EE 230
Lecture 42

Data Converters

Nonideal Effects

Review from Last Time:

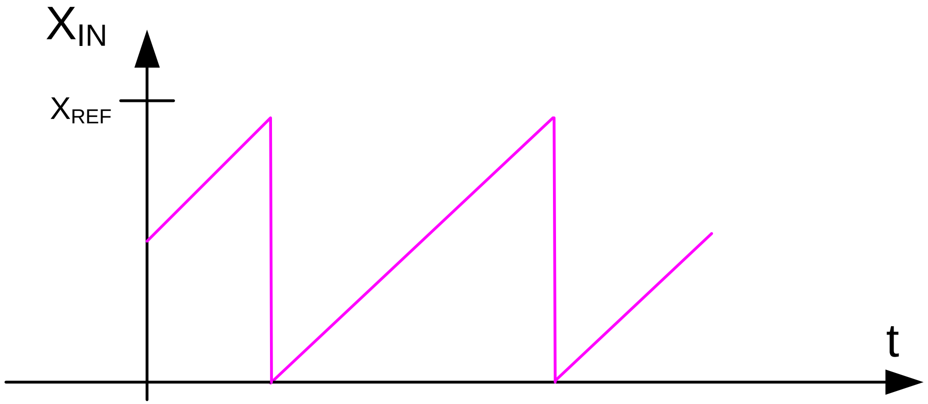
Characterization of Quantization Noise

Saw tooth excitation

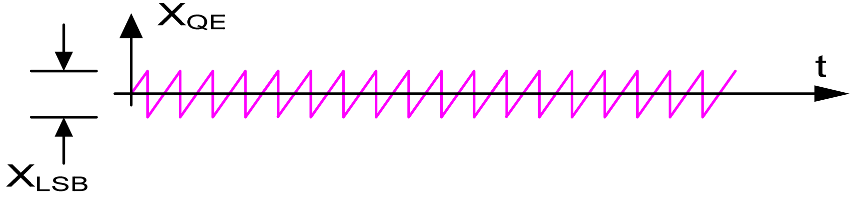
$$X_{QRMS} = \frac{X_{lSB}}{\sqrt{12}}$$

$$SNR = \frac{X_{SIG\text{-}RMS}}{X_{NOISE\text{-}RMS}}$$

What is $X_{SIG\text{-}RMS}$?



$$X_{SIG-RMS} = \frac{X_{REF}}{\sqrt{12}}$$

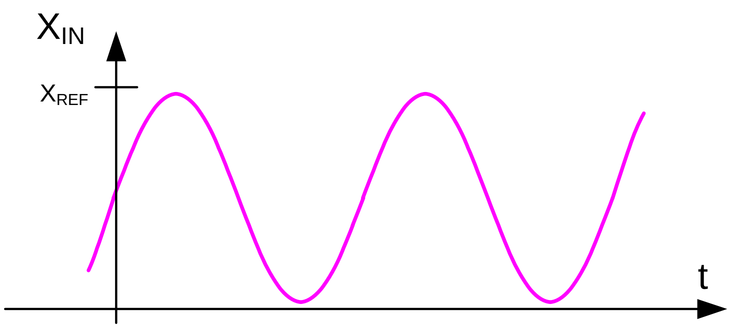


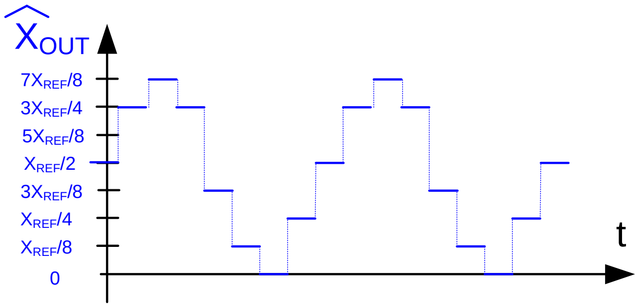
Review from Last Time:

Characterization of Quantization Noise

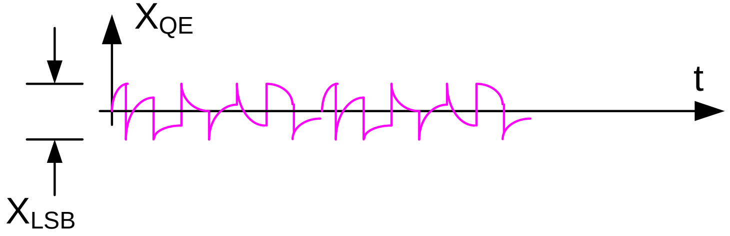
Sinusoidal excitation

- Consider an ADC





Quantization noise is difficult to analytically characterize



Still need RMS value of $X_{QE}(t)$

Will consider error in interpreted output

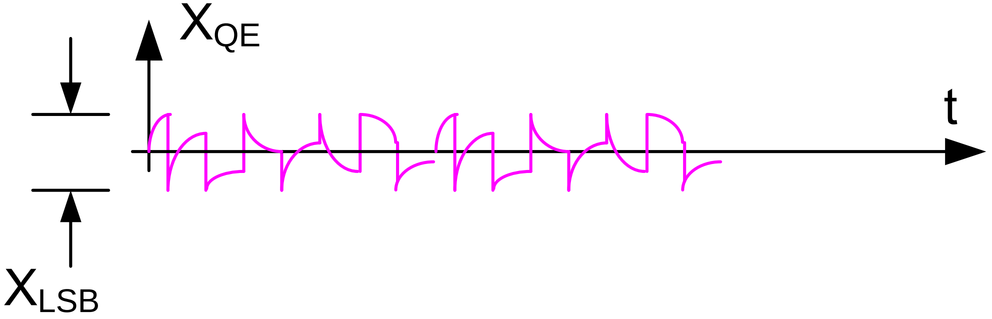
Review from Last Time:

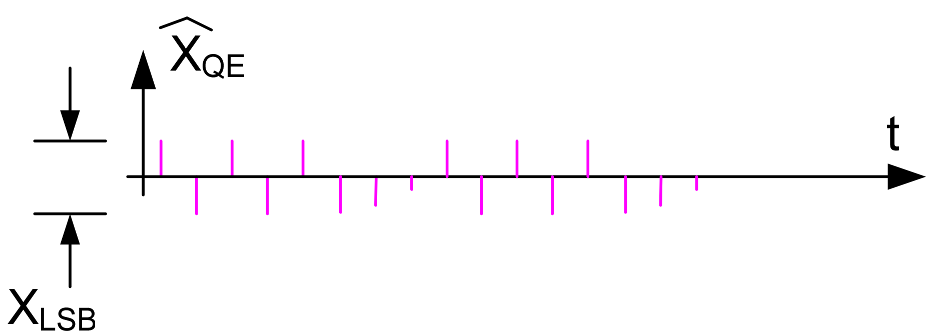
Characterization of Quantization Noise

Sinusoidal excitation

- Consider an ADC

Will consider error in interpreted output



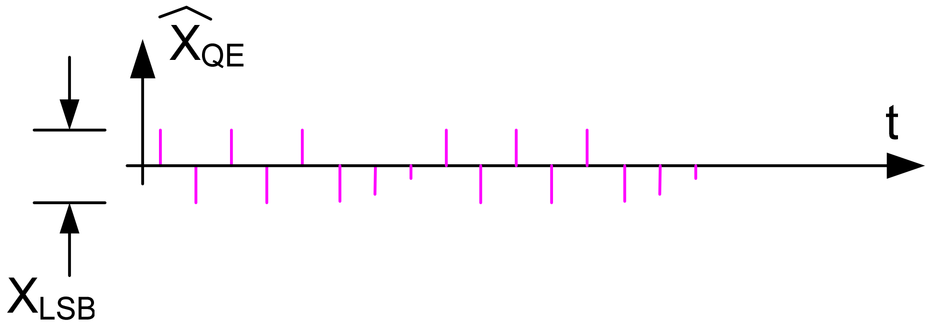


Review from Last Time:

Characterization of Quantization Noise

Sinusoidal excitation

- Consider an ADC (clocked)



Theorem: If n(t) is a random process, then $V_{RMS} \cong \sqrt{\sigma^2 + \mu^2}$

provided that the RMS value is measured over a large interval where the parameters σ and μ are the standard deviation and the mean of <n(kT)>

This theorem can thus be represented as

$$V_{RMS} \cong \sqrt{\frac{1}{T_L}\int_{t_1}^{t_1+T_L} n^2(t)\,dt} \cong \sqrt{\sigma^2 + \mu^2}$$

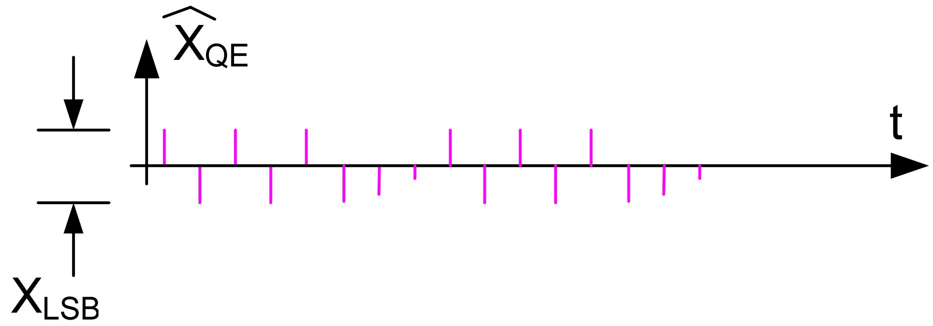
where T is the sampling interval and T_L is a large interval

Review from Last Time:

Characterization of Quantization Noise

Sinusoidal excitation

- Consider an ADC



The quantization noise samples of the ADC output are approximately uniformly distributed between in the interval $[-X_{LSB}/2\ ,\ X_{LSB}/2]$

$$\langle n(kT)\rangle \sim \mathcal{U}[-X_{LSB}/2\ ,\ X_{LSB}/2]$$

A random variable that is U[a,b] has distribution parameters μ and σ given by

$$\mu = \frac{A+B}{2} \qquad \sigma = \frac{B-A}{\sqrt{12}}$$

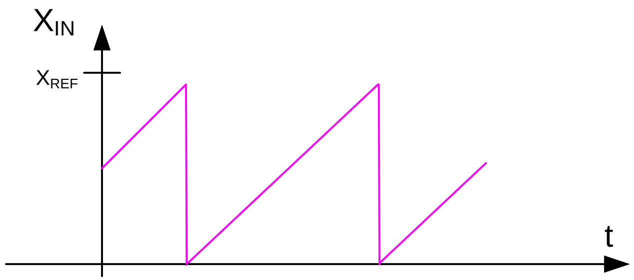
thus, the random variable n(kT) has distribution parameters

$$\mu = 0 \qquad \sigma = \frac{X_{LSB}}{\sqrt{12}}$$

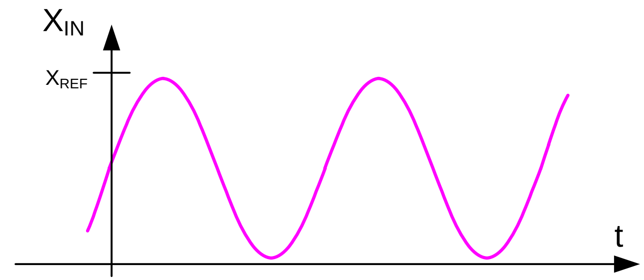
Review from Last Time:

Characterization of Quantization Noise

Saw tooth excitation



Sinusoidal excitation



$$X_{Q\text{-}RMS} \cong \frac{X_{LSB}}{\sqrt{12}}$$

$$\text{SNR} = 2^n$$

$$\text{SNR}_{dB} = 6.02n$$

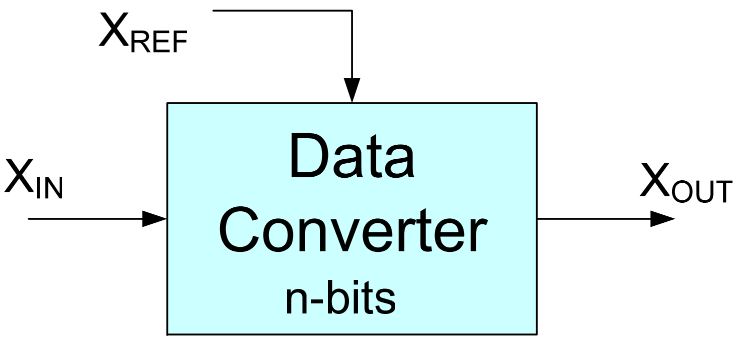
$$\text{SNR} = 1.225 \bullet 2^n$$

$$\text{SNR}_{dB} = 6.02n + 1.76$$

Although derived for an ADC, same expressions apply for DAC
SNR for saw tooth and for triangle excitations are the same
SNR for sinusoidal excitation larger than that for saw tooth by 1.76dB
SNR will decrease if input is not full-scale
Equivalent Number of Bits (ENOB) often given relative to quantization noise SNR_{dB}
Remember – quantization noise is inherent in an ideal data converter!

Review from Last Time:

Equivalent Number of Bits (ENOB)



$$\mathrm{ENOB} = \frac{\mathrm{SNR} - 1.76}{6.02} \qquad \mathrm{ENOB} = \frac{\mathrm{SNDR} - 1.76}{6.02}$$

These definitions of ENOB are based upon noise or noise and distortion

Some other definitions of ENOB are used as well – e.g. if one is only interested in distortion, an ENOB based upon distortion can be defined.

ENOB is useful for determining whether the number of bits really being specified is really useful

Engineering Issues for Using Data Converters

1. Inherent with Data Conversion Process

- Amplitude Quantization
- Time Quantization

(Present even with Ideal Data Converters)

2. Nonideal Components

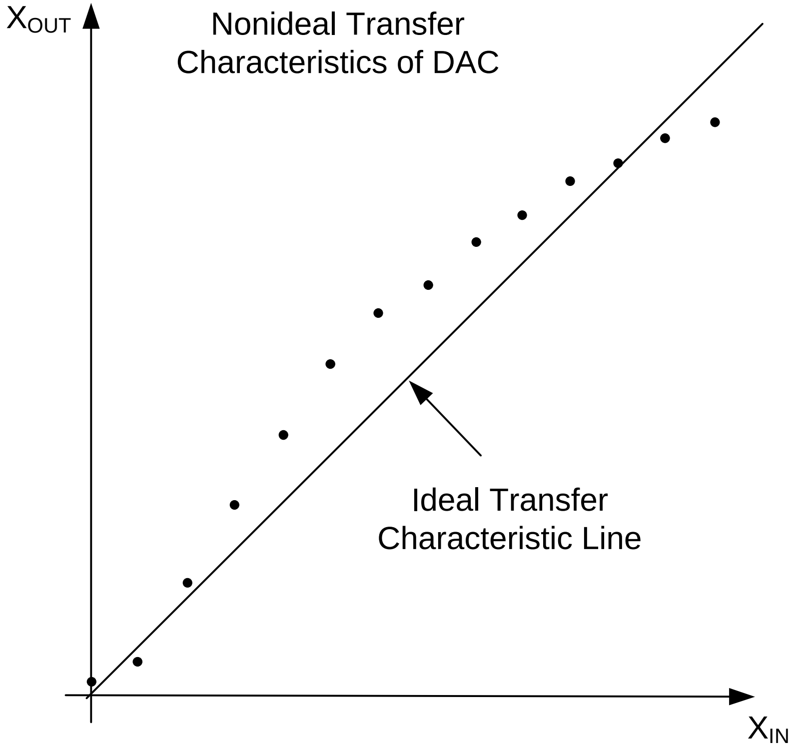
- Uneven steps
- Offsets
- Gain errors
- Response Time
- Noise

(Present to some degree in all physical Data Converters)

How do these issues ultimately impact performance ?

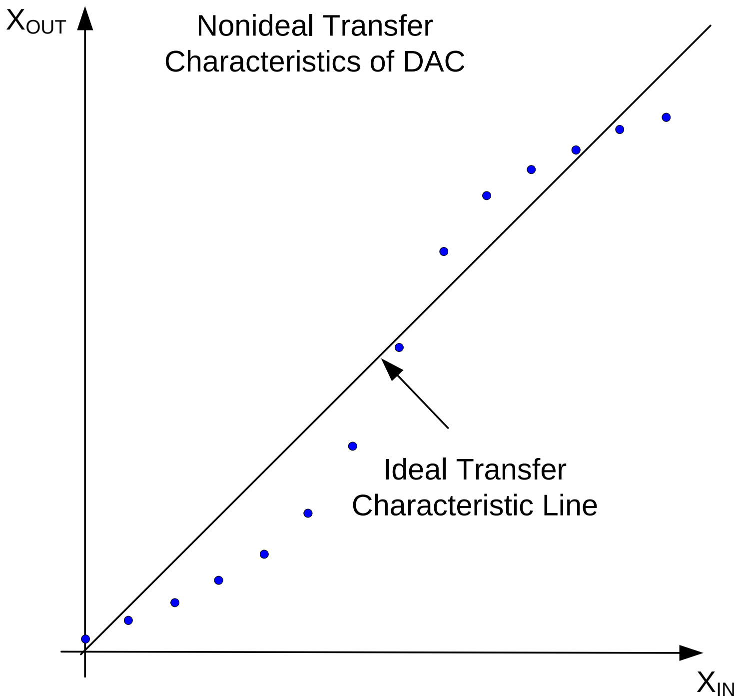
Nonideal Transfer Characteristics

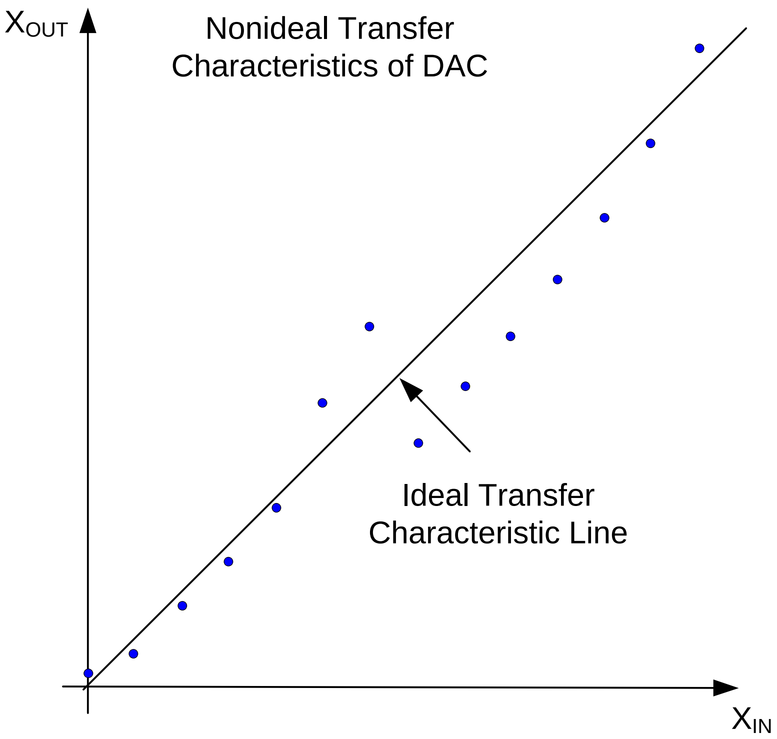
Uneven Steps



Nonideal Transfer Characteristics

Uneven Steps

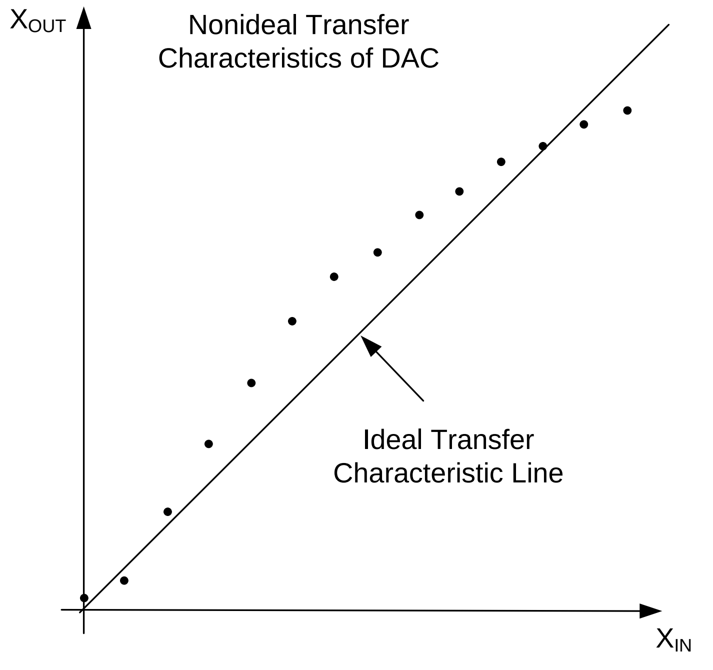




Actual transfer characteristics can vary considerably from one device to another

Nonideal Transfer Characteristics

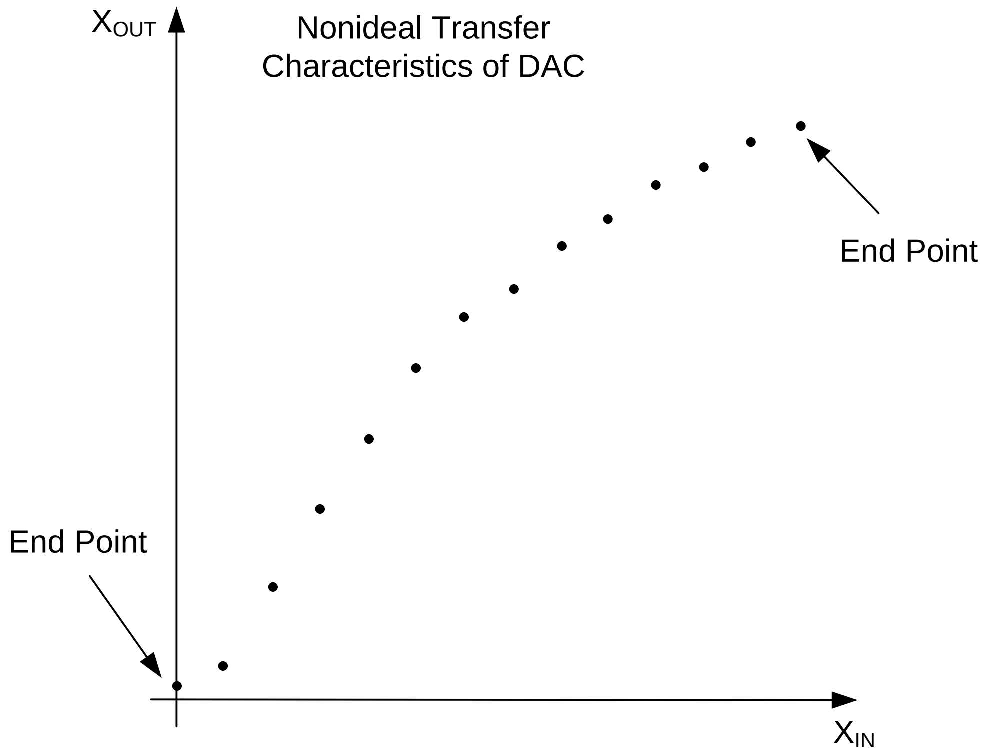
Uneven Steps



This is termed a nonlinearity in the data converter

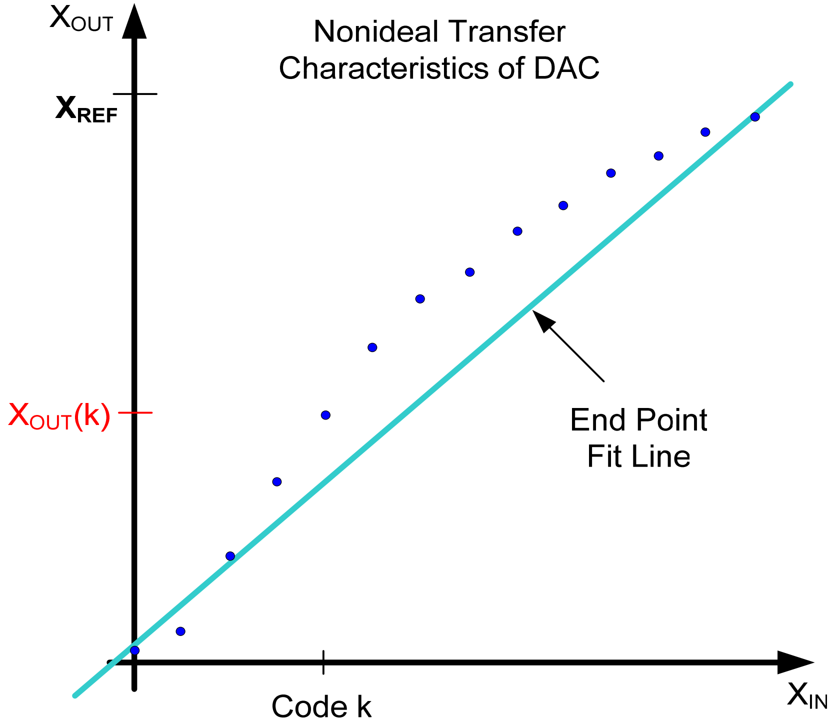
Linearity metrics (specifications) include INL, DNL, THD and SFDR

Characterization of Nonlinearities



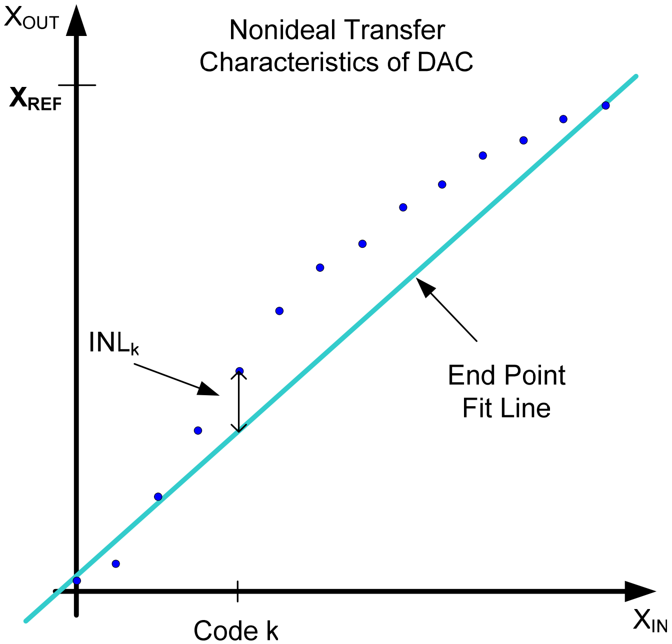
End points are the outputs at the two extreme Boolean inputs

Characterization of Nonlinearities



End point fit line

Characterization of Nonlinearities



Linearity metrics:

- INL
- DNL
- THD
- SFDR

Integral Nonlinearity (INL)

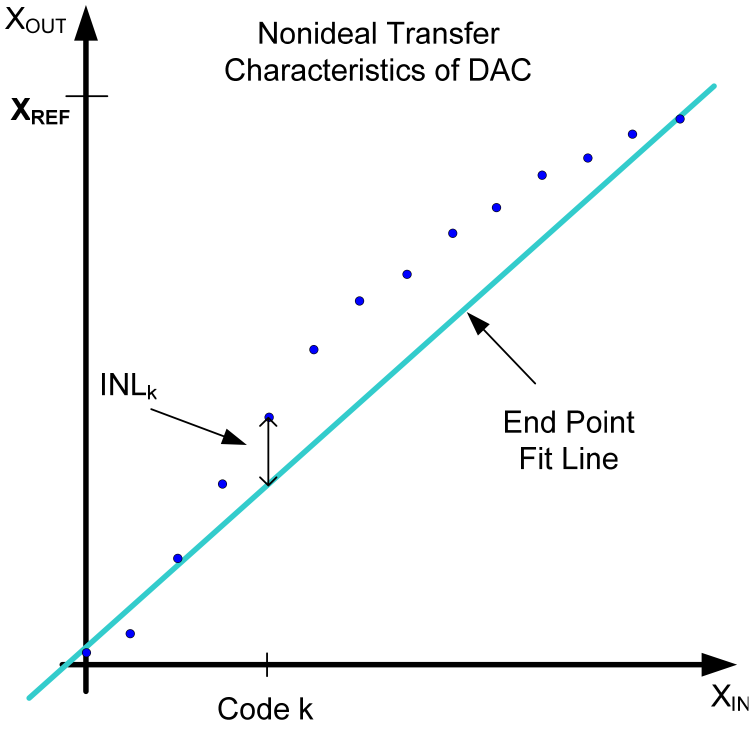
Measure of worst-case deviation from linear

Define the INL at any input code k by:

$$INL_k = X_{OUT}(k) - X_{FIT}(k)$$

Integral Nonlinearity (INL)

Linearity metrics:
- INL
- DNL
- THD
- SFDR



Define the INL by:

$$\mathrm{INL} = \max_{1 \le k \le N} \left\{ \left| \mathrm{INL}_k \right| \right\}$$

Integral Nonlinearity (INL)

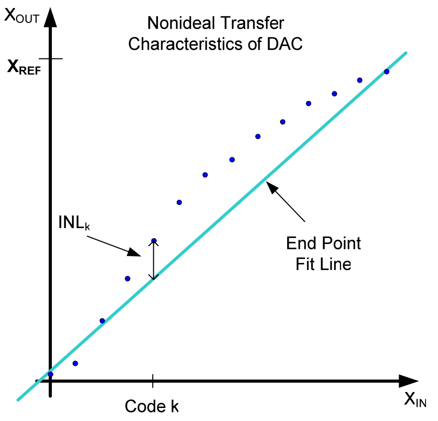
$$\text{INL} = \max_{1 \le k \le N} \left\{ \left| \text{INL}_k \right| \right\}$$

Often expressed in LSB:

$$\text{INL}_{\text{LSB}} = \frac{\text{INL}}{X_{\text{LSBF}}}$$

where

$$X_{\text{LSBF}} = \frac{X_{\text{OUT}}(N) - X_{\text{OUT}}(1)}{N-1}$$



Linearity metrics:

- INL
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Integral Nonlinearity (INL)

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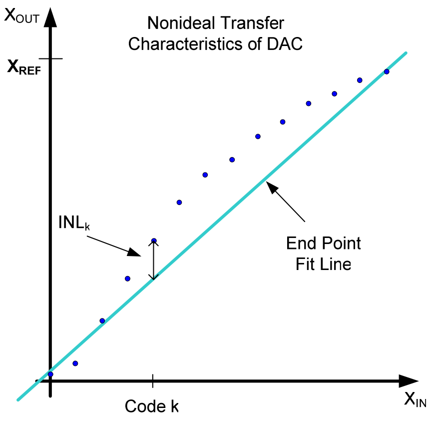
$$\mathrm{INL}_{\mathrm{LSB}} = \frac{\mathrm{INL}}{X_{\mathrm{LSBF}}}$$

where

$$X_{\mathrm{LSBF}} = \frac{X_{\mathrm{OUT}}(N) - X_{\mathrm{OUT}}(1)}{N-1}$$

but

$$X_{\mathrm{LSBF}} = \frac{X_{\mathrm{OUT}}(N) - X_{\mathrm{OUT}}(1)}{N-1} \cong \frac{X_{\mathrm{REF}}}{2^n}$$



Linearity metrics:

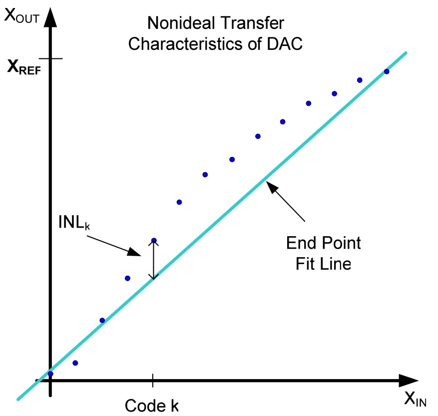
- INL
- DNL
- THD
- SFDR

$$\mathrm{INL}_{\mathrm{LSB}} \cong 2^n \frac{\mathrm{INL}}{X_{\mathrm{REF}}}$$

Integral Nonlinearity (INL)

$$\mathrm{INL} = \max_{1 \le k \le N} \left\{ \left| \mathrm{INL}_k \right| \right\}$$

$$\mathrm{INL}_{LSB} \cong 2^n \frac{\mathrm{INL}}{X_{REF}}$$



Linearity metrics:
- INL
- DNL
- THD
- SFDR

What is the ideal INL?

$$\mathrm{INL}_{IDEAL} = 0_{LSB}$$

What is an acceptable INL?

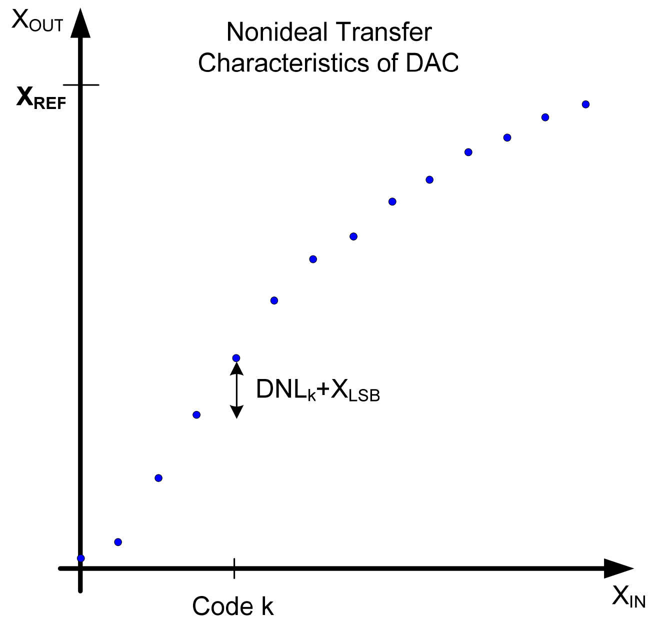
If INL<0.5LSB, it is <u>generally</u> considered acceptable

This would be the quantization error for an n-bit ADC

What is the INL of a DAC?

Varies from part to part, often close to 0.5LSB, occasionally better, but often worse - Given in Data Sheet

Characterization of Nonlinearities



Linearity metrics:

INL

DNL

THD

SFDR

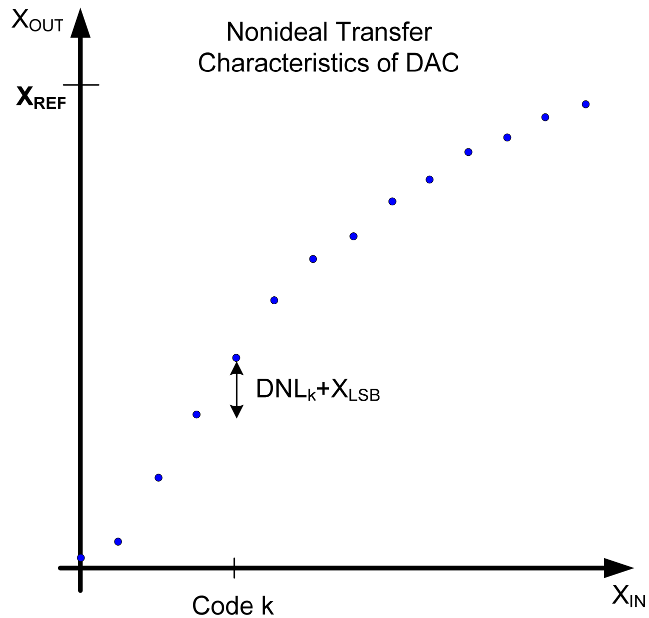
Differential Nonlinearity (DNL)

Measure of worst-case resolving capabilities

Define the DNL at any input code k by:

$$DNL_k = X_{OUT}(k) - X_{OUT}(k-1) - X_{LSBF} \cong X_{OUT}(k) - X_{OUT}(k-1) - X_{LSB}$$

Differential Nonlinearity (DNL)



Linearity metrics:

- INL
- DNL
- THD
- SFDR

$$DNL_k \cong X_{OUT}(k)\text{-}X_{OUT}\left(k\text{-}1\right)\text{-}X_{LSB}$$

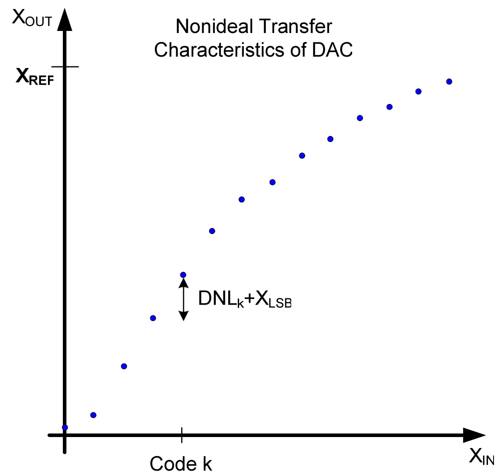
$$DNL = \max_{1<k\leq N}\left\{\left|DNL_k\right|\right\}$$

Often expressed in LSB

$$DNL_{LSB} = \frac{DNL}{X_{LSBF}}$$

$$DNL_{LSB} \cong 2^n \frac{DNL}{X_{REF}}$$

Differential Nonlinearity (DNL)



Linearity metrics:
- INL
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$$\mathrm{DNL} = \max_{1<k\le N}\left\{\left|\mathrm{DNL}_k\right|\right\}$$

$$\mathrm{DNL}_{LSB} \cong 2^n \frac{\mathrm{DNL}}{X_{REF}}$$

What is the IDEAL DNL of a DAC?

Ideal DNL $=0_{LSB}$

What is an acceptable DNL of a DAC?

If DNL<0.5LSB, it is <u>generally</u> considered acceptable

What is the INL of a DAC?

Varies from part to part, often close to 0.5LSB, occasionally better, but often worse - Given in Data Sheet

End of Lecture 42