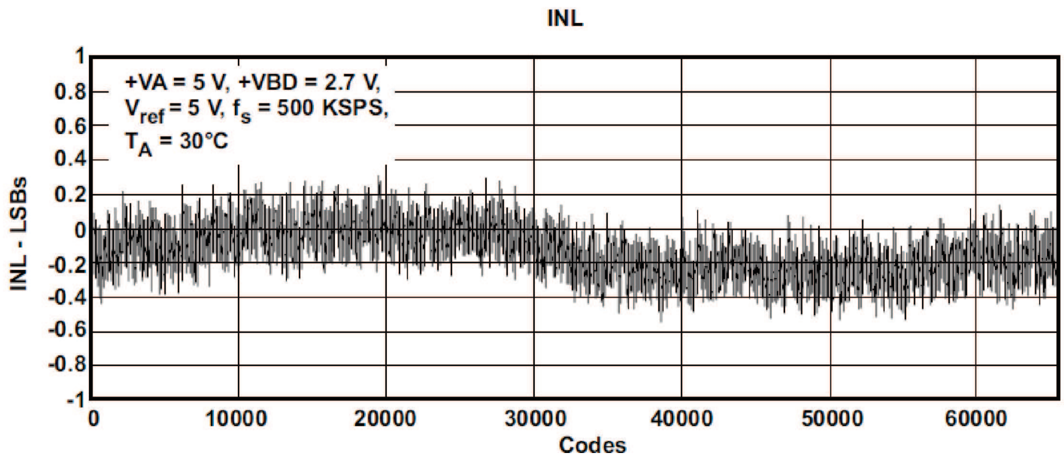

Figure 5. INL

INL value is usually specified using one of the following units: LSB or %FSR.

The equations explained in Offset Error and Gain Error sections can be used to convert between LSB to %FSV.

For the example ADC, 3 LSB error = 0.0046% FSV.

2.5 Total Unadjusted Error (TUE)

The Total Unadjusted Error (TUE) specification is an indication of the ADC's worst rms error without applying any Offset or Gain Error correction. The TUE number is not calculated as a summation of Offset, Gain, DNL and INL errors.

Since it is an RMS number, the TUE is calculated as

TUE = sqrt (sq(Offset Error) + sq(Gain Error) + sq(DNL) + sq(INL))

It is important to convert all the errors to same units.

For example, ADC with Offset Error = 3 LSB, Gain Error = 4 LSB, DNL = 1 LSB and INL = 2 LSB, will have

TUE = sqrt (9 + 16 + 1 + 4) and TUE = 5.48 LSB

Since the offset and gain error can be calibrated out from the ADC transfer curve, the actual error in the application will be dominated by INL and DNL errors.

3 AC (or Dynamic) Errors

An ADC's performance has different important specifications when the input varies quickly. These different parameters which define the ADC performance with Dynamic input are mostly specified using single input frequency. The ADC output array is processed using FFT and analyzed for dynamic specifications. Each specification is usually associated with input signal specs in terms of frequency and amplitude.

A typical ADC output spectrum plot is shown in Figure 6.

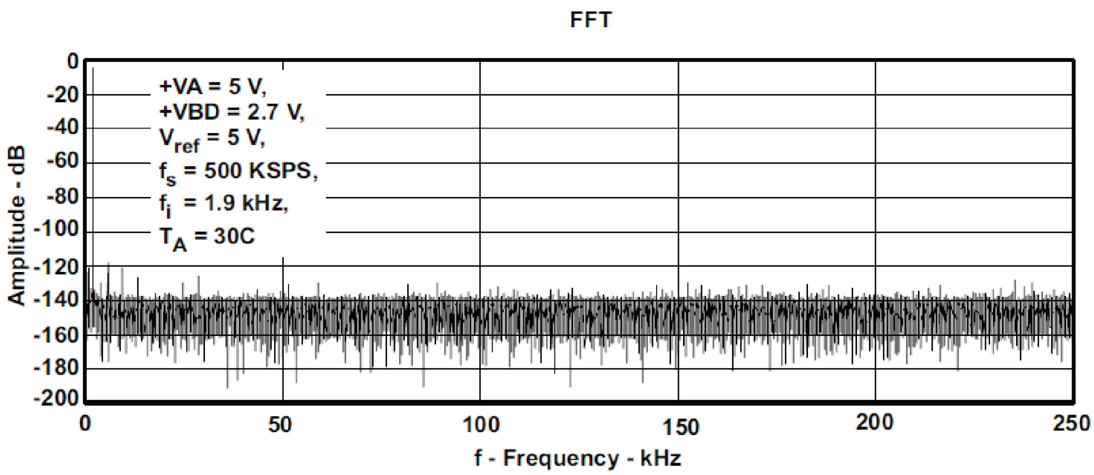

Figure 6. Typical ADC Output Spectrum Plot

3.1 Total Harmonic Distortion (THD)

The Total Harmonic Distortion (THD) specification provides information regarding the harmonic energy present in the frequency spectrum for a particular input frequency. The frequency spectrum is typically shown till the Nyquist frequency and the THD calculation usually takes into account all the harmonics energy till Nyquist. Harmonics beyond Nyquist fall back into the frequency spectrum as noise or spurious tone. These are taken care of in the SNR and SINAD specifications.

The parameter is usually specified in terms of dB or %.

THD = Summation of harmonic energy / Fundamental input energy

3.2 Signal-to-Noise Ratio (SNR)

The Signal-to-Noise Ratio (SNR) specification provides information regarding the noise energy excluding the fundamental and harmonic energy present in the frequency spectrum for a particular input frequency. The SNR calculation usually integrates noise till Nyquist frequency. If not, the specifications will imply the band of frequency where the noise is integrated.

The parameter is usually specified in terms of dB, Vrms, or %.

SNR = Fundamental input energy / Summation of noise energy

3.3 Signal-to-Noise and Distortion (SINAD)

The Signal-to-Noise and Distortion (SINAD) specification provides information regarding the noise and harmonic energy present in the frequency spectrum.

The parameter is usually specified in terms of dB, Vrms, or %.

SINAD = Fundamental input energy / Summation of noise + distortion energy

3.4 Spurious Free Dynamic Range (SFDR)

The Spurious Free Dynamic Range (SFDR) specification provides information regarding the difference between maximum amplitude tone in frequency spectrum and the fundamental input tone.

The parameter is usually defined in dB.

SFDR = Fundamental input energy – Max (all frequency bins except fundamental)

3.5 Conversion Between Units

- Percentage to dB
  - dB = 20 × log (Percentage / 100)
  - that is, 1% = –40 dB and 0.1% = –60 dB
- dB to Vrms
  - Assuming input amplitude as 1 Vrms and for 60 dB SNR,
  - Noise Amplitude is dB = 20 × log (Input Amplitude / Noise Amplitude)
  - Noise Amplitude Vrms = 0.001, that is, 1 mVrms
  - If the spec is –60 dB, then the formula will be dB = 20 × log (Noise Amplitude / Input Amplitude)

4 References

1. *Understanding Data Converters* – SLAA013
2. ADS8318 data sheet – SLAS568A