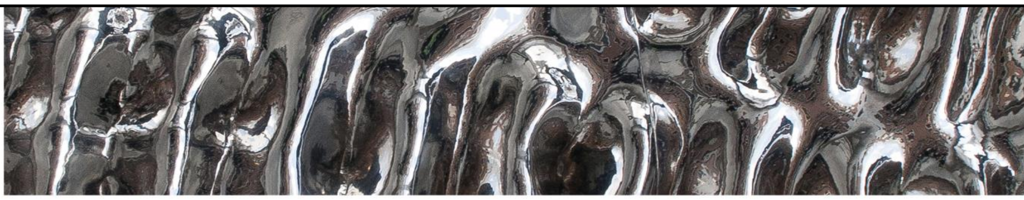

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INF4420

Data Converter Fundamentals

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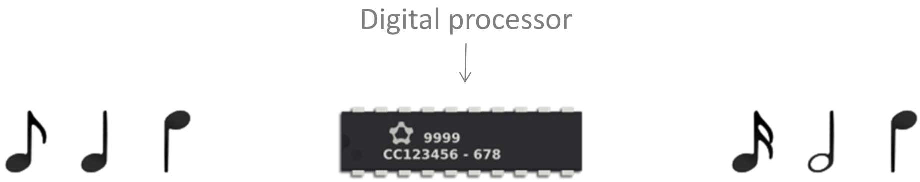
Outline

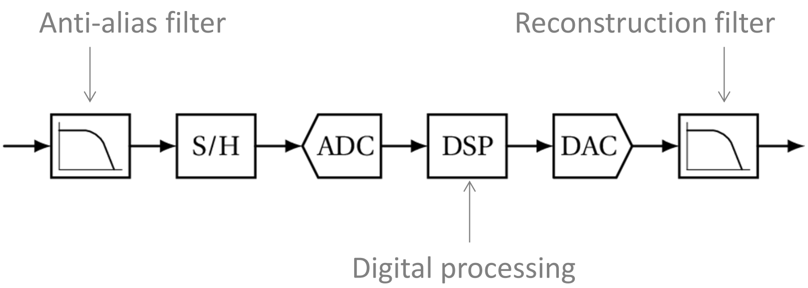
- Quantization
- Static performance
- Dynamic performance

Introduction



Signal processing is usually more efficient, robust, and convenient in the digital domain (algorithms in digital circuits and software). Need to convert to and from analog to interface with the world

Introduction



When interacting with the real world, the inputs and outputs are analog:

Audio, video, motion, light level, …

Introduction

Data conversion accuracy limits system performance

In-depth understanding of data converter performance is important in many applications

How do we quantify data converter performance?

Introduction

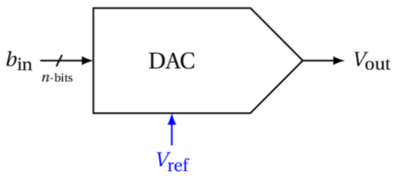
Important to pay close attention to mixed signal issues when designing, such as layout.

Data converters combine sensitive high accuracy circuits for generating reference levels (bandgaps) with digital switching (current spikes).

For high resolution converters, the external environment (e.g. PCB) is very important.

Digital to analog conversion

A digital to analog converter (DAC) converts a digital word to an analog voltage



$$V_{out} = V_{ref} \times (b_1 2^{-1} + b_2 2^{-2} + \cdots + b_n 2^{-n})$$

V_{ref} is typically generated by a bandgap reference

Digital to analog conversion

We want each bit to represent a fixed (constant) voltage

$$V_{LSB} \equiv \frac{V_{ref}}{2^N} \quad [\text{Volt}]$$

We relate many performance metrics to the unitless least significant bit (LSB)

$$1 \text{ LSB} = \frac{1}{2^N}$$

Digital codes

Several possibilities for representing the digital values

- Unipolar
- Sign magnitude
- 1's complement
- 2's complement
- Offset binary

Analog to digital conversion

Ideally, the analog input has infinite precision

- Limited by noise
- Distortion sets a practical limit

The output has a finite number of information carrying units (bits)

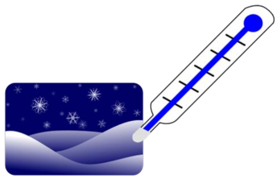
The ADC **quantizes** the input voltage to a finite number of bits

Quantization

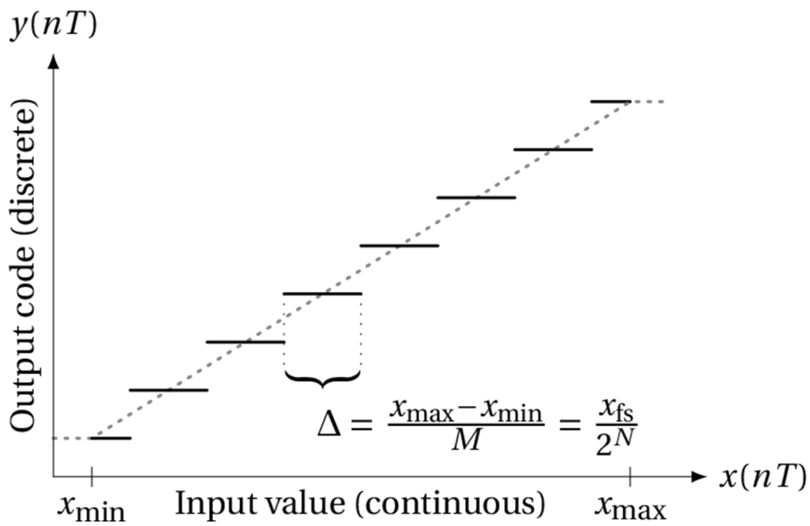
Data converters must represent continuous values in a range using a set of discrete values. A binary code is used to represent the value.

Information is lost!

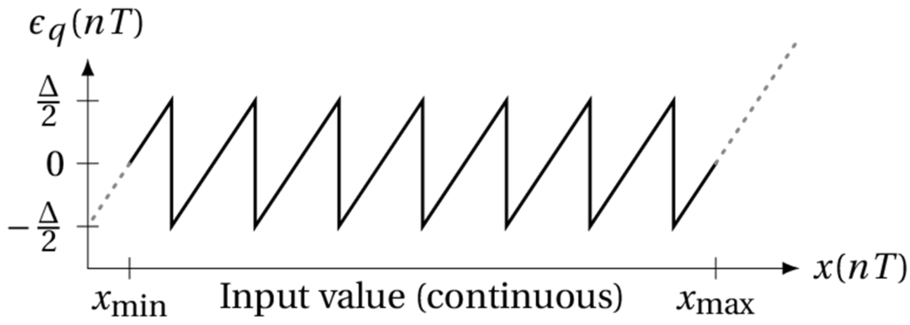
- Hot or cold
- Freezing, cold, warm, or hot
- $-20\ °\mathrm{C}, -19.5\ °\mathrm{C}, \ldots, 20\ °\mathrm{C}$



Quantization



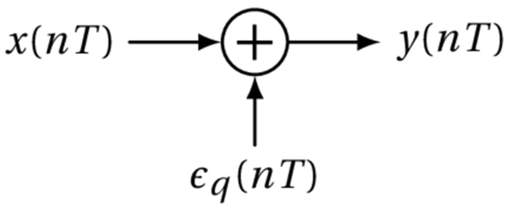
Quantization



The quantization error is restricted to the range $-\frac{\Delta}{2}$ to $\frac{\Delta}{2}$. The quantization is non-linear.

Quantization noise

Model the quantization error as noise added to the original signal. Enables linear analysis.



Quantization noise

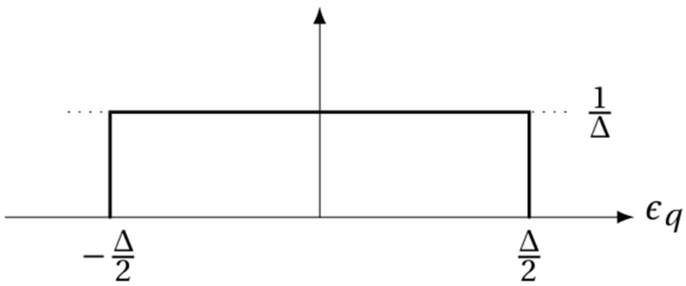
Quantization noise assumptions:

- All quantization levels have equal probability
- Large number of quantization levels, *M*
- Uniform quantization steps, constant Δ
- Quantization error uncorrelated with input

⇨ Quantization noise is white

Quantization noise

Probability density function, p



$$P_q = \int_{-\infty}^{\infty} \epsilon_q^2 \, p(\epsilon_q) \, d\epsilon_q = \int_{-\frac{\Delta}{2}}^{\frac{\Delta}{2}} \frac{\epsilon_q^2}{\Delta} \, d\epsilon_q = \frac{\Delta^2}{12}$$

Quantization noise

Assuming sine wave input

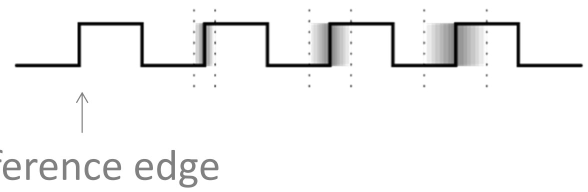
$$P_s = \frac{1}{T}\int_0^T \frac{x_{\text{fs}}^2}{4}\sin^2(2\pi f t)\,dt = \frac{x_{\text{fs}}^2}{8} = \frac{\Delta^2 2^{2N}}{8}$$

SNR due to quantization noise

$$\text{SNR}_q = \frac{P_s}{P_q} = \frac{3\cdot 2^{2N}}{2} \approx 6.02N + 1.76\,\text{dB}$$

Sampling jitter

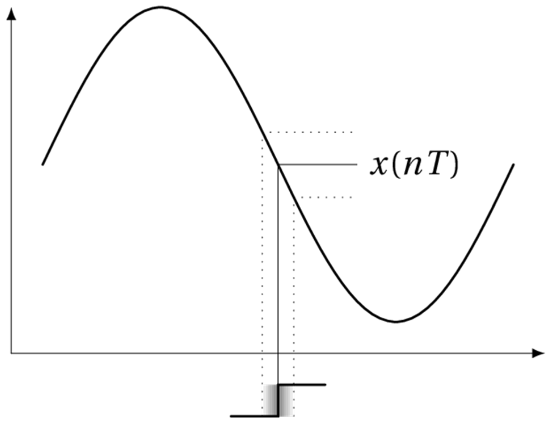
Uncertainty in the timing of the sampling clock due to circuit electrical noise (white noise and flicker noise).



Sampling jitter

Sampling time uncertainty translates to an error in the input voltage.

Need a low noise sampling clock to get high accuracy.



Sampling jitter

Assume f_{in} is half the sampling frequency (worst case). The input is:

$$x(t) = \frac{x_{fs}}{2}\sin\frac{\pi t}{T} \Rightarrow \frac{dx}{dt} = \frac{\pi x_{fs}}{2T}\cos\frac{\pi t}{T}$$

Assume we want the error to be less than half LSB

$$\Delta t\frac{\pi x_{fs}}{2T} \leq \frac{\Delta}{2} \Rightarrow \Delta t \leq \frac{T}{\pi 2^N}$$

Performance specifications

How precise is the data conversion? Different metrics to quantify the performance. Achieving high resolution is costly (in terms of power and complexity). Important to understand the performance requirements of the application.

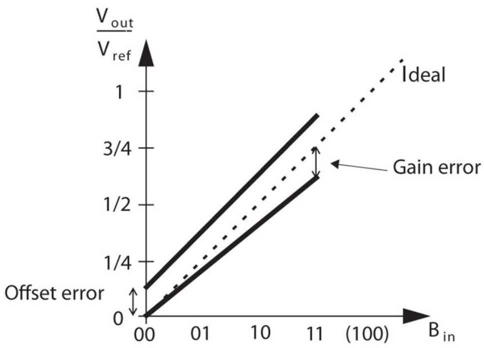
Static specifications

- Gain
- Offset
- INL
- DNL
- Missing codes
- Monotonicity
- ...

Gain and offset

Easily corrected, does not limit accuracy.

Corrected before calculating INL and DNL, etc.

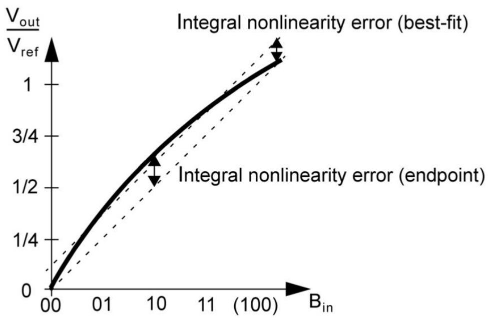


Integral non-linearity error

INL measures deviation from a straight line (best fit straight line or based on end points), after correcting for offset and gain error.

Result usually given in LSBs.

Static, meaning measured from DC inputs.



Differential non-linearity error

DNL is a measure of the step size error. Ideally the distance between two codes are exactly 1 LSB (after correcting for gain and offset).

Like INL measured at DC.

Both INL and DNL are common measures of data converter accuracy.

Monotonicity and missing codes

Monotonicity is applicable to DACs. Increasing the input code should always increase the output voltage. Severe non-linearity will cause the output to decrease when the input increases.

Missing codes in ADCs when an output code does not occur for any input voltage.

Settling time and finite speed also important to consider.

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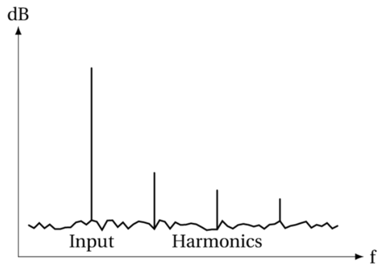
Dynamic specifications

Measure the performance when the input is a sine wave. Look at the converter output spectrum.

- SNR
- SINAD (SNDR)
- SFDR
- THD
- DR



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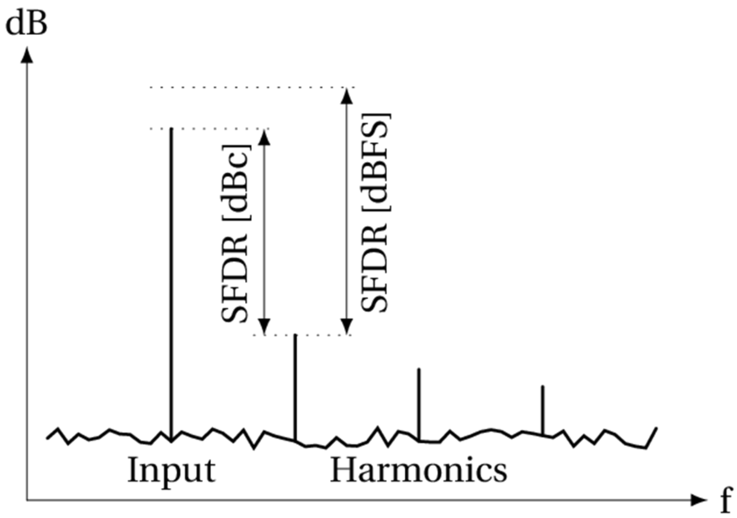
SFDR



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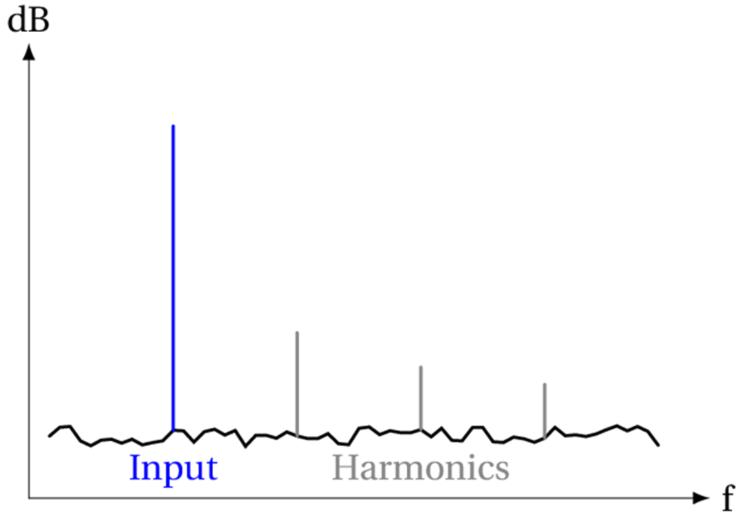
SNR



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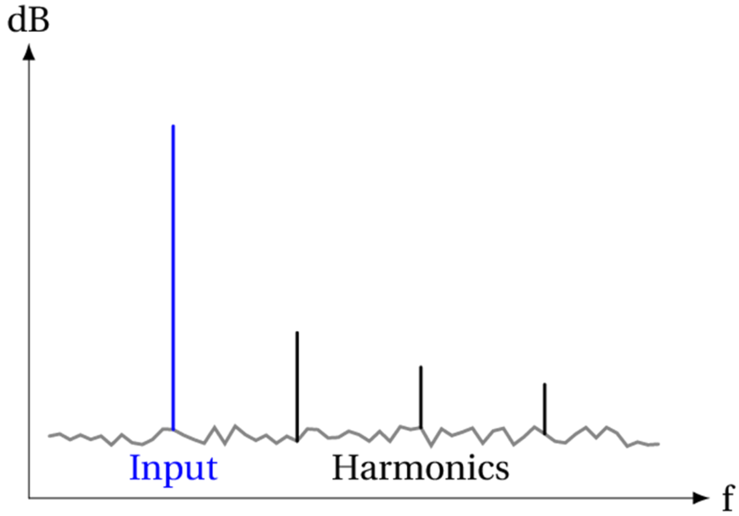
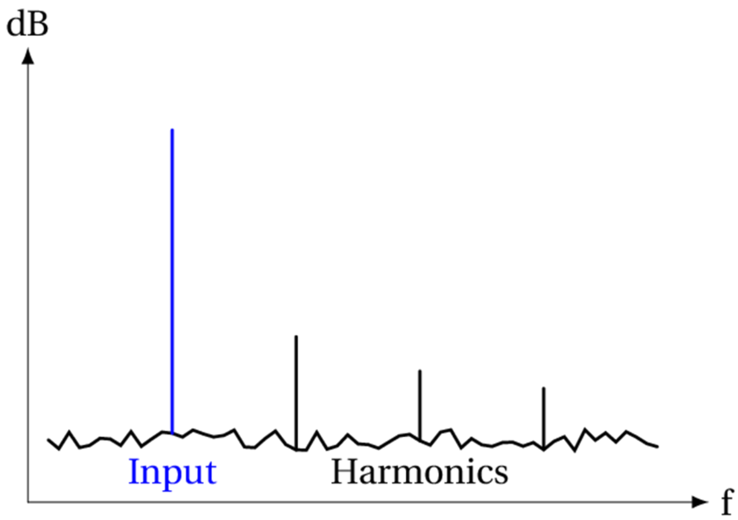
THD



SINAD



Dynamic specifications

Other dynamic specifications

- Intermodulation distortion
- Glitching
- …

Effective number of bits

Data converter resolution is the number of "physical" bits in the system. The effective number of bits (ENOB) tells us how many of these bits contains useful information. Relate the data converter performance to a converter limited only by quantization noise

$$\text{ENOB} = \frac{\text{SINAD} - 1.76\ \text{dB}}{6.02\ \text{dB}}$$

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Figure of merit

Try to come up with an equation that tells us how good the data converter is. Several possibilities. Non are perfect. One commonly used figure of merit (FoM) is

$$\text{FoM} = \frac{P}{2^{ENOB} f_N}$$

Not necessarily a fair comparison, but tells us that if we want one bit improvement, we should expect the power consumption to double.

Effective bandwidth

Dynamic performance metrics requires us to test with a sine wave input. Which frequency should we use?

The effective bandwidth tells us the frequency where the SINAD is 3 dB lower than the best case value.

Resources

Converter Passion (blog covering many aspects of data converters)

Kester , *The Data Conversion Handbook*, Analog Devices, 2004.