ADC Measurement

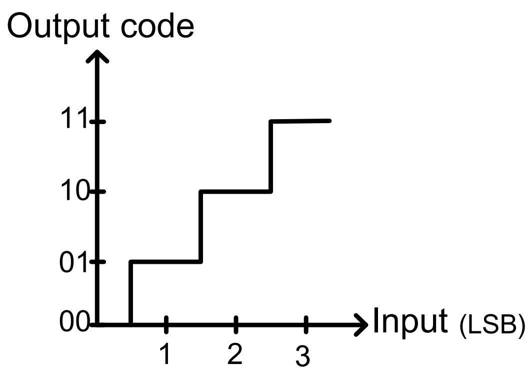
Outline

- Introduction of ADC
- Static testing
- Dynamic testing
- Measurement example
- Reference

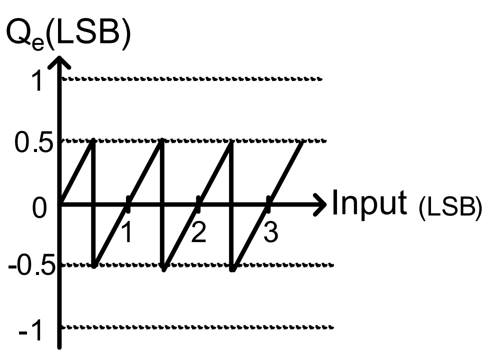
Introduction of ADC

- Conversion of signal from analog to digital

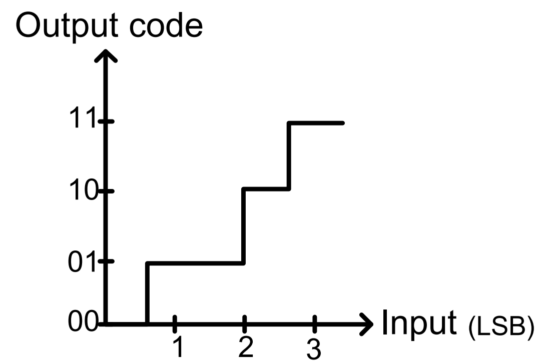
- Ideal 2-bit ADC
  - Input-output transfer curve



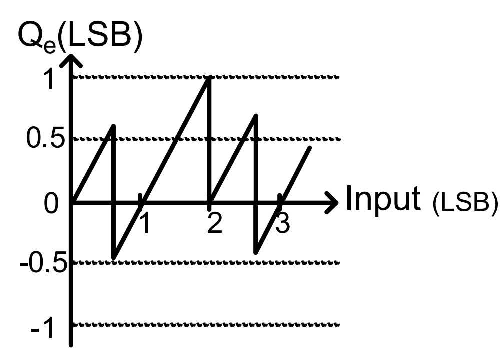
  - Quantization error



- Non-ideal 2-bit ADC
  - Input-output transfer curve



  - Quantization error



Outline

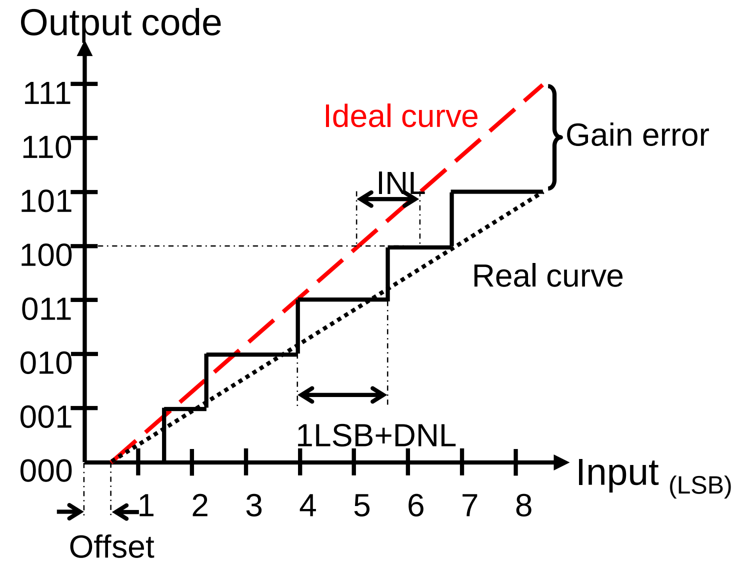
- Introduction of ADC
- Static testing
  - Static errors
  - Histogram testing
    - Ramp signal
    - Sinusoidal signal
      - A_{sin} Fitting Methods
      - Summary of A_{sin} Fitting Methods
      - Normalization of transitions
      - Consideration of offset voltage
      - Illustration of relationship between threshold voltage and output code
      - The Influence of input amplitude to histogram
      - Verification of MATLAB code for static testing
  - Aperture Uncertainty Measurement
  - Limitation of number of sampling points

Outline(Cont.)

- Dynamic testing
- Measurement example
- Reference

Static Testing

- Introduction of static errors with a 3-bit ADC
  - Offset
  - Gain error
  - Differential nonlinearity (DNL)
    - The difference between an actual step width and the ideal value of 1 LSB
    - $\text{DNL}(k) = \dfrac{\text{code width}(k) - 1\text{LSB}}{1\text{LSB}}, \quad k : \text{output code}$
  - Integral nonlinearity (INL)
    - Deviation of code transition from its ideal location
    - $\text{INL}(k) = \sum_{i=1}^{k} \text{DNL}(i)$



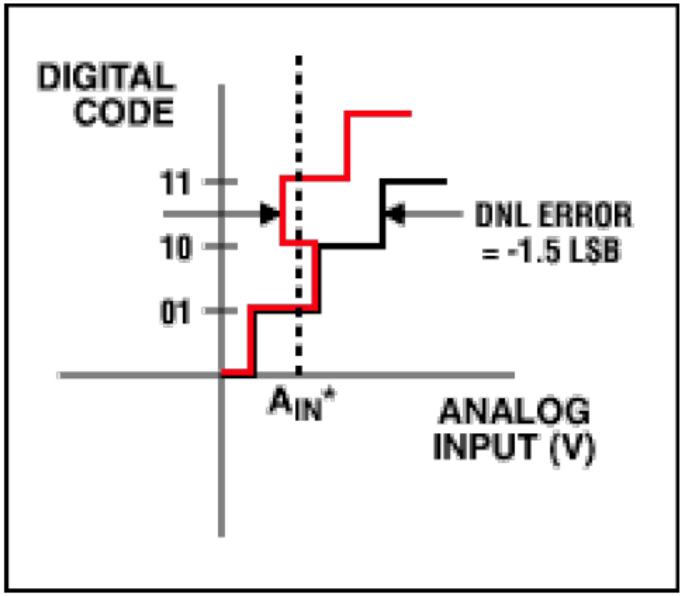
DNL<-1?

- DNL is defined as:

$$DNL(k) = \frac{\text{code width}(k) - 1LSB}{1LSB}$$

➔ DNL <-1 if and only if code width <0

- Transfer curve of DNL <-1 case[8]

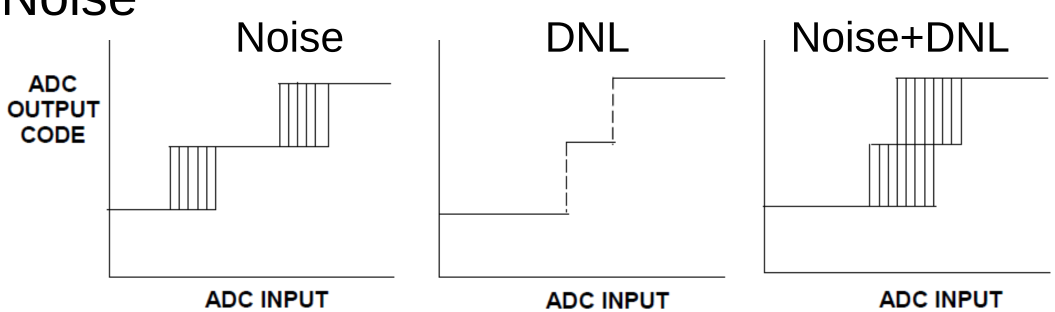


At A_{IN*} the digital code can be one of three possible values. When the input voltage is swept, Code 10 will be missing.

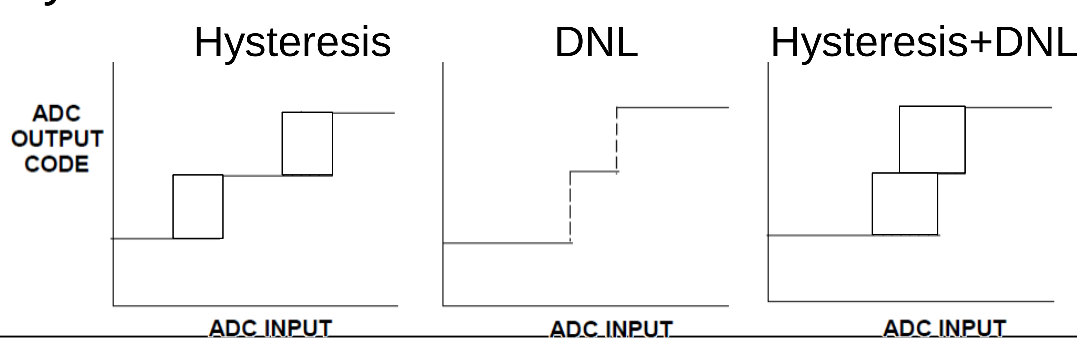
Measurement of DNL <-1

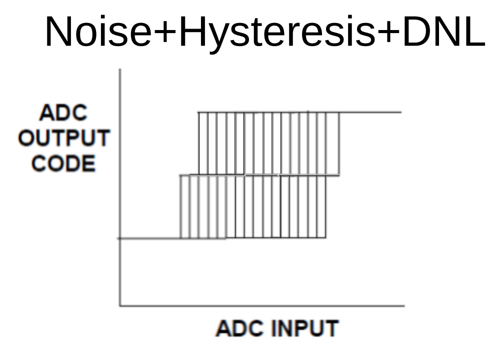
- Measurement detecting transition points[9]
  - LED display test
  - Integrating servo-loop test
  - Computer controlled servo-loop test

- More than one output possibility with same input
  - Noise

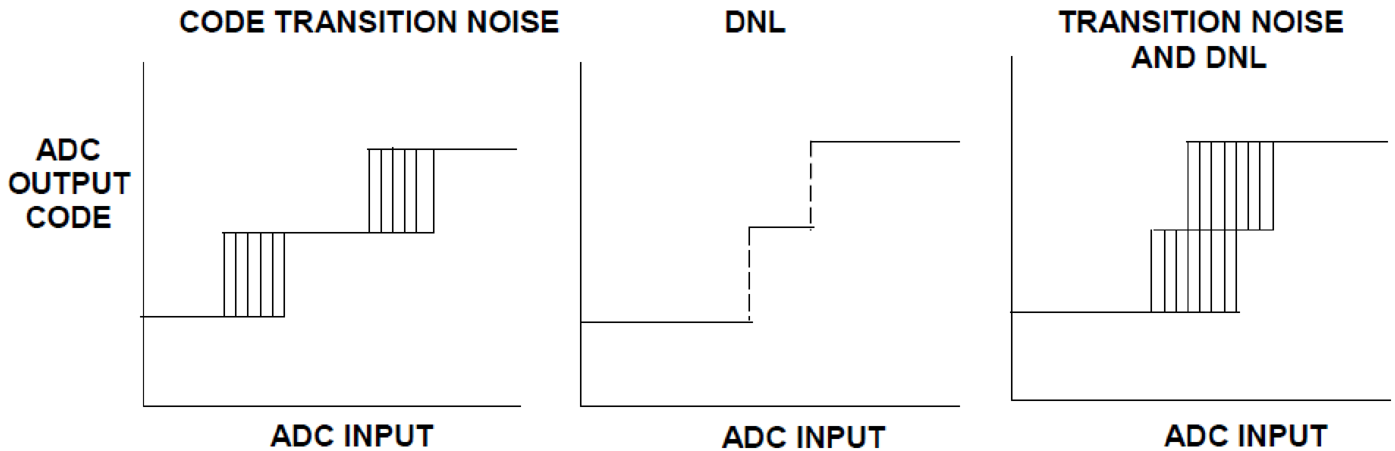


  - Hysteresis





Combined Effect of Code transition Noise and DNL



- "No missing codes" can be defined as a combination of transition noise and DNL which guarantees some level (perhaps 0.2 LSB) of noise-free code for all codes.

- Within large noise, the manufacturer must define "noise levels" and "resolution" in some other way. Which method is used is less important, but the data sheet should contain a clear definition of the method used and the performance to be expected[10]

Histogram Testing

- Features
  - Averaging effect of noise and hysteresis

    → Suitable for very high resolution or wide bandwidth sampling ADCs
  - Monotonic assumption

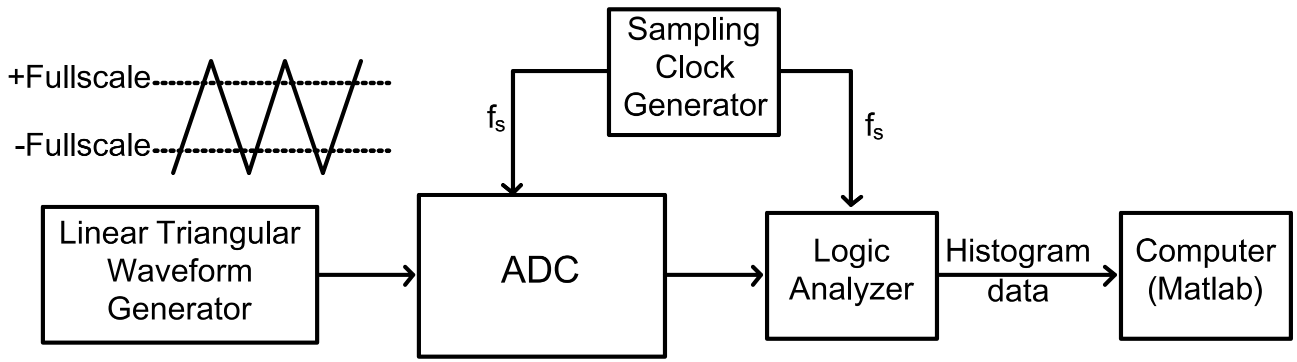
    → Not accurate while testing non-monotonic ADCs

- Testing steps
  - Applying input signal (e.g. ramp wave, sinusoidal wave) with known probability density function (PDF)
  - Measurement of output PDF
  - Using histogram to calculate DNL and INL

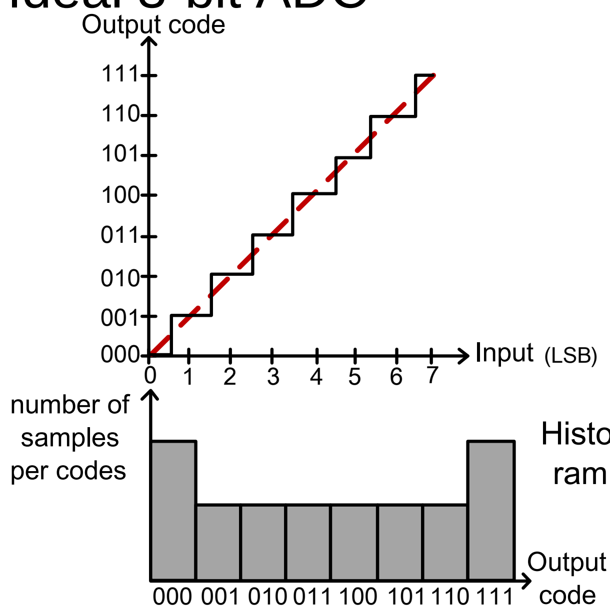
➔ Widely used in modern static testing

Histogram Testing with Ramp Signal

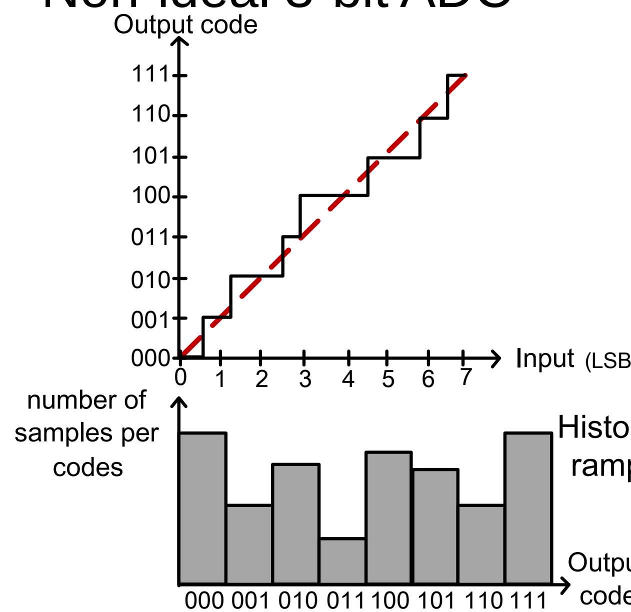
- A linear triangular waveform which slightly exceeds both ends of the ADC range is usually used for testing



- Ideal 3-bit ADC



- Non-ideal 3-bit ADC



Histogram Testing with Ramp Signal (Cont.)

- DNL calculation
  - Removing the histogram results of min. and max. output codes
  - Normalizing histogram results to mean value

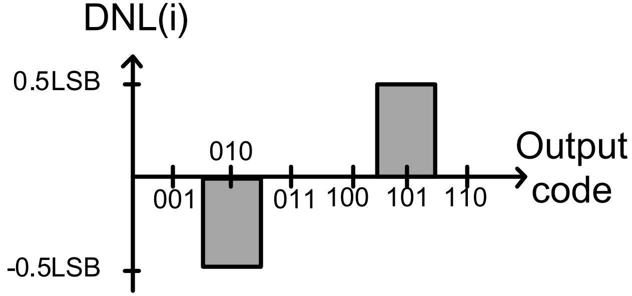
$$\Rightarrow h_{normal}(i) = h(i) \Big/ mean\big(h(i)\big)$$

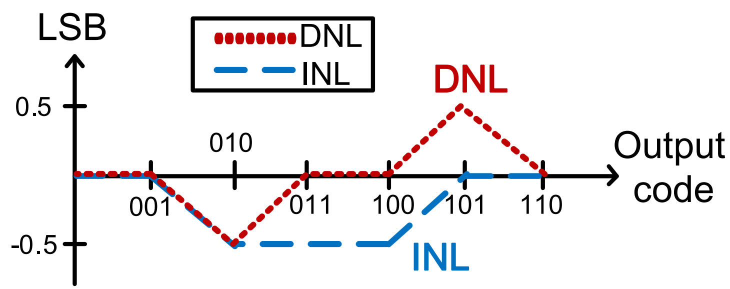
  - Subtracting 1 from the normalized histogram to get DNL(i)

$$\Rightarrow DNL(i) = h_{normal}(i) - 1$$

- INL calculation

The formula of i-th INL is $INL(i) = \sum_{k=1}^{i-1} DNL(k)$ (end-point)





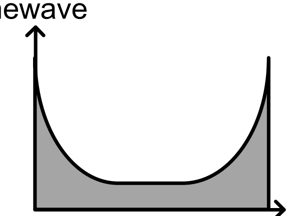
- Disadvantage of histogram testing with ramp signal

Hard to filter the out-of-band noise because triangle wave is composed by many different frequencies

$\Rightarrow$ Ideal triangular wave: $x_{triangle}(t) = \frac{8}{\pi^2}\left(\sin(\omega t) - \frac{1}{9}\sin(3\omega t) + \frac{1}{25}\sin(5\omega t) + \cdots\right)$

Histogram Testing with Sinusoidal Signal

- The probability density of sinusoidal signal
  - A_{sin} is the amplitude of sine wave, V_a and V_b are any voltage in the interval of $(-A_{sin},A_{sin})$
  - $P(V_a,V_b)=\frac{1}{\pi}\{\sin^{-1}[\frac{V_b}{A_{\sin}}]-\sin^{-1}[\frac{V_a}{A_{\sin}}]\}$, which $V_b > V_a \cdots$ eq.(1)
  - Assume V_b - V_a=1LSB ,converting continuous probability $P(V_a,V_b)$ to discrete probability P(i)



$$\Rightarrow P(i)=\frac{1}{\pi}\{sin^{-1}[\frac{V_{LSB}\cdot(i-2^{N-1})}{A_{sin}}]-sin^{-1}[\frac{V_{LSB}\cdot(i-1-2^{N-1})}{A_{sin}}]\}\cdots \text{eq.(2)}$$

- Let h(i) be the histogram result of n-th output code

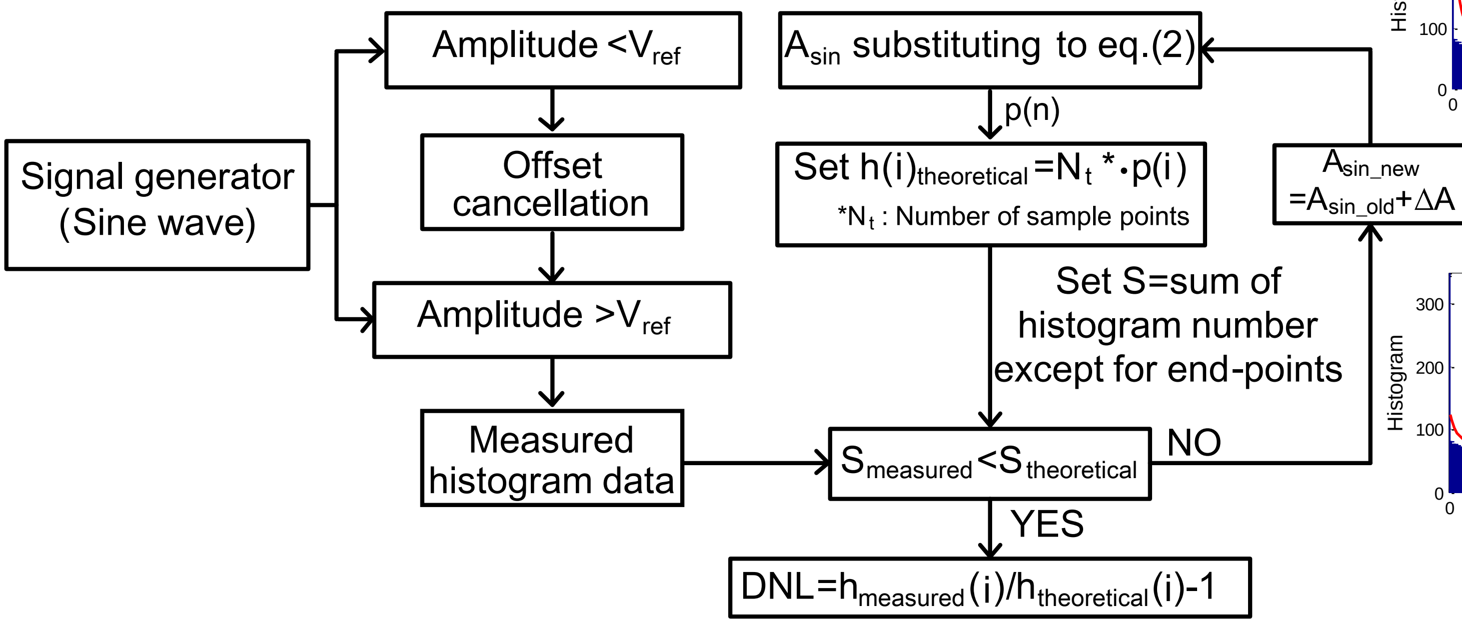
DNL can be calculated by $\frac{h(i)/N_t}{P_{ideal}(i)}-1\cdots$ eq.(3)

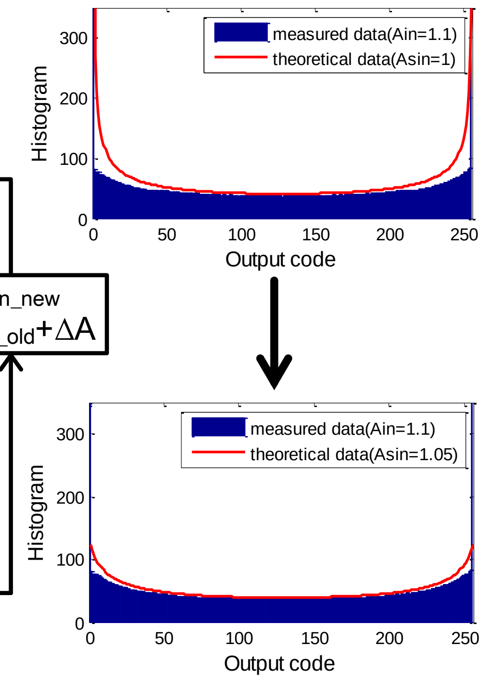
N_t : number of sample points
$P_{ideal}(i)$: PDF of ideal sine wave input

  - However, this formula is unfeasible to get DNL because A_{sin} must be known with great precision
  - To overcome this problem, different methods are proposed by different companies

A_{sin} Fitting Methods

- Method-1 from Maxim[11]
  - We can't get real amplitude information A_{in} and only know the estimated amplitude information A_{sin}
  - Flow chart of method-1





Advantage	Accurate DNL information
Disadvantage	Exhausting analysis and iterative simulation

A_{sin} Fitting Methods (Cont.)

- Method-2 from ADI[10]
  - Procedure of DNL calculation
    - A_{sin} should be estimated to $\dfrac{V_{FS}}{\sin\left(\dfrac{N_t}{N_t + h(0) + h(2^N - 1)} \cdot \dfrac{\pi}{2}\right)} \cdots \text{eq.}(4)$

      which $V_{FS} \approx$ full-scale voltage
    - Estimated value of A_{sin} from eq.(4) is used in eq.(2)

      $\Rightarrow h(i)_{theoretical} = p(i) \cdot N_t$
    - DNL could be calculated by eq.(3) $\Rightarrow DNL(i) = \dfrac{h(i)_{measured}}{h(i)_{theoretical}} - 1$
  - MATLAB verification

	A_{in}	**A_{sin}**
f_s=80MHz f_{in}=9.82MHz $N_t=2^{14}$; V_{ref}=2V	2 $V_{p\text{-}p}$	2.0158 $V_{p\text{-}p}$
	3 $V_{p\text{-}p}$	3.0238 $V_{p\text{-}p}$

-

Advantage	A_{sin} is estimated directly
Disadvantage	Not accurate enough in high-resolution ADC

Summary of A_{sin} Fitting Methods

- In method-1: iteration times ∝ accuracy

- In method-2: accuracy of DNL information is not good enough in high-resolution ADC

- Except A_{sin} fitting methods, we could get accurate DNL information quickly by abandoning both ends codes* information based on [1]
  - To get DNL information, recovering the real transition level from normalized transition level would be used
  - The details of this method will be introduced in the next pages

* Both ends codes is acquired from the measured codes

Normalization of Transitions

- Before normalizing, P(i) is replaced with $h(i)/N_t$ in eq.(2) to calculate threshold voltage, V(i)

$$P(i)=\frac{1}{\pi}\{\sin^{-1}[\frac{V_{LSB}\cdot(i-2^{N-1})}{A_{\sin}}]-\sin^{-1}[\frac{V_{LSB}\cdot(i-1-2^{N-1})}{A_{\sin}}]\}$$

$$\Rightarrow h(i)/N_t=\frac{1}{\pi}\{\sin^{-1}[\frac{V(i)}{A_{\sin}}]-\sin^{-1}[\frac{V(i-1)}{A_{\sin}}]\}$$

$$\Rightarrow V(i)=V(i-1)\cos(\frac{\pi\cdot h(i)}{N_t})+\sin(\frac{\pi\cdot h(i)}{N_t})\sqrt{A_{\sin}{}^2-V^2(i-1)}$$

Set boundary condition V(0)=-$A_{\sin}$

$$\Rightarrow V(i)=-A_{\sin}\cos(\frac{\pi\cdot\sum h(i)}{N_t})$$

- V(i) can be normalized to $A_{\sin}$

$$\Rightarrow V(i)=-\cos(\frac{\pi\sum h(i)}{N_t})$$

  - ◆ The full range of transitions is (-1,+1)
  - ◆ Before recovering the real transition, some assumptions about initial condition are necessary

Consideration of Offset Voltage

- Offset could be calculated by histogram
  - If V_{offset}=0V, the number of codes above zero (N_p) equals the number of codes below zero (N_n)
  - Let p_p be the probability of positive sampled voltage which in the range of (0,A_{sin}+V_{offset}), and p_n is the probability of negative sampled voltage which in the range of (-A_{sin}+V_{offset},0)

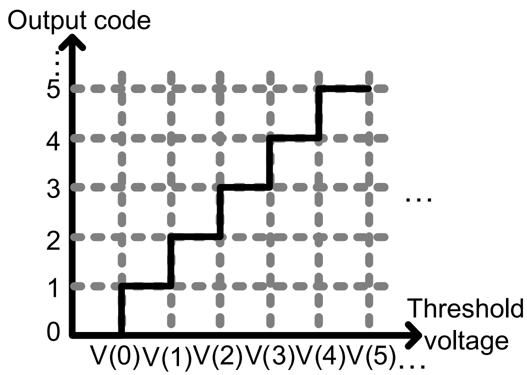
$$\Rightarrow V_{offset} = A_{\sin} \sin\left(\frac{\pi}{2}\cdot(p_p - p_n)\right) = A_{\sin} \sin\left(\frac{\pi}{2}\cdot(\frac{N_p - N_n}{N_t})\right)$$

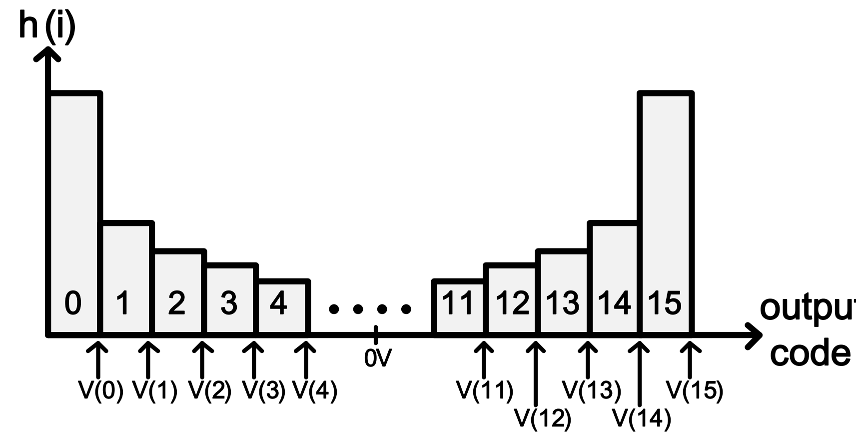
- Correction of transitions with offset error
  - $V(i) = -A_{\sin} \cos(\frac{\pi\cdot\sum h(i)}{N_t}) + A_{\sin} \sin\left(\frac{\pi}{2}\cdot(p_p - p_n)\right)$
  - V(i) could also be normalized to A_{sin}

$$\Rightarrow V(i) = -\cos(\frac{\pi\cdot\sum h(i)}{N_t}) + \sin\left(\frac{\pi}{2}\cdot(\frac{N_p - N_n}{N_t})\right)$$

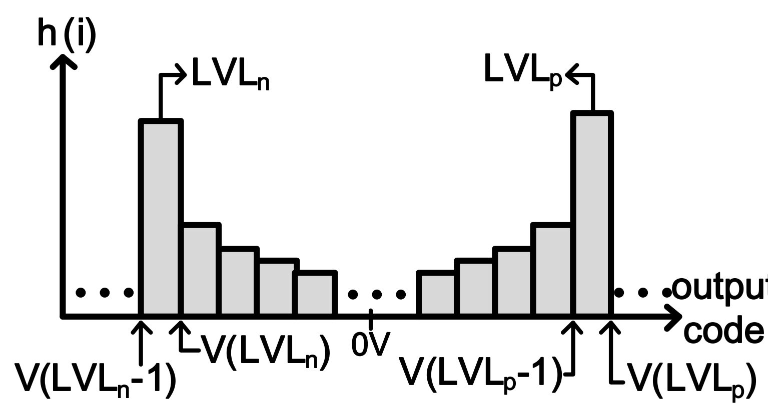
Illustration of Relationship between Threshold Voltage and Output Code

- Presentation of threshold voltage $V(i)$ with a 4-bit example
  - $V(i) = -\cos(\frac{\pi h(i)}{N_t})$
  - Input-output transfer curve



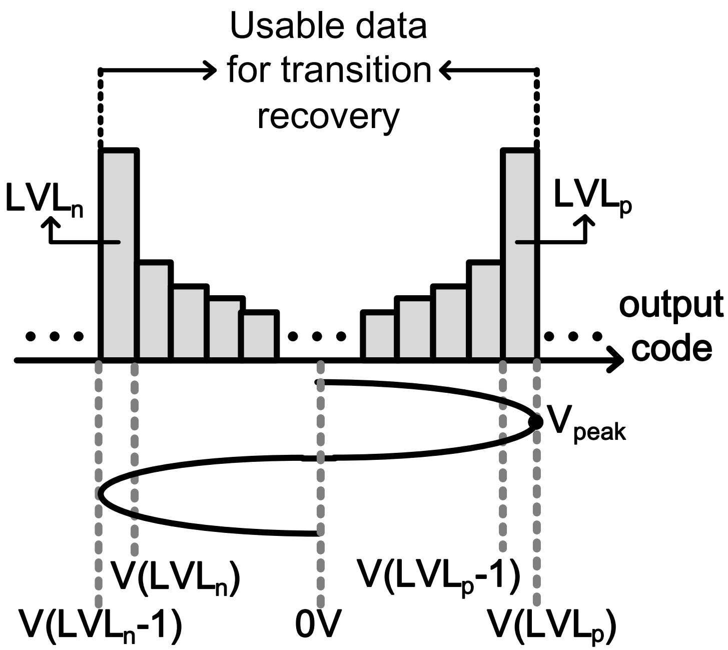


- Definition of LVL_n and LVL_p
  - LVL_n: the output level with max. h(i) value in negative voltage
  - LVL_p: the output level with max. h(i) value in positive voltage



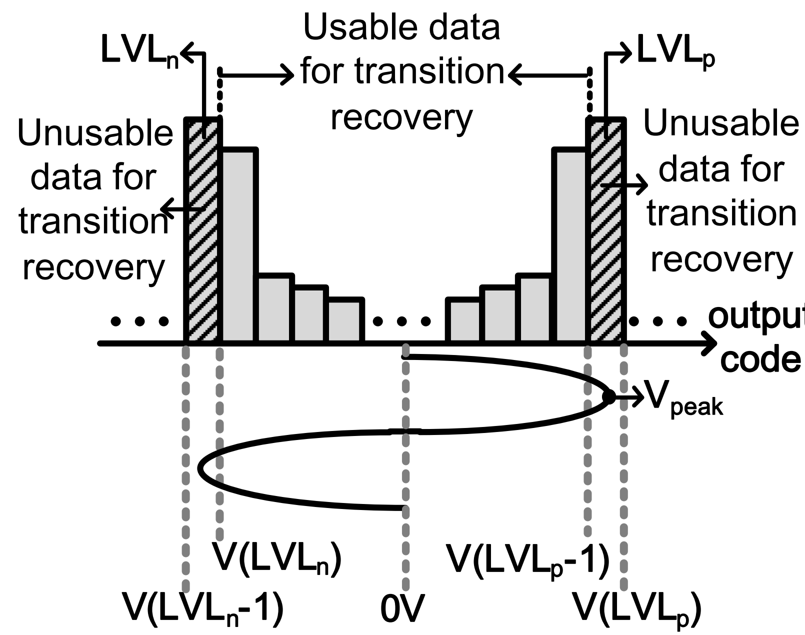
The Influence of Input Amplitude to Histogram

- There are three kinds of conditions under test
  - V_{peak} is equals to $V(LVL_p)$
  - V_{peak} is slightly smaller than $V(LVL_p)$



Usable range:

$V(LVL_n\text{-}1)$~$V(LVL_p)$



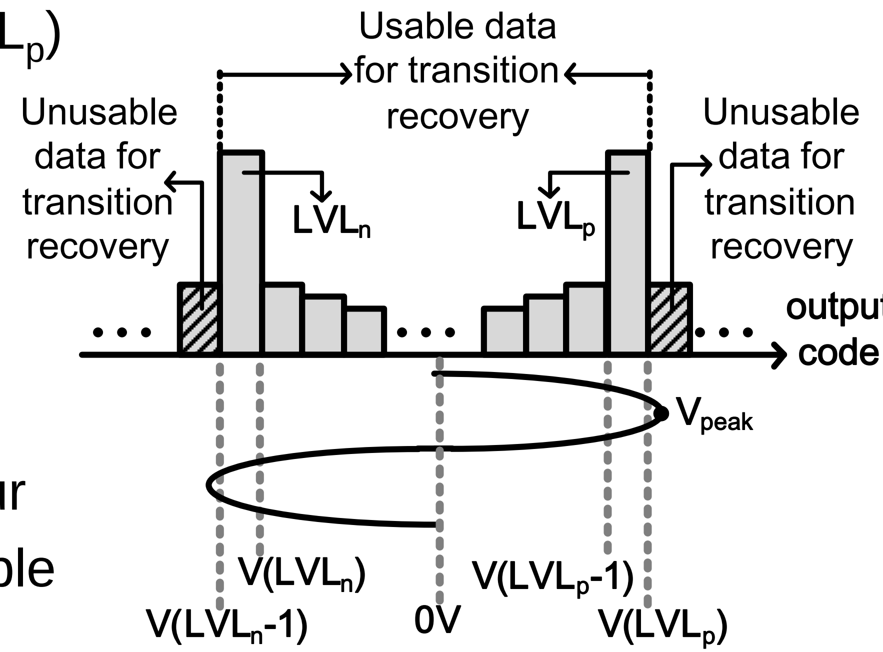
Usable range:

$V(LVL_n)$~$V(LVL_p\text{-}1)$

The Influence of Input Amplitude to Histogram (Cont.)

- V_{peak} is slightly larger than $V(LVL_p)$

Usable range:
$V(LVL_n\text{-}1)$~$V(LVL_p)$



- Because the above conditions occur randomly, we need to take the usable data in the range from $V(LVL_n)$ to $V(LVL_p\text{-}1)$ in order to recover the correct transitions

- DNL of unused codes are set to zero
  - DNL(0)=DNL(1)=···=DNL(LVL_n)=0
  - DNL(LVL_p)=DNL(LVL_p+1)=···=DNL(2^{bit}-1)=0

Calculation of DNL and INL

- Recovery of the real transitions from normalized transitions
  - Find the LVL_n and LVL_p
  - Create the transitions normalized to A_{sin}

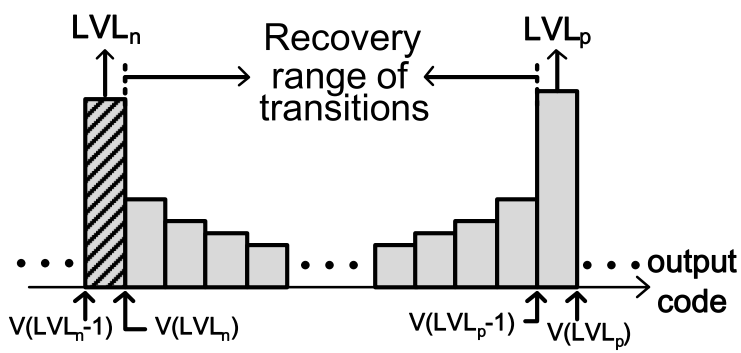
$$V(i) = -\cos\left(\frac{\pi \cdot \sum h(i)}{N_t}\right) + V_{offset} = -\cos\left(\frac{\pi \cdot \sum h(i)}{N_t}\right) + \sin\left(\frac{\pi}{2} \cdot \left(\frac{N_p - N_n}{N_t}\right)\right)$$

  - Recover the normalized transitions to real voltage

$$V_{real}(i) = \frac{\text{Difference between } V(LVL_p\text{-}1) \text{ and } V(LVL_n) \text{ for real transitions}}{\text{Difference between } V(LVL_p\text{-}1) \text{ and } V(LVL_n) \text{ for normalized transitions}} \cdot V(i)$$

$$= \frac{(LVL_p - LVL_n - 2) \cdot V_{LSB}}{V(LVL_p - 1) - V(LVL_n)} \cdot V(i)$$

➔The transitions from $V(LVL_n)$ to $V(LVL_p\text{-}1)$ are recovered

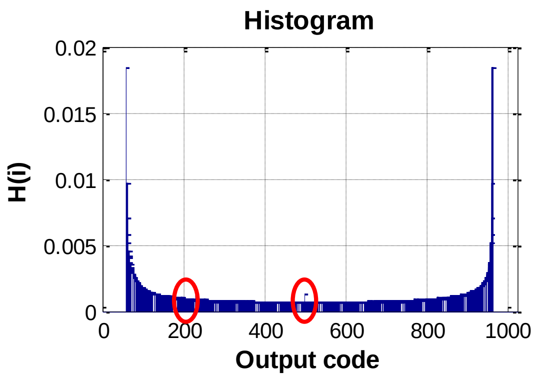


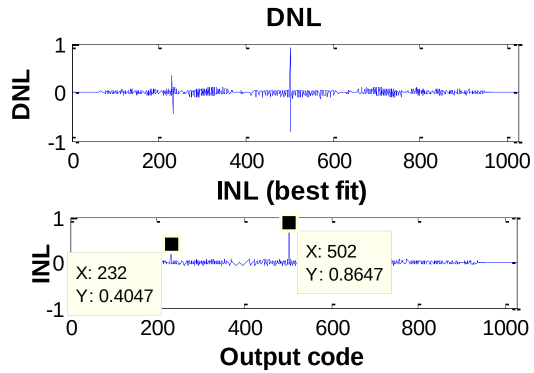
Calculation of DNL and INL (Cont.)

- DNL and INL can be calculated with recovered transitions
  - $DNL(i) = V_{real}(i) - V_{real}(i-1)$, which $i = (LVL_n + 1) \sim (LVL_p - 1)$
  - Based on previous assumption, DNL of unused code are set to zero
    - $DNL(0)=DNL(1)=\ldots=DNL(LVL_n)=0$
    - $DNL(LVL_p)=DNL(LVL_p+1)=\ldots=DNL(2^{bit}-1)=0$
  - $INL(i) = \sum_{k=0}^{i} DNL(k)$, which $i = 0 \sim (2^{bit} - 1)$

Verification of MATLAB Code for Static Testing

- Artificial non-ideal ADC with given DNL
  - Set DNL(500)=0.8, DNL(501)=-0.8, DNL(230)=0.4, DNL(231)=-0.4





10bits
V_{ref}=1.7V
A_{input}=1.5V
$N_t=2^{16}$

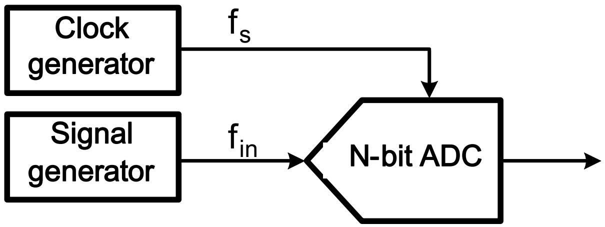
- Comparison between different conditions

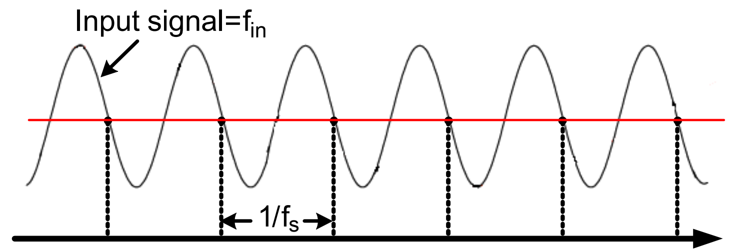
	DNL(500)	DNL(501)	DNL(230)	DNL(231)
All DNL(i)=0	0	0	0	0
Verification results	0.04	0.04	-0.051	-0.049
Given DNL(i)	0.8	-0.8	0.4	-0.4
Verification results	0.905	-0.83	0.3557	-0.457

- This method is verified in the artificial ADC

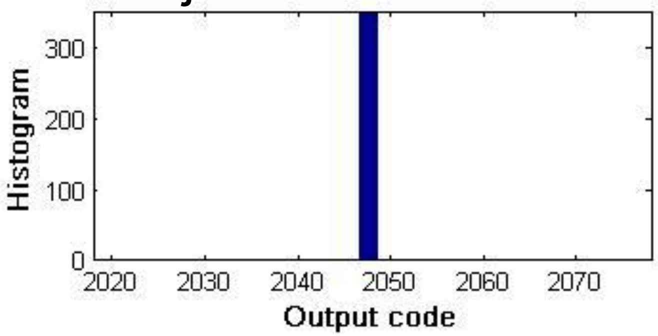
Aperture Uncertainty Measurement

- Locked histogram testing [13]
  - Set f_{in} equals to f_s



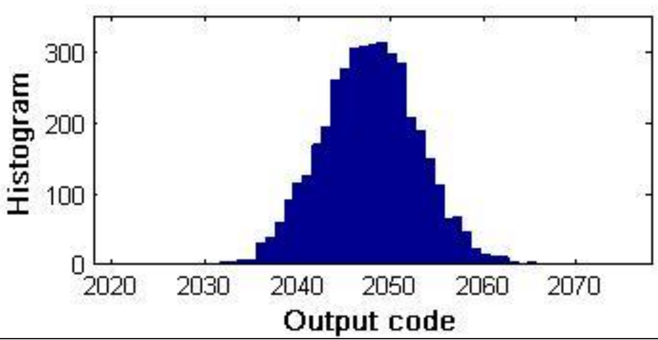


  - Without jitter effect → Hit the same code



12-bit ADC
$f_{in}=f_s=20MHz$
$\sigma_{Jitter}=0ps$

  - With jitter effect → Get σ_{Jitter} from histogram



12-bit ADC
$f_{in}=f_s=20MHz$
$\sigma_{Jitter}=20ps$

Limitation of Number of Sampling Points

- Number of sample points (N_t)
  - $$N_t \geq \frac{Z_{\alpha/2}{}^2 \cdot \pi \cdot 2^{N-1}}{\beta^2}$$
    - N : Number of bit
    - β : DNL resolution in LSB
    - $Z_{\alpha/2}$: Number of standard deviations from the mean values
  - Calculated DNL lies in range $(\mu - Z_{\alpha/2} \cdot \sigma, \mu + Z_{\alpha/2} \cdot \sigma)$ with 100(1-α) percent probability, where μ is excepted value ,σ is standard deviation and α is chosen desired confidence level
  - Standard normal distribution table for the given α

α	Confidence(1-α)	$Z_{\alpha/2}$
0.1	90%	1.64
0.05	95%	1.96
0.02	98%	2.33
0.01	99%	2.58

  - Example of a 10-bit ADC with 0.01LSB precision and 99% confidence

$$N_t \geq \frac{2.58^2 \cdot \pi \cdot 2^{10-1}}{0.01^2} = 107067890 \approx 2^{26}$$

Outline

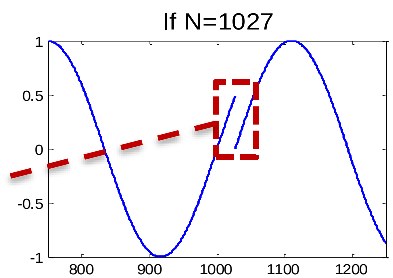
- Introduction of ADC
- Static testing
- Dynamic testing
  - Coherent sampling
  - Introduction of window function
  - Performance metrics of dynamic testing
  - ENOB Calculation
- Measurement example
- Reference

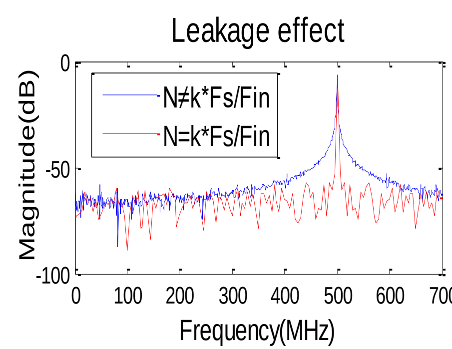
Coherent Sampling

- Relationship between input frequency, sample frequency, number of cycles and number of samples

$$\Rightarrow \frac{f_{in}}{f_s} = \frac{N_{cycles}}{M_{samples}} \begin{cases} f_{in}: \text{input frequency}, N_{cycles}: \text{number of cycles} \\ f_s: \text{sample frequency}, M_{samples}: \text{number of samples} \end{cases}$$

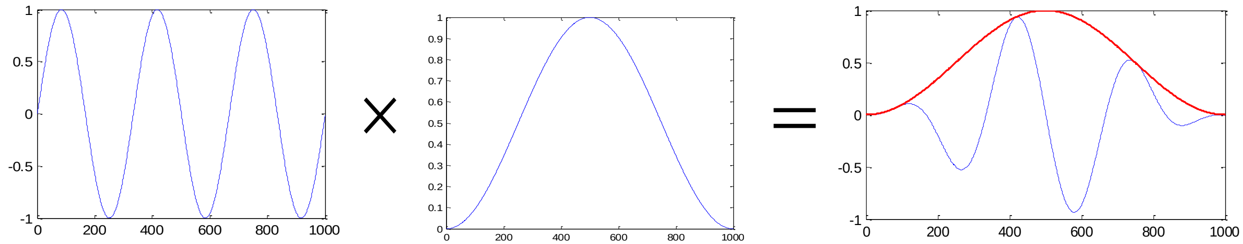
  - Non-coherent sampling
    - N_{cycles} is non-integral
      - In frequency domain → leakage effect
      - In time domain → discontinuity
    - N_{cycles} is integral but N_{cycles} and $M_{samples}$ are not co-prime
      - Discontinuity elimination
      - Periodicity of quantization error





  - Coherent sampling
    - N_{cycles} is prime number
      - Quantization error is not periodic
- Another method of solving discontinuity is applying window

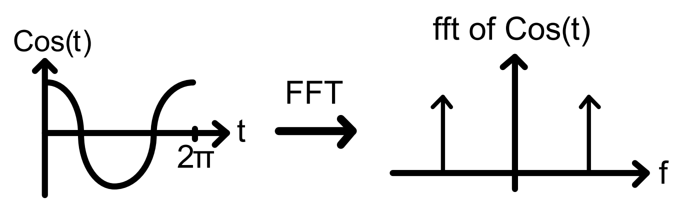
Introduction of Window Function

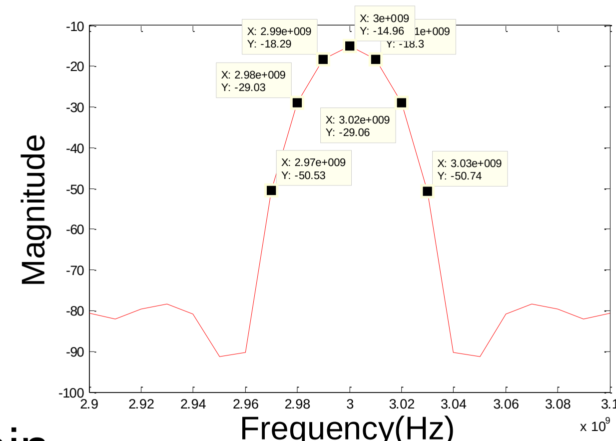
- Applying window to signal
  - 

- Blackman-Harris window (Minimum-4-terms window)
  - $w[n] = a_0 - a_1 \cos(\frac{2\pi n}{N-1}) + a_2 \cos(\frac{4\pi n}{N-1}) - a_3 \cos(\frac{6\pi n}{N-1})$

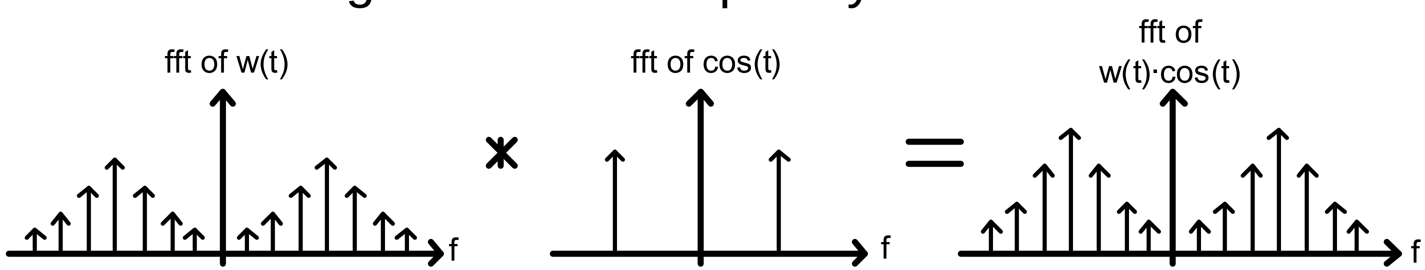
    $a_0 = 0.3588, a_1 = 0.4883, a_2 = 0.1413, a_3 = 0.0117$

  - $\cos(x) = \frac{e^{jx} + e^{-jx}}{2}$





  - Effect of adding window in frequency domain



Performance Metrics of Dynamic Testing

- SNR(Signal-to-Noise Ratio)

$$SNR = 10 \cdot \log_{10}\left(\frac{P_{signal}}{P_{noise}}\right)$$

- SNDR(Signal-to-Noise and Distortion Ratio)

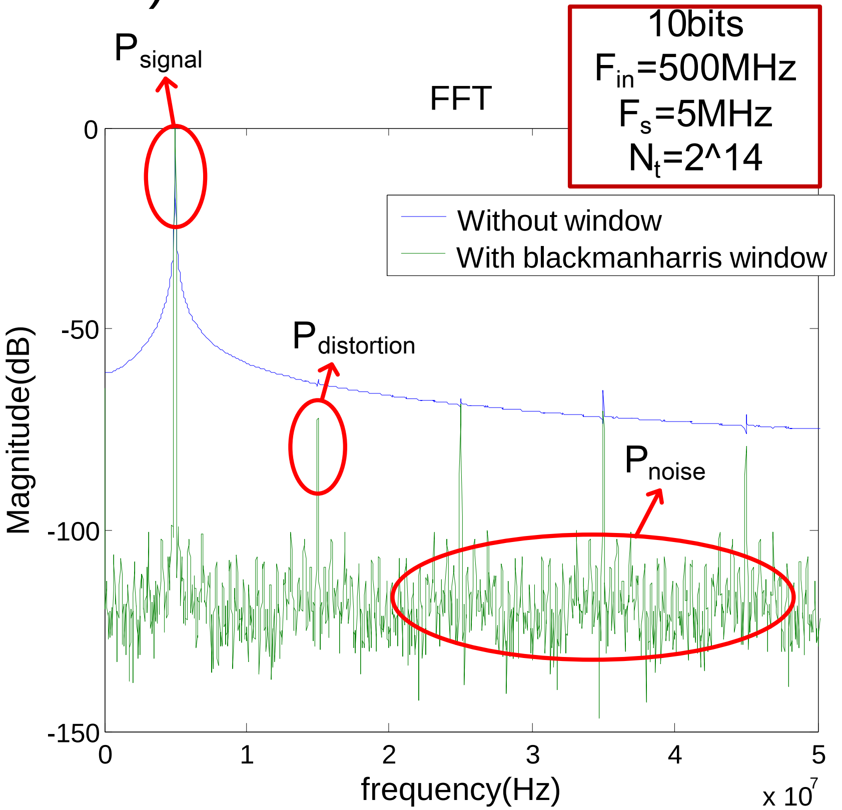
$$SNDR = 10 \cdot \log_{10}\left(\frac{P_{signal}}{P_{noise} + P_{distrotion}}\right)$$

- Total Harmonic Distortion + Noise

$$THD + N = \left(\frac{P_{noise} + P_{distrotion}}{P_{signal}}\right) \times 100\%$$

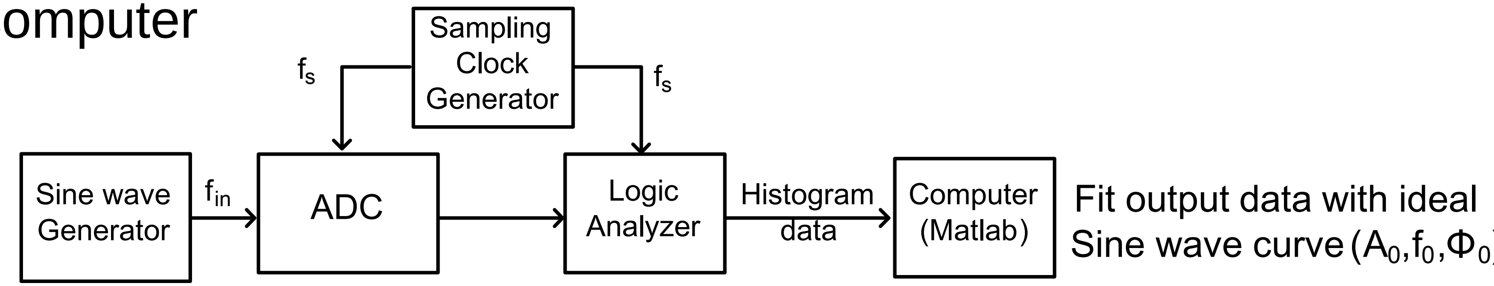
- Spurious-Free Dynamic Range

$$SFDR = 10 \cdot \log_{10}\left(\frac{P_{signal}}{P_{\max - tone}}\right)$$

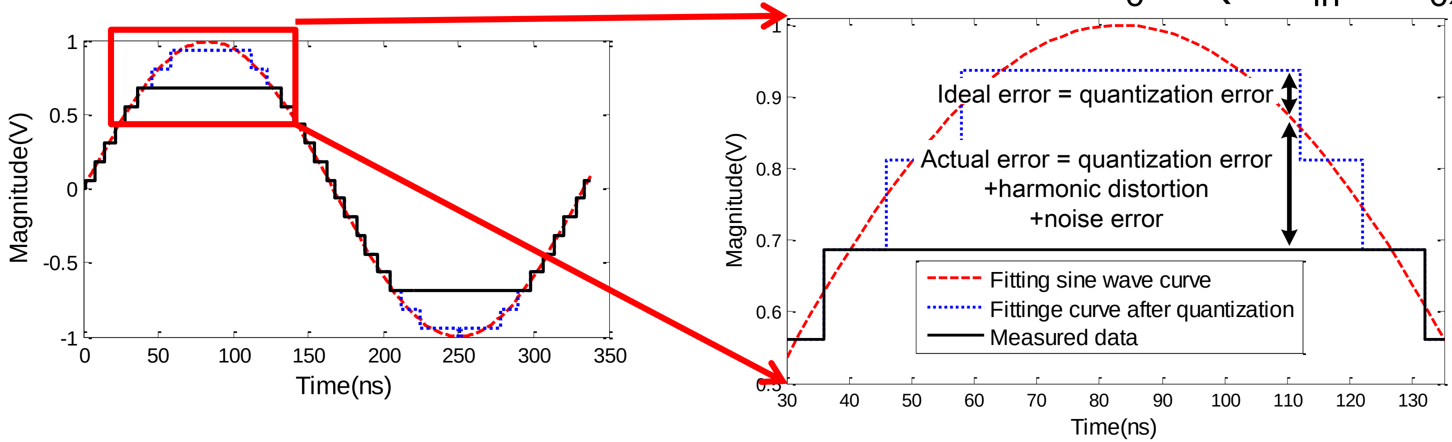


ENOB Calculation

- Two methods for ENOB calculation
  - Sine wave curve fitting [10], [12]
    - Measured data are acquired by logic analyzer and processed by computer



    - Fit the measured data with the sine wave $A_0\sin(2\pi f_{in}t+\Phi_0)+V_{os}$



    - $\text{ENOB} = N - \log_2\left(\frac{\text{actual rms error}}{\text{ideal rms error}}\right)$; $\text{ideal rms error} = \frac{V_{LSB}}{\sqrt{12}}$

ENOB Calculation(Cont.)

- Relationship between SNDR and ENOB [1]
  - With full-scale input

$$\mathrm{ENOB} = \frac{\mathrm{SNDR} - 1.76}{6.02} \, (\mathrm{bit})$$

  - Without full-scale input

$$\mathrm{ENOB} = \frac{\mathrm{SNDR} - 1.76 + \Delta x}{6.02} \, (\mathrm{bit})$$

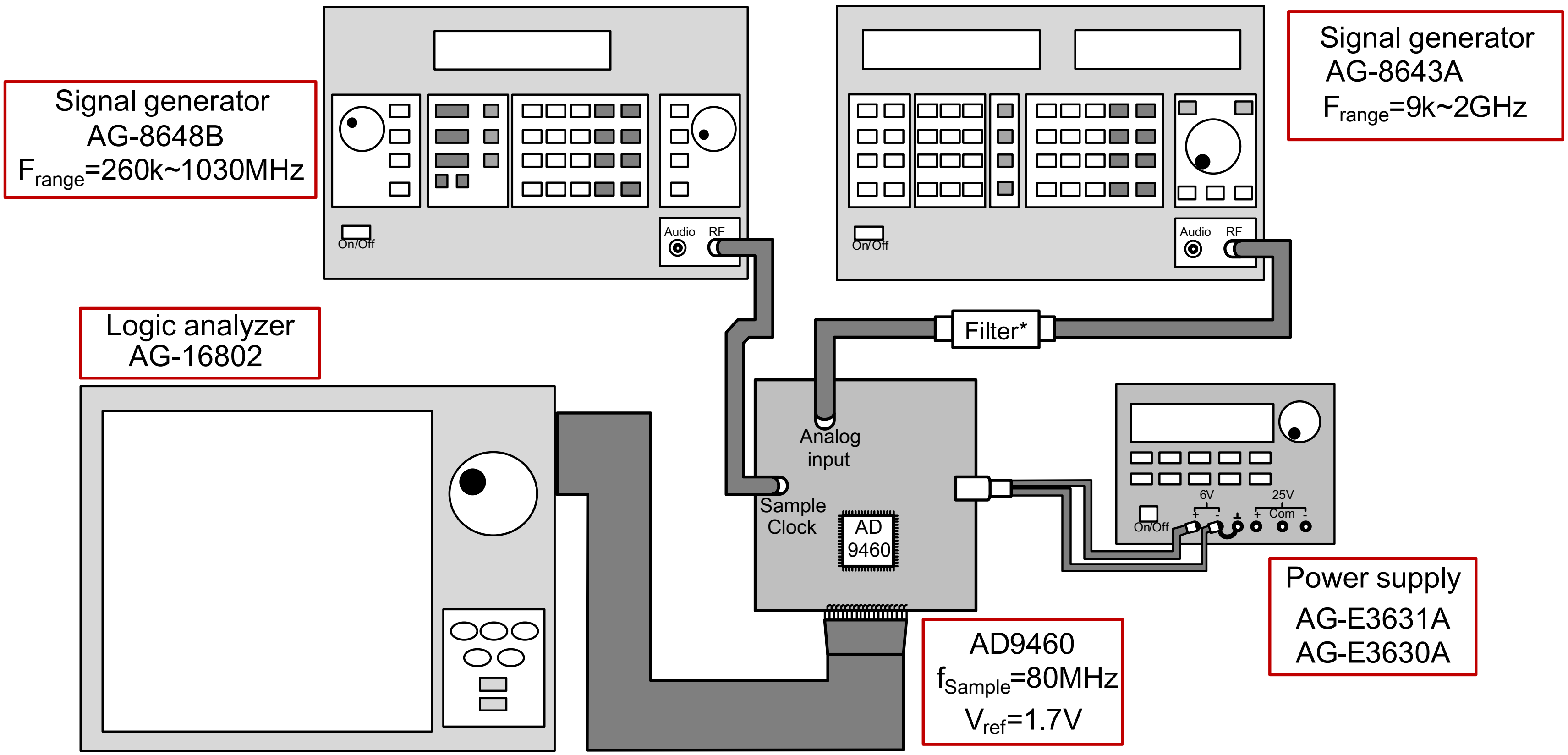
$$\Delta x \approx \text{Level of signal below full-scale(dB)}$$

Outline

- Introduction of ADC
- Static testing
- Dynamic testing
- Measurement example
  - Setup of ADC measurement
  - Static testing
    - Relationship between DNL and number of sample points
    - Mismatch between A_{in} and A_{sin}
    - Comparison of static performance
- Reference

ADC Measurement Setup

- ADC measurement setup



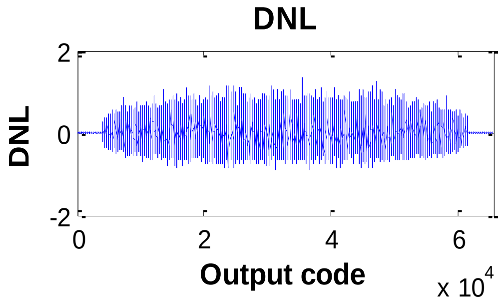
- *Filter
  - ◆ Low pass filter:TTE-LC7-10M-LPF
  - ◆ Band pass filter: K&L-5M-BPF

Relationship between DNL and Number of Sample Point

- 16-bit ADC with f_{clock}=80MHz, A_{clock}=1.5V_{p-p}, f_{in}=9.41MHz, A_{in}=3.03V_{p-p}
  - Assume DNL lie in range $(\mu - Z_{\alpha/2}\sigma, \mu + Z_{\alpha/2}\sigma)$ with 95% probability

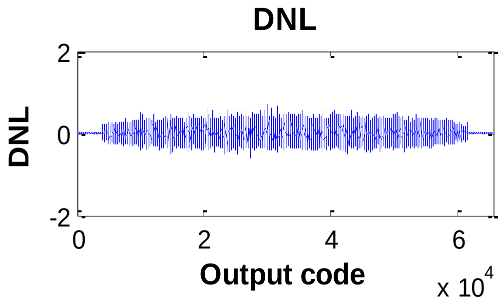
$$\text{DNL resolution}, \beta \geq \sqrt{\frac{Z_{\alpha/2}^{\ 2} \cdot \pi \cdot 2^{N-1}}{N_t}}$$

  - The limitation of logic analyzer
    - The max. number of output data is 2^{20}
    - To get larger N_t, output data should be exported for many times
  - $N_t=2^{20}$(β=0.614 LSB)



(DNL⁺,DNL⁻) =(1.323,-0.92) (LSB)

  - $N_t=2^{22}$ (β=0.307 LSB)

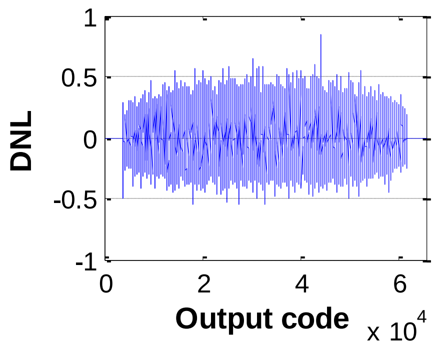


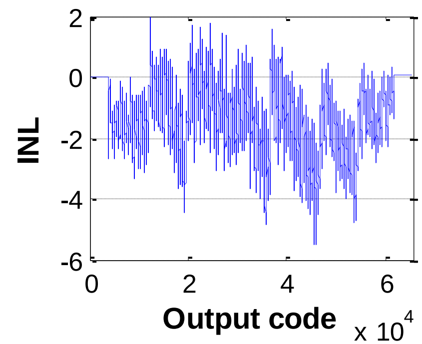
(DNL⁺,DNL⁻) =(0.698,-0.597) (LSB)

➔ Higher N_t would get more accuracy of static testing

Mismatch between A_{in} and A_{sin}

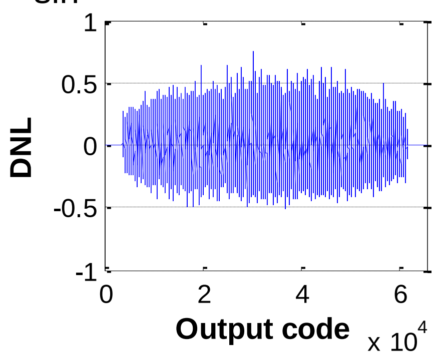
- A_{in}: actual signal amplitude generated from signal generator
  A_{sin}: estimated amplitude for theoretical value in eq.(2)
- Using $V_i = -A_{sin} \cdot \cos(\pi \sum h(i) / N_t)$ to calculate DNL and INL
  A_{clock}=1.65$V_{p\text{-}p}$, f_{clock}=80MHz,A_{sin}=1.50743V, f_{in}=5MHz ,using K&L-5M-BPF
  - ◆ A_{sin} matches to A_{in} $\Rightarrow$ $A_{in} \approx A_{sin}$=1.50743 V

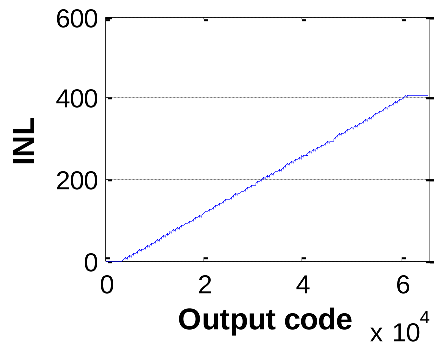




DNL$^+$= 0.847 LSB
DNL$^-$ =-0.551 LSB
INL(2^{16}-1)=0.09 LSB

  - ◆ A_{sin} mismatches to A_{in} $\Rightarrow$ A_{in}=1.497V $\neq$ A_{sin}





DNL$^+$= 0.756 LSB
DNL$^-$ =-0.504 LSB
INL(2^{16}-1)=407 LSB

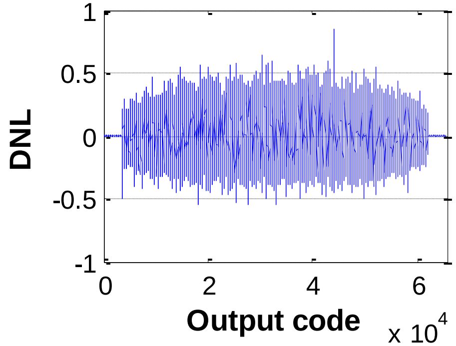
➔ So A_{sin} must be equal to A_{in}

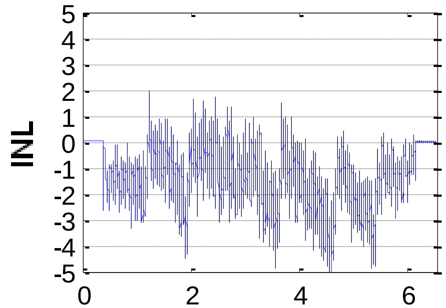
Mismatch between A_{in} and A_{sin} (Cont.)

- Using the method of calculating DNL and INL from P18~P19

  A_{clock}=1.65$V_{p\text{-}p}$, f_{clock}=80MHz,A_{sin}=1.50743V, f_{in}=5MHz,using K&L-5M-BPF

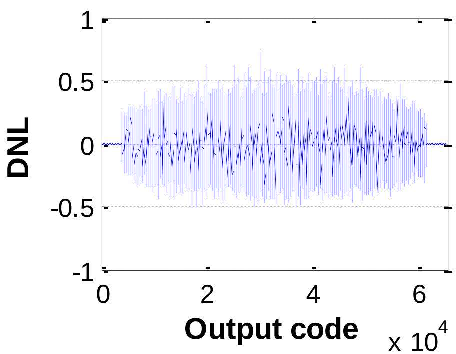
  - A_{sin} matches to A_{in} $\Rightarrow$ $A_{in} \approx A_{sin}$=1.507425 V

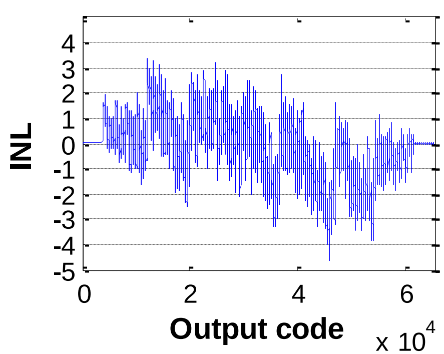




DNL⁺= 0.847 LSB
DNL⁻=-0.551 LSB
INL(2^{16}-1)=0 LSB

  - A_{sin} mismatches to A_{in} $\Rightarrow$ A_{in}=1.497V $\neq$ A_{sin}





DNL⁺= 0.743 LSB
DNL⁻=-0.507 LSB
INL(2^{16}-1)=0 LSB

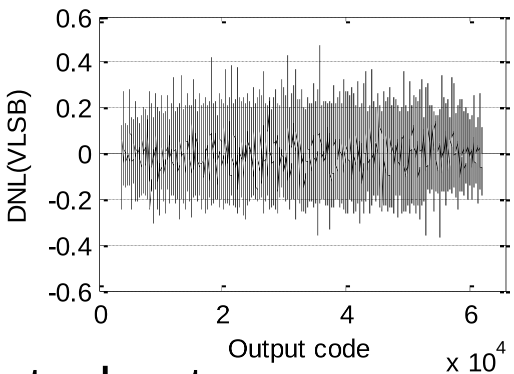
➔ Adopting this method, A_{sin} mustn't be equal to A_{in}

Comparison of Static Performance

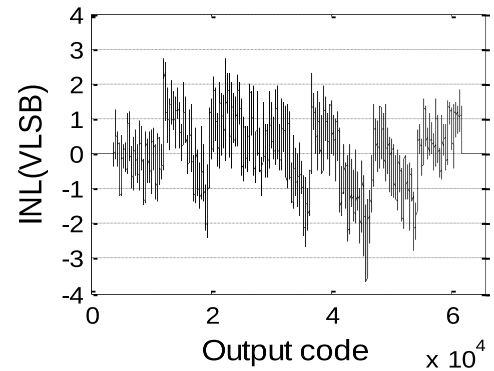
- Measured data

Conditions $\begin{cases} A_{clock}=1.65V_{p\text{-}p},\ f_{clock}=80\text{MHz},\ A_{in}=3.03V_{p\text{-}p},\ f_{in}=5\text{MHz} \\ \text{using 5M-BPF},\ N_t=2^{24} \end{cases}$

◆ DNL



◆ INL

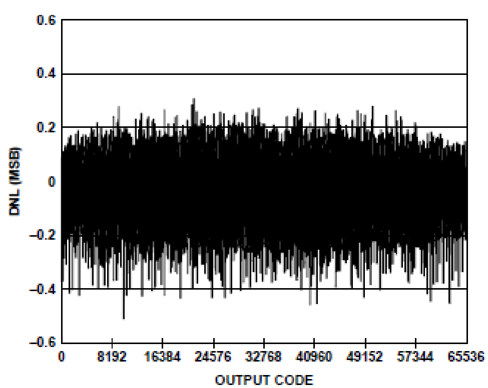


◆ Performance summary

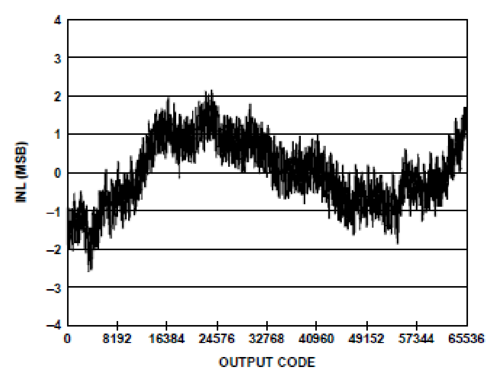
DNL^{+}=0.471 LSB
DNL^{-}=-0.367 LSB
INL^{+}=2.6 LSB
INL^{-}=-3.62 LSB

- Datasheet

◆ DNL



◆ INL



◆ Performance summary

DNL^{+}=0.3 LSB
DNL^{-}=-0.5 LSB
INL^{+}=2.1 LSB
INL^{-}=-2.5 LSB

Outline

- Introduction of ADC
- Static testing
- Dynamic testing
- Measurement example
- Reference

Reference

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