Code Selective Histogram Method: Two-Tone Signal for ADC Linearity Test Time Reduction

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Outline

- **Background and Objective**
- **ADC Test with Histogram Method**
- **Sine Wave Histogram and Waveform Missing**
- **Combine Multiple Sine Waves**
- **General Two-Tone Input Signal Configuration**
- **Conclusion**

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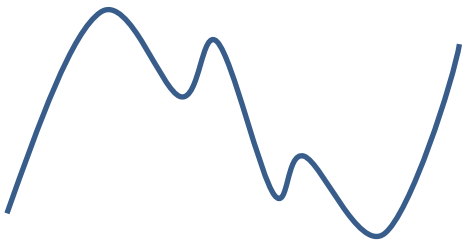
Background

IoT era is coming !

ADC is a key component

◆ Analog signal



Sampling

A/D Conversion

◆ Digital signal

01010101110
10101010111
11101101010

High quality & Low cost ADC test is required

Research Objective & Approach

SAR ADC linearity test takes a long time

- low-speed sampling
- high-resolution

Test cost ⇒ Proportional to test time

This Work

ADC linearity test with histogram method:
Investigation of ″high efficiency relationship″ between input and sampling frequencies

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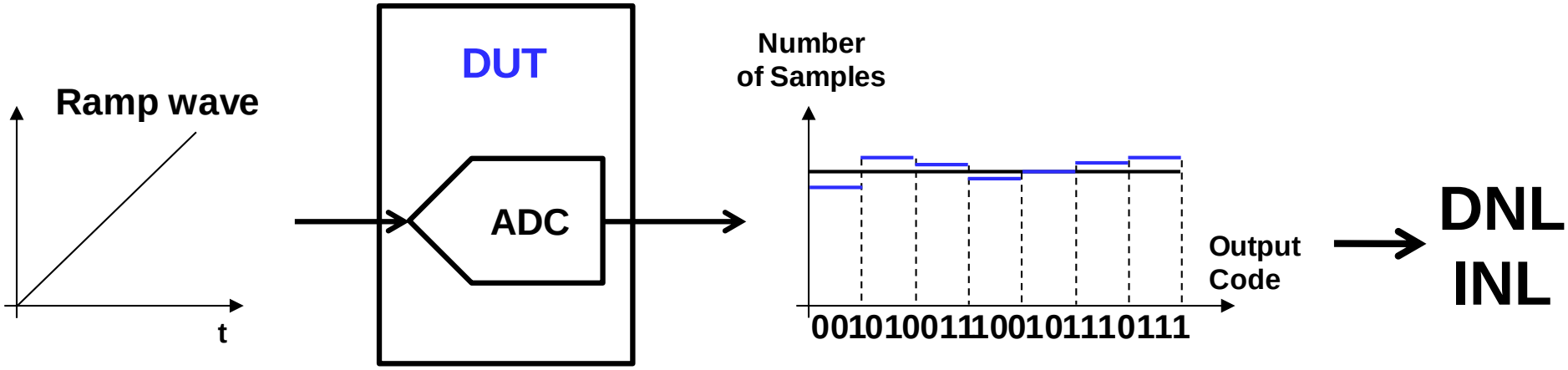
Conventional Linearity Testing 1

■ Histogram method (Ramp wave input)



- if ADC is perfectly linear ➡

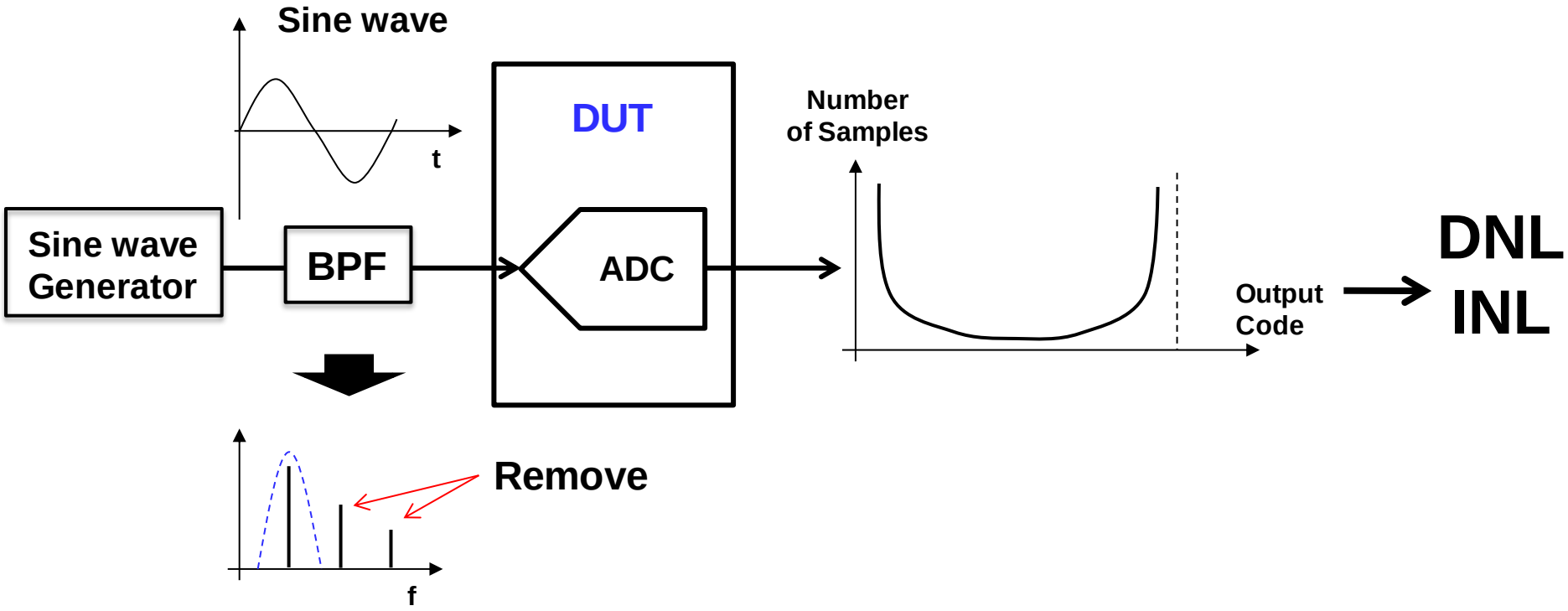
  "ADC output histograms for all bins ➡ Equal"

- Highly linear ramp signal generation ➡ Difficult

  (limitation up to 14-bit ADC)

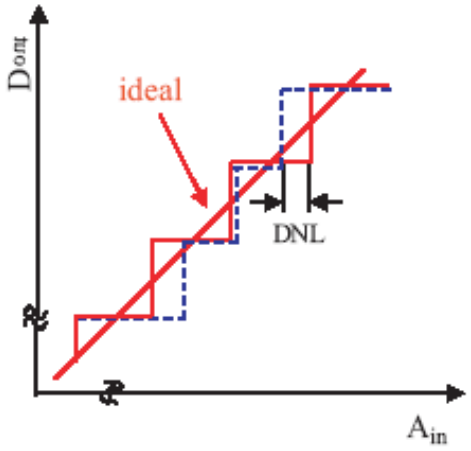
Conventional Linearity Testing 2

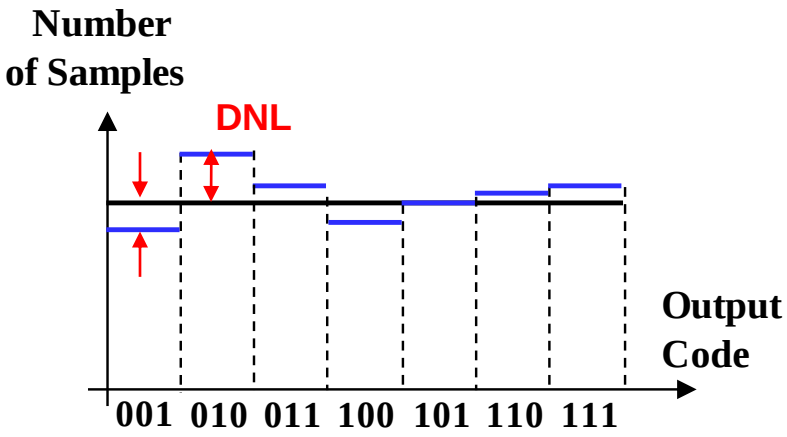
■ Histogram method(Single sine wave input)

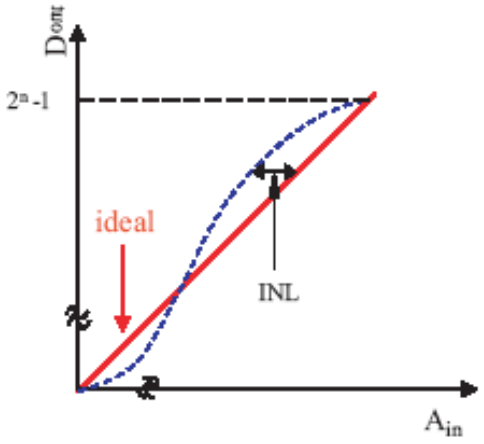


- Low distortion sine using an analog filter
- Number of samples is small around the middle of output range ➡ Many samples required (long test time)

DNL & INL







- Important ADC testing items

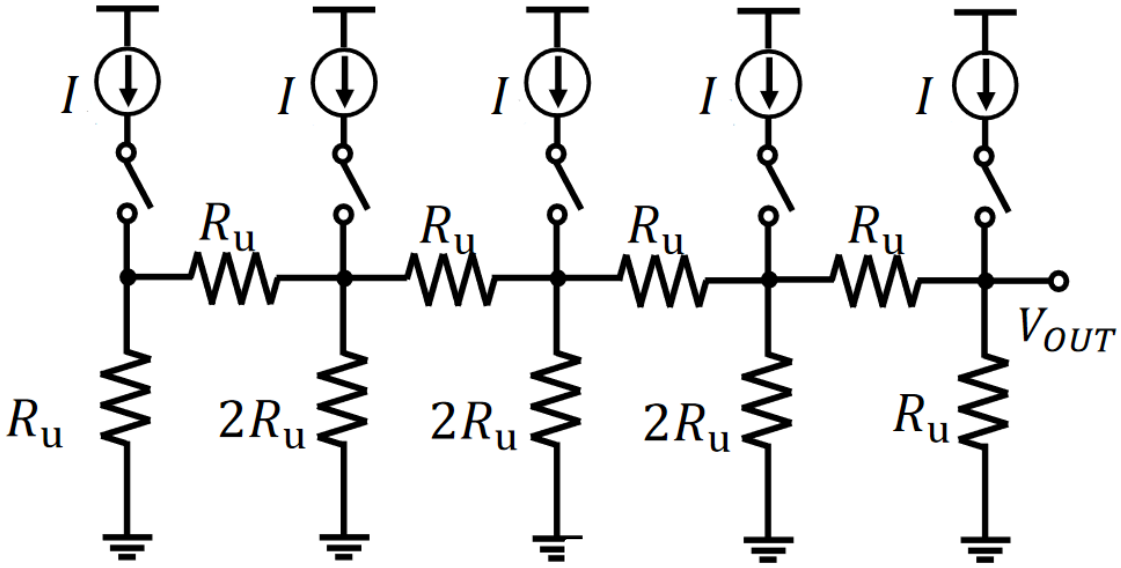
DNL : Difference between
actual step width and ideal value

INL : Deviation from ideal conversion line

$$INL(k) = \sum_{i=1}^{k} DNL(i)$$

DAC Inside ADC

DAC linearity inside ADC ⇨ Entire ADC linearity



R-2R ladder network DAC.

Target SAR ADC under test ⇨ Binary-weighted DAC inside.

In 10-bit case, large DNL ⇨
At digital codes of 512, 256, 768, 128, 384, 640, 896, …

ADC Codes Prone to Non-linearity

Increase the number of histogram points in these codes.
→ Measure DNL with high accuracy.

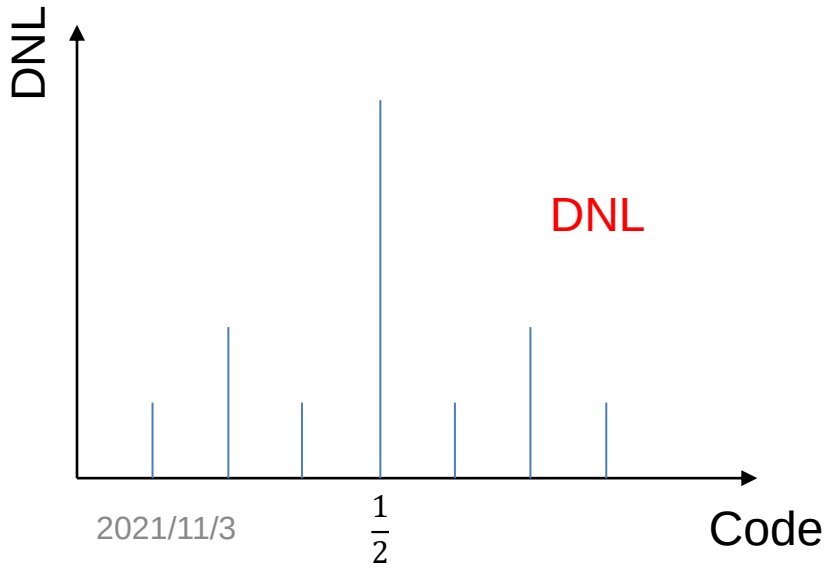
All codes of ADC digital output during testing.

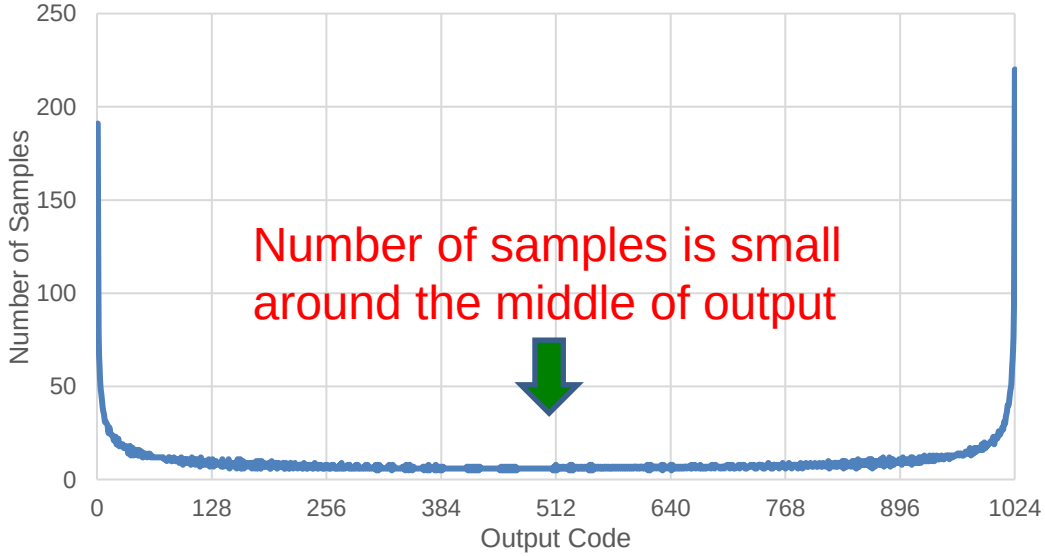
↓ Change

Focus on specific codes prone to non-linearity.

↓

Test time can be shortened.





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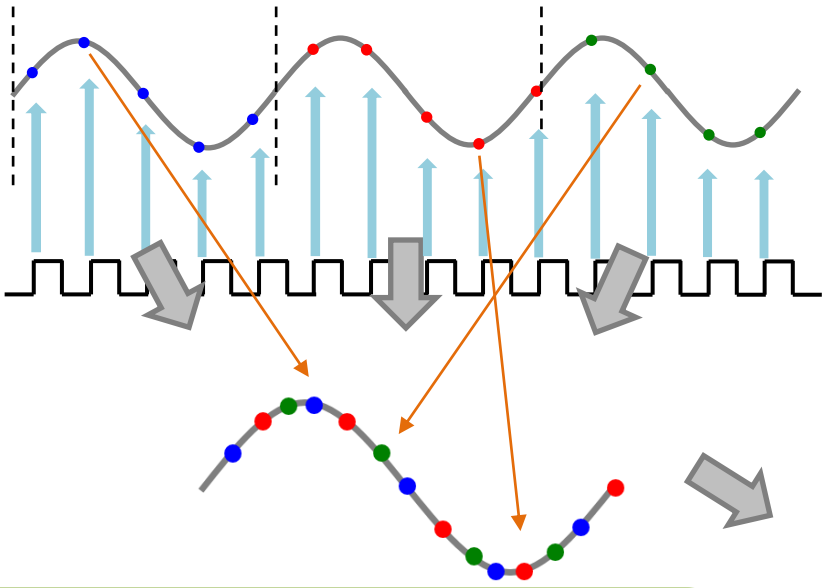
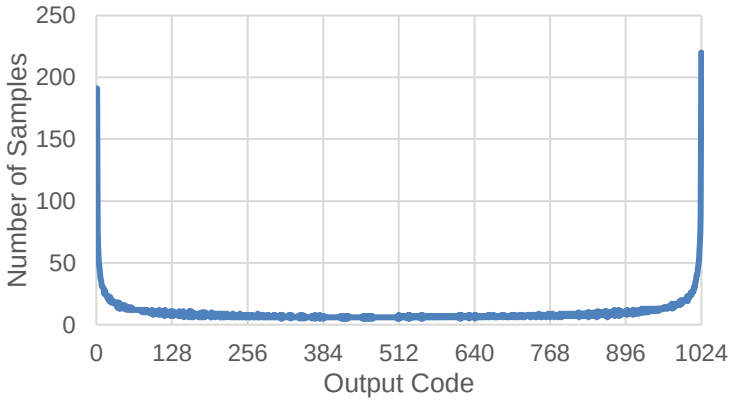
Sine Wave Histogram



- Sampled histogram is compared with PDF.
- Histogram is obtained. - DNL , INL are calculated.

PDF:
Probability Distribution Function

$$p_{(v)} = \frac{1}{\pi\sqrt{A^2 - v^2}}$$



Repetitive waveform sampled asynchronously

↓

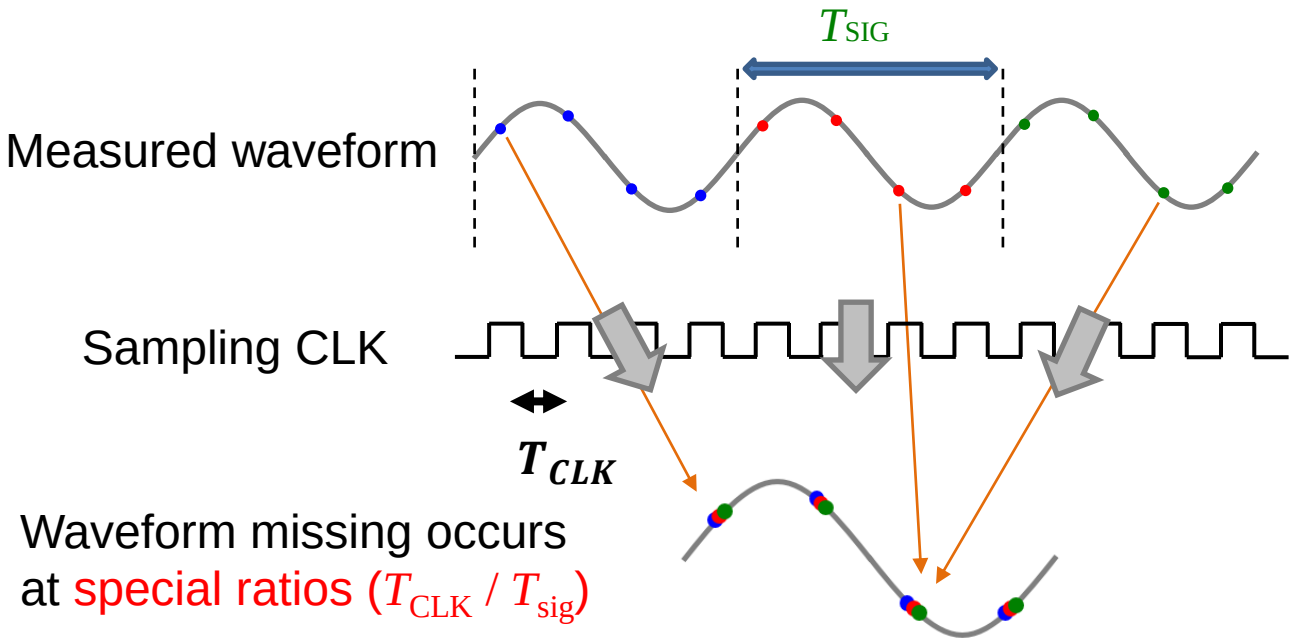
Reconstruct a 1-period waveform

Waveform Missing Phenomena

Repetitive waveform sampled asynchronously

⇩

Reconstruct a 1-period waveform

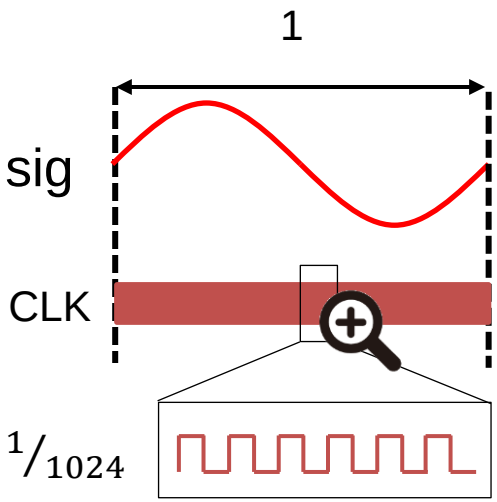


Waveform missing occurs
at special ratios (T_{CLK} / T_{sig})

A large amount of data are required to reconstruct the waveform ⇨ Test time: long

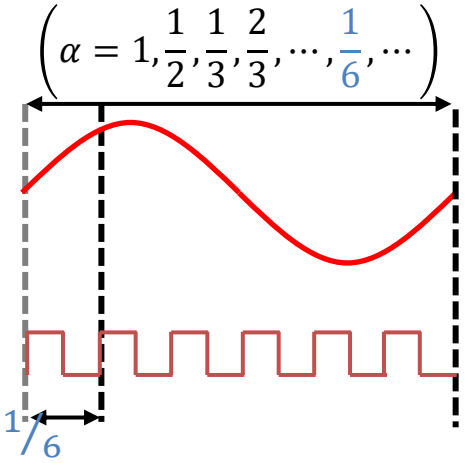
Waveform Missing for Sine Signal

$f_{CLK} \gg f_{sig}$



$f_{CLK} \approx \frac{1}{\alpha} f_{sig}$

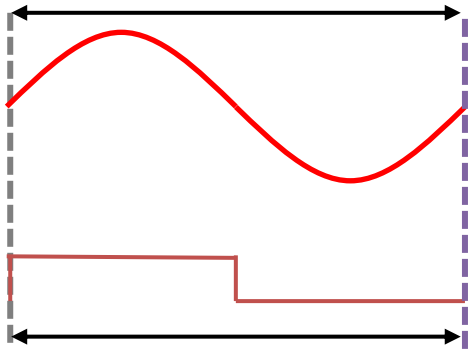
$\left(\alpha = 1, \frac{1}{2}, \frac{1}{3}, \frac{2}{3}, \cdots, \frac{1}{6}, \cdots\right)$

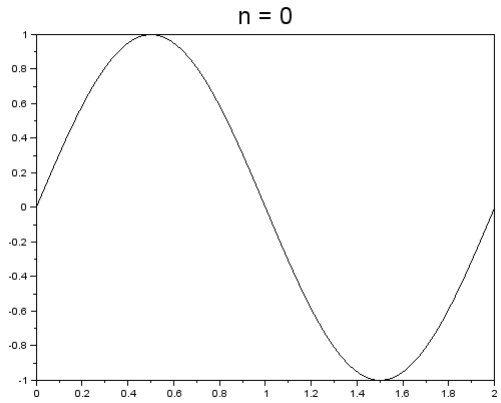


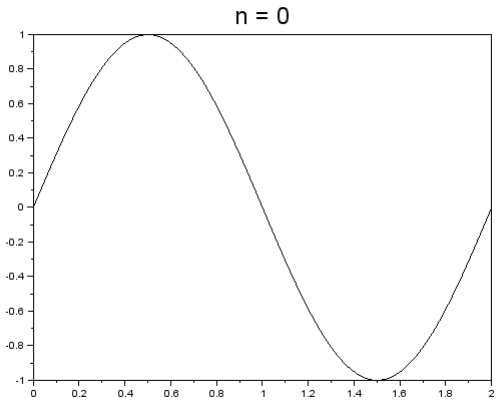
Special ratios

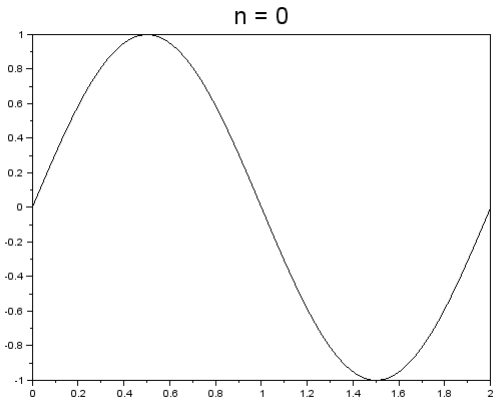
T_{CLK} and T_{sig}, f_{CLK} and f_{sig}

$f_{CLK} \approx f_{sig}$



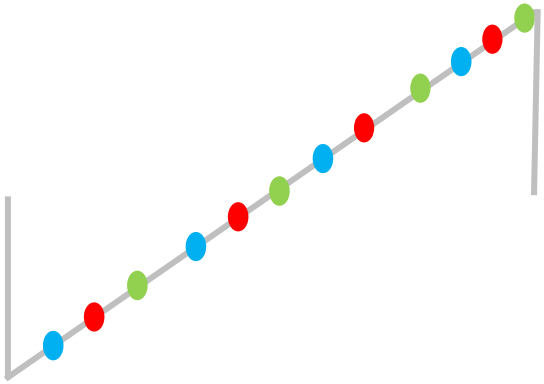


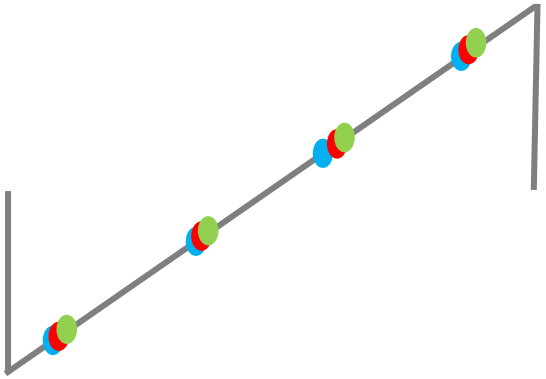




Yuto Sasaki, Yujie Zhao, Anna Kuwana Haruo Kobayashi, "Highly Efficient Waveform Acquisition Condition in Equivalent-Time Sampling System", 27th IEEE Asian Test Symposium, Hefei, Anhui, China (Oct. 2018)

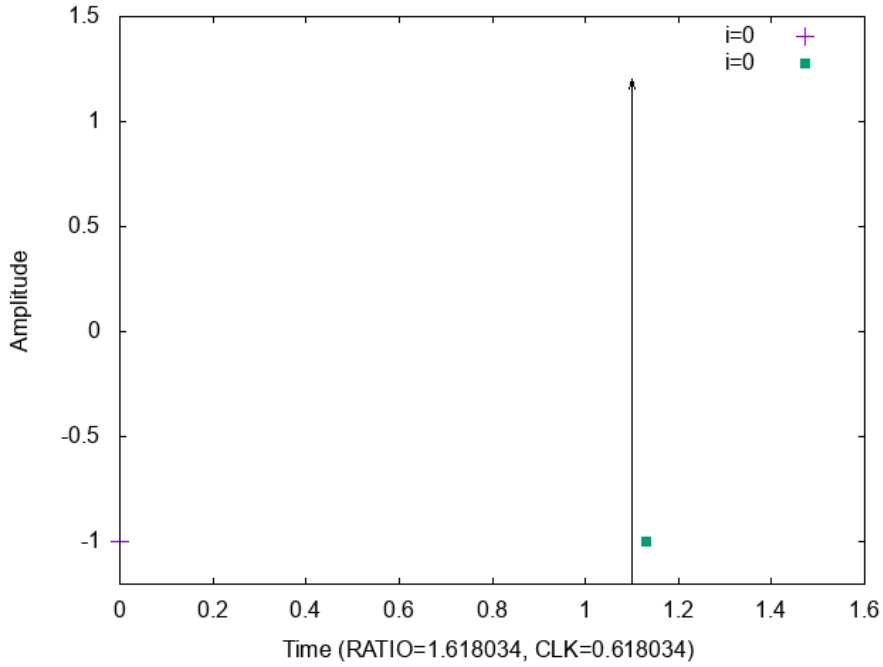
Waveform Missing for Saw Signal

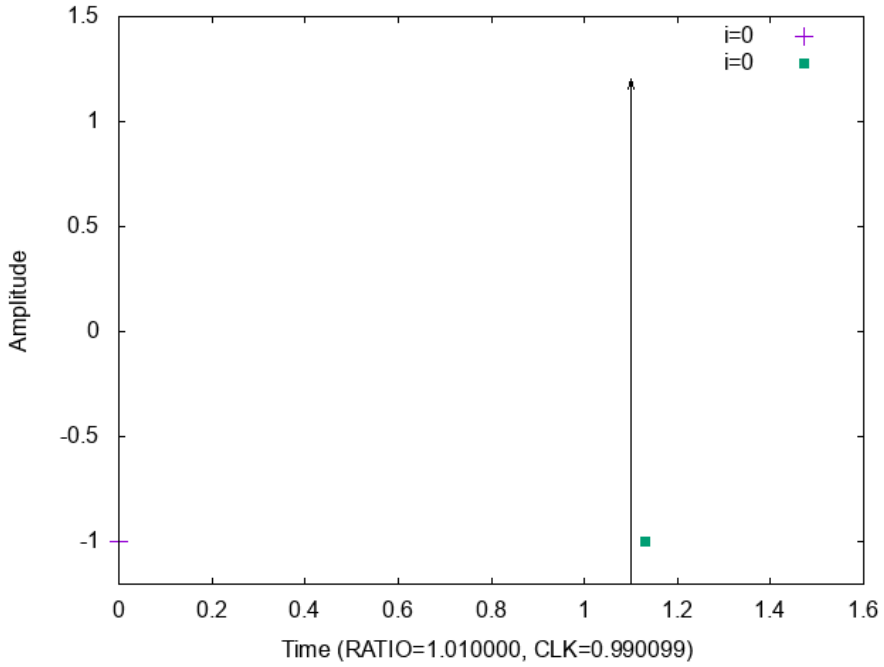




Normal situation

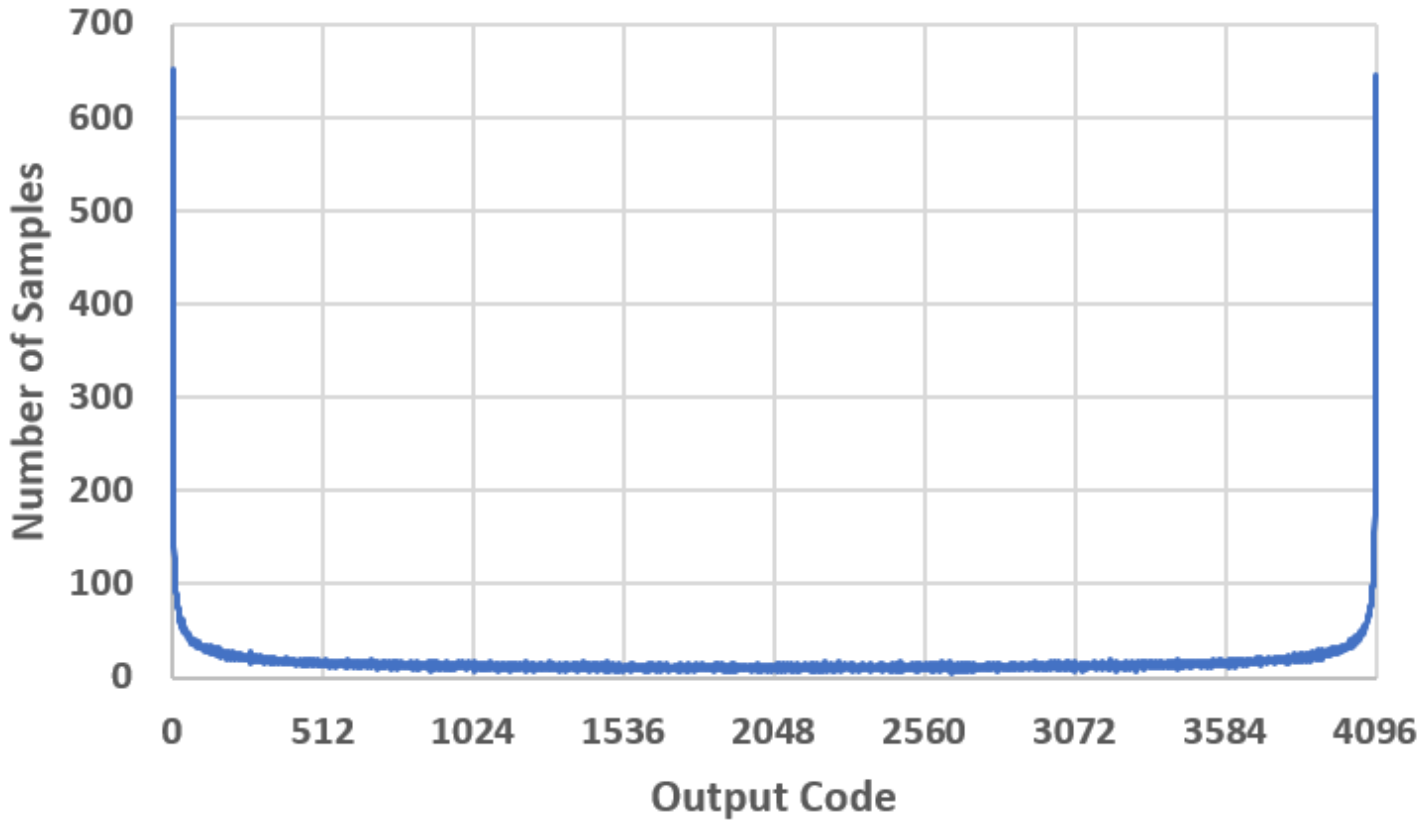
Waveform Missing





Use Waveform Missing

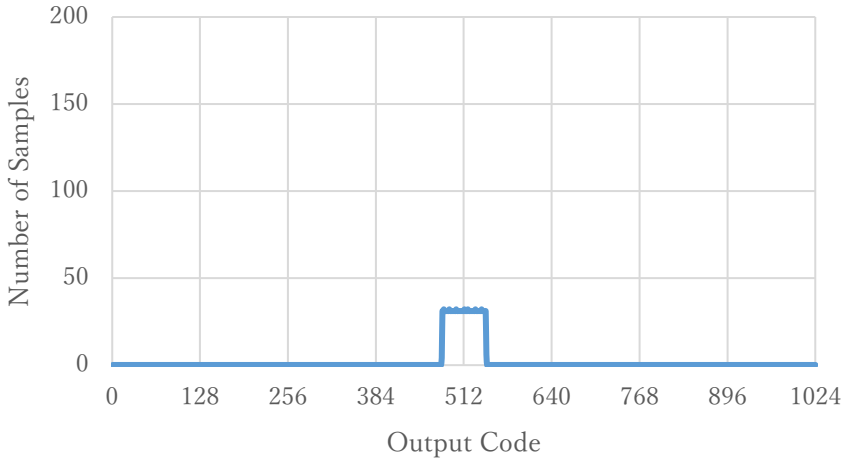
Using waveform missing ⇨ Focus on specific codes

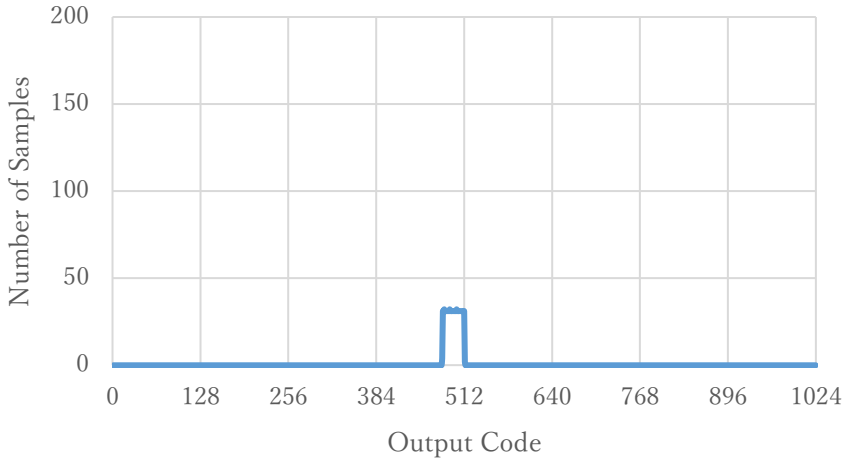


Sine Wave Histogram

Examples of Using Waveform Missing

Histogram can be focused on specific codes:



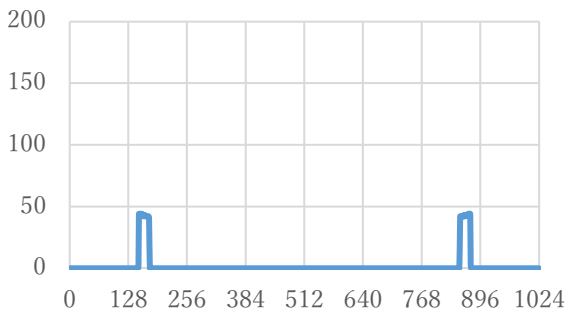
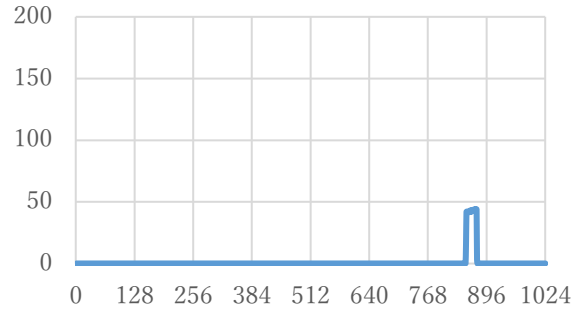
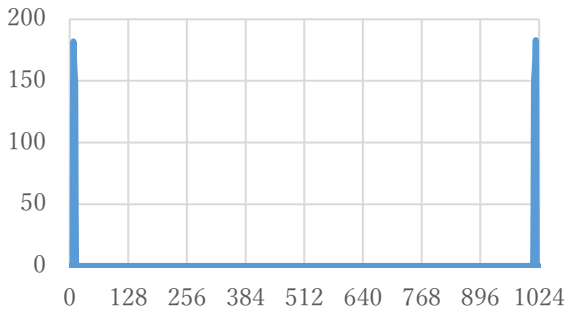
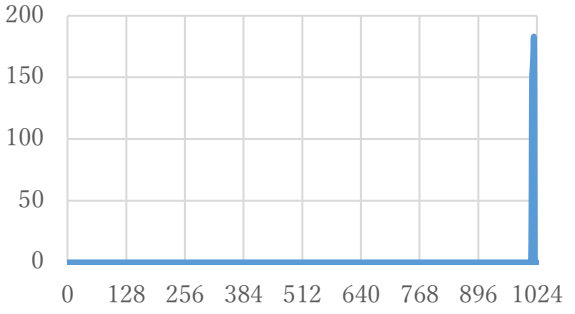


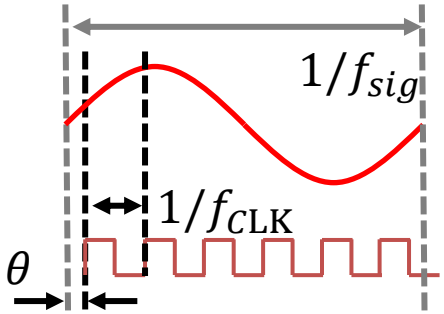
$$f_{CLK} = f_{sig} \times \frac{2 \times (1 + 100000)}{100000}$$

$$f_{CLK} = f_{sig} \times \frac{1 + 100000}{100000}$$

 Relationship of f_{CLK}、f_{sig}、θ(Initial phase of input sine wave)

Problem of Using Waveform Missing

	$f_{CLK} = f_{sig} \times \frac{2 \times (1 + 100000)}{100000}$	$f_{CLK} = f_{sig} \times \frac{1 + 100000}{100000}$
$\theta = \pi/2 \times 0.5$		
$\theta = \pi/2 \times 0.9$		



$f_{CLK} = f_{sig} \times$ ● → Concentration

θ → Position to concentrate

→Can be adjusted

☹ For implementation, free adjust θ ⇨ difficult

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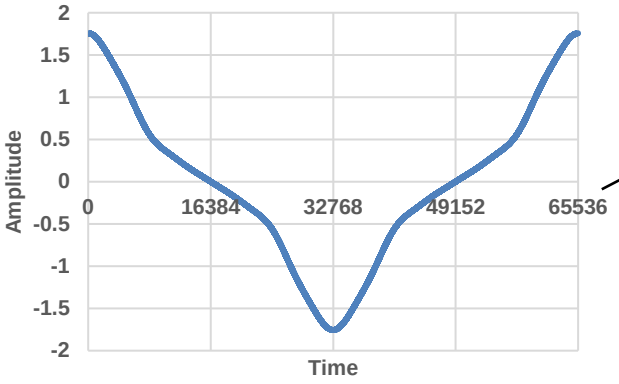
Our Previous Research

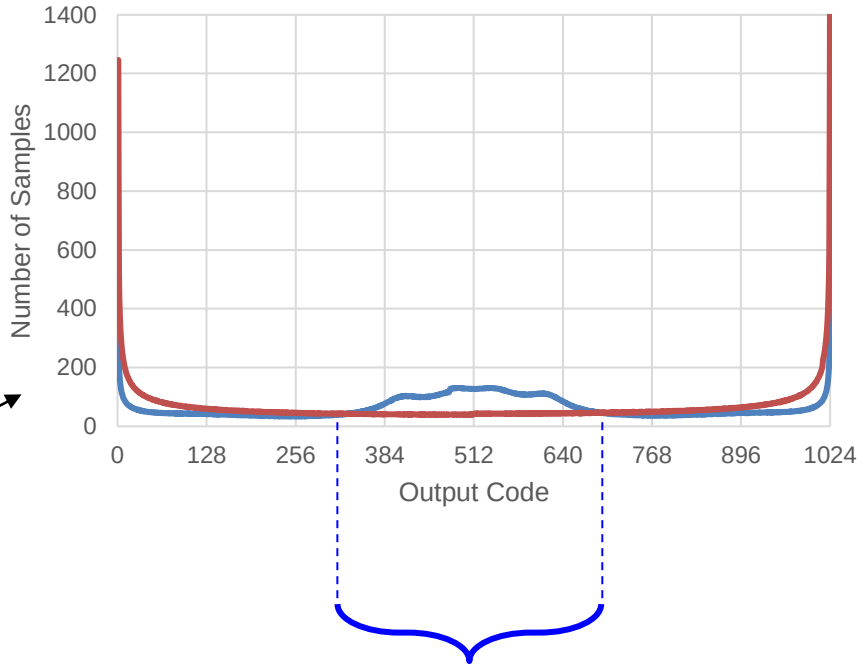
Single sine wave (red)

$$f(t) = \sin \omega t$$

Two-tone signal (blue)



histogram



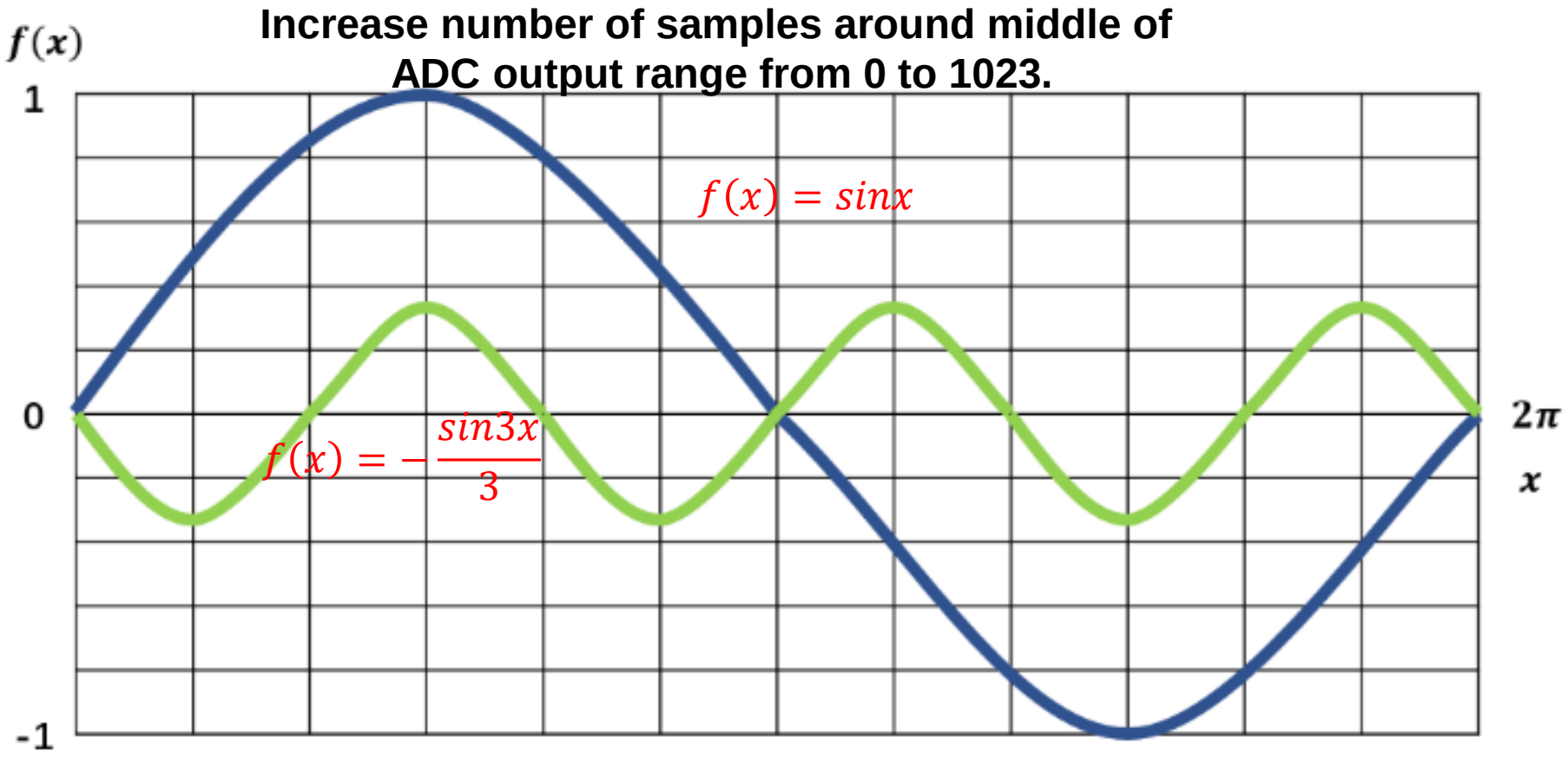
Histogram focused on a specific code

$$f(t) = A(W_1 + 2.6 \cdot W_2 + 1.8 \cdot W_3 + 1.4 \cdot W_6 + 1.2 \cdot W_7) + V_{OS}$$

$$W_m = \frac{\cos((2m-1)\omega t)}{(2m-1)^2} \qquad A = 2.90[V] \qquad V_{OS} = 4.0[V]$$

S. Uemori, T. Yamaguchi, S. Ito, Y. Tan, H. Kobayashi, N. Takai, K. Niitsu, N. Ishikawa,
"ADC linearity test signal generation algorithm", 2010 IEEE Asia Pacific Circuits and Systems Conference (APCCAS) .

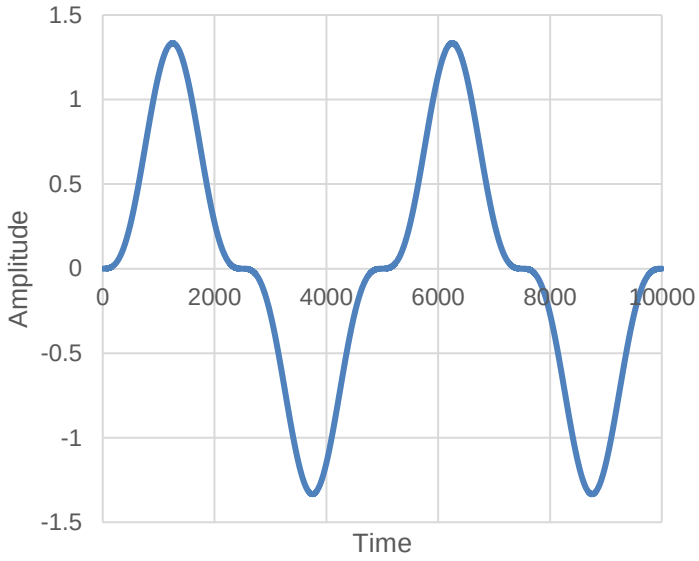
Multiple Sine Waves Combination



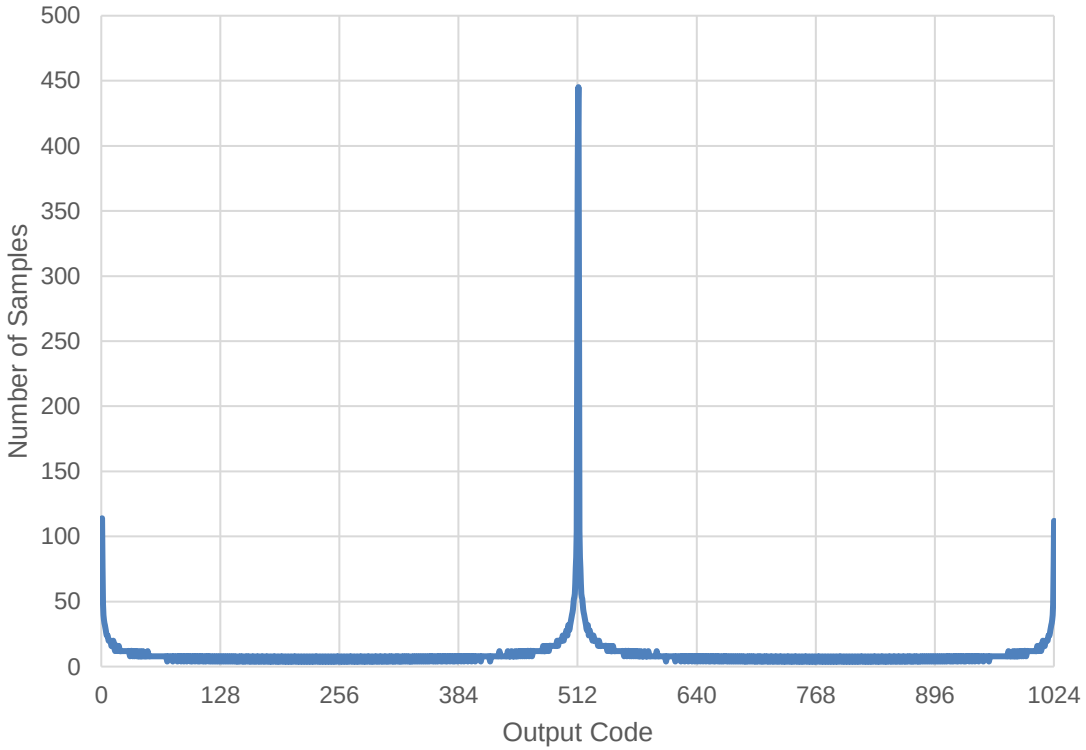
Smaller slope of input signal → More samples in histogram

Consider the input signal slope reduction
at target amplitude positions by combining sine waves.

Result of Multiple Sine Waves

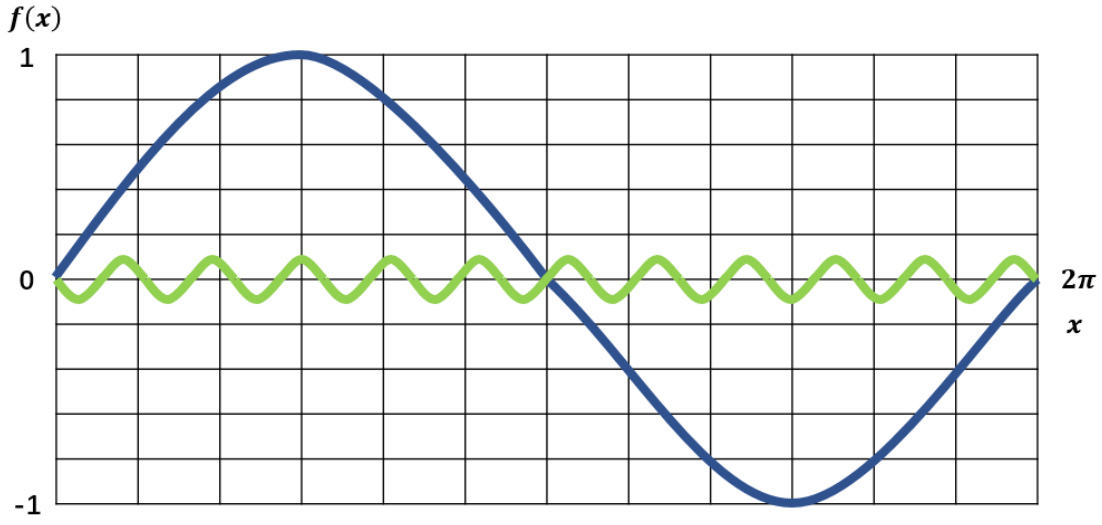


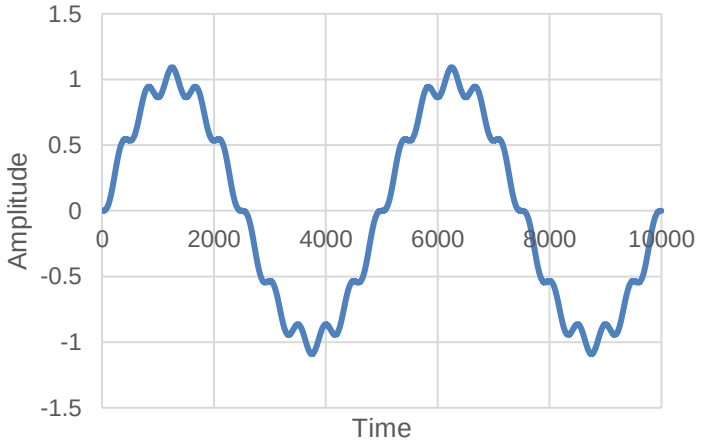
$$f(x) = sinx - \frac{sin3x}{3}$$



Number of samples around the middle (digital output 512) is increased.

Result of Other Codes



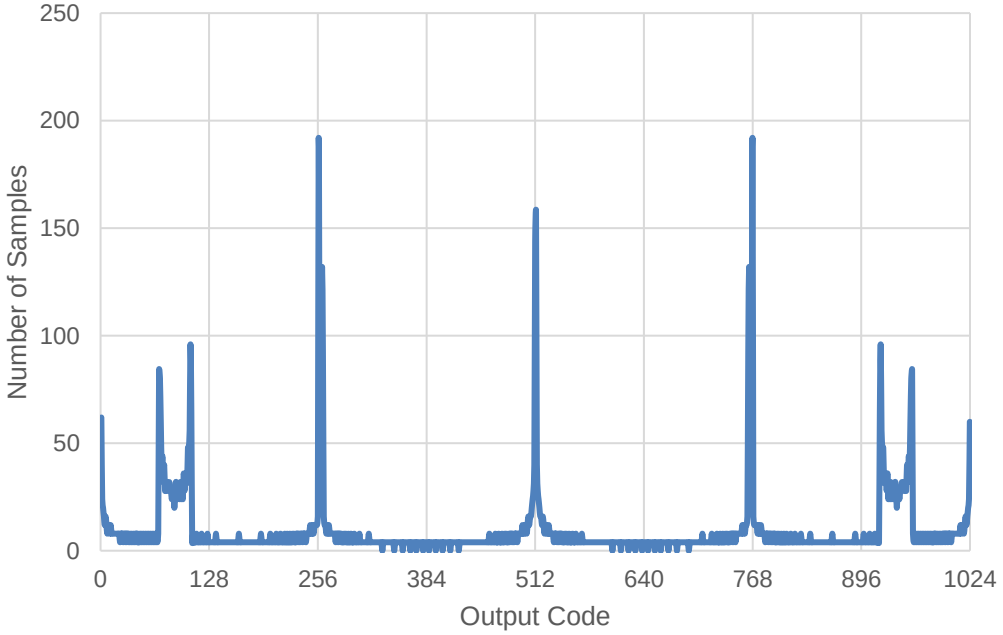


$$f(x) = \sin x - \frac{\sin 11x}{11}$$

Consider to increase 256 and 768 in output range from 0 to 1023.

$\arcsin\frac{1}{2} = \frac{\pi}{6}$ ($\frac{1}{12}$ of period 2π)

Try to use 11.

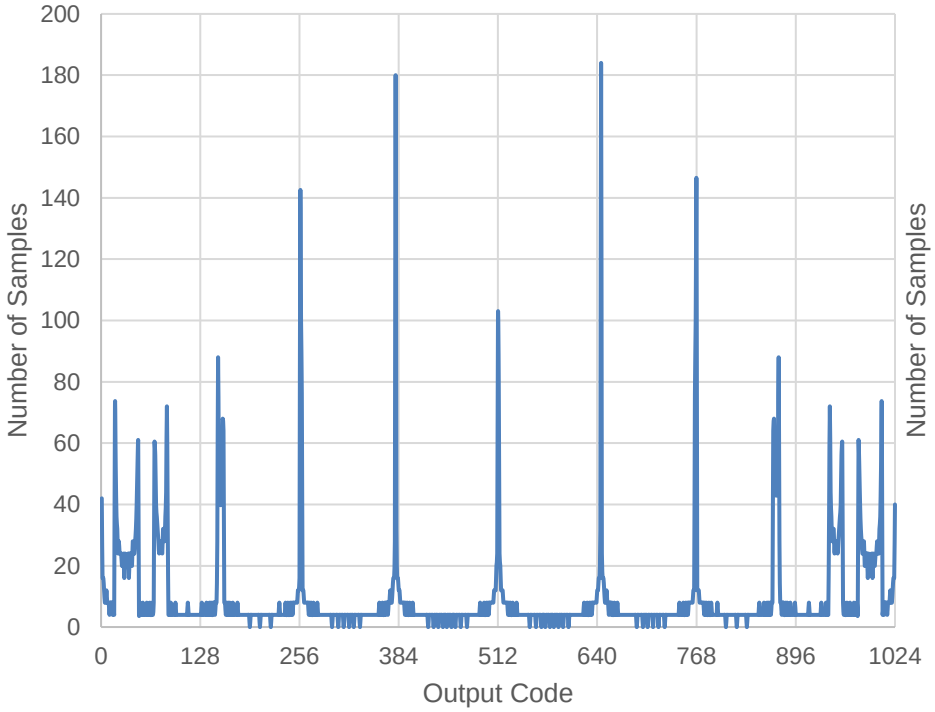


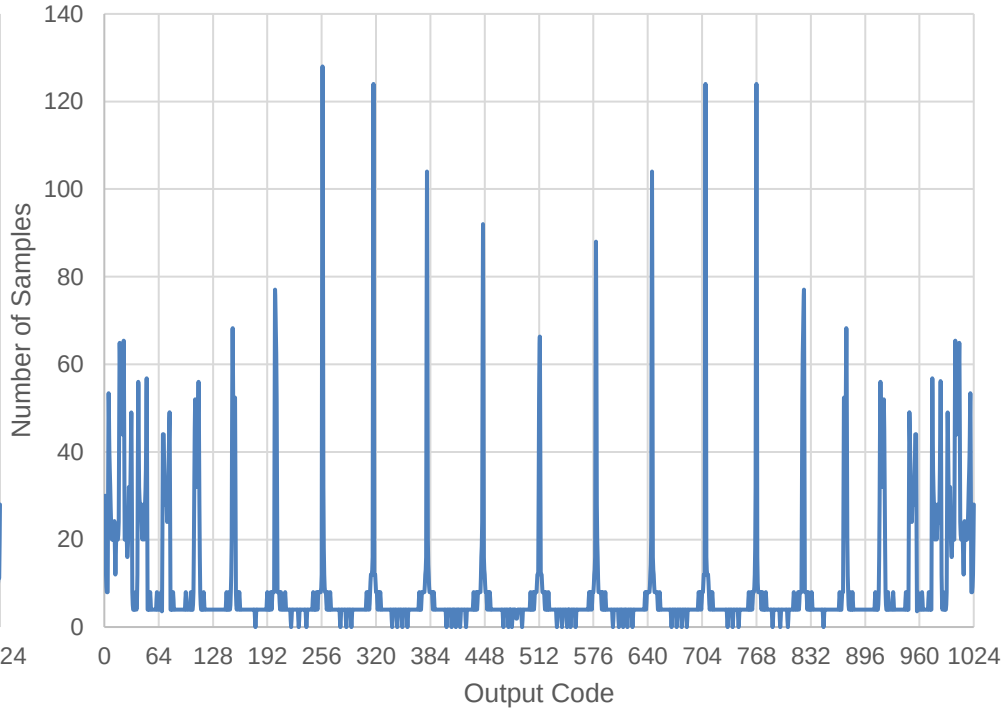
Results of More Codes

In the same way

$$f(x) = \sin x - \frac{\sin 23x}{23}$$

$$f(x) = \sin x - \frac{\sin 49x}{49}$$





Numbers of samples around the target digital output codes ➡ Increase.

$$f(x) = \sin(\omega_1 x) - \frac{\sin(\omega_2 x)}{k}$$

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Two-Tone Input Signal Configuration

$$f(x) = sin(\omega_1 x) - \frac{sin(\omega_2 x)}{k}$$

General two-tone input signal for ADC linearity histogram test

Simulating the following waveforms and obtained ADC histograms.

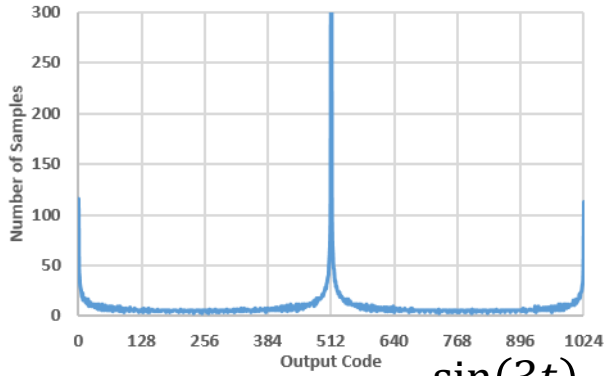
$$g_{3,3}(t) = \sin(t) - \frac{\sin(3t)}{3} \qquad g_{11,11}(t) = \sin(t) - \frac{\sin(11t)}{11}$$

$$g_{3,3.5}(t) = \sin(t) - \frac{\sin(3t)}{3.5} \qquad g_{11,11.5}(t) = \sin(t) - \frac{\sin(11t)}{11.5}$$

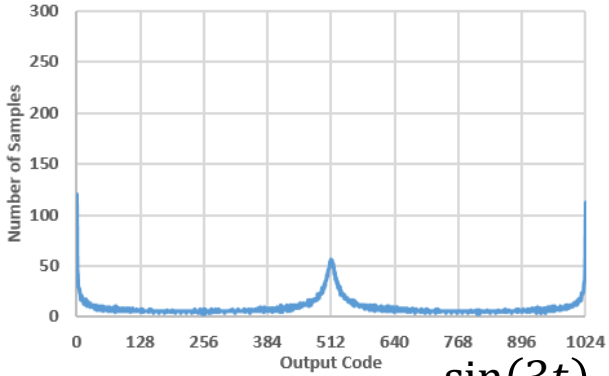
$$g_{3,4}(t) = \sin(t) - \frac{\sin(3t)}{4} \qquad g_{11,12}(t) = \sin(t) - \frac{\sin(11t)}{12}$$

Using AWG (Arbitrary Waveform Generator) for signal generation

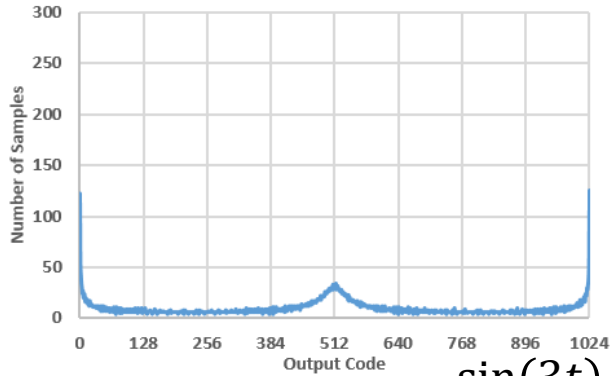
Results of Simple Configuration



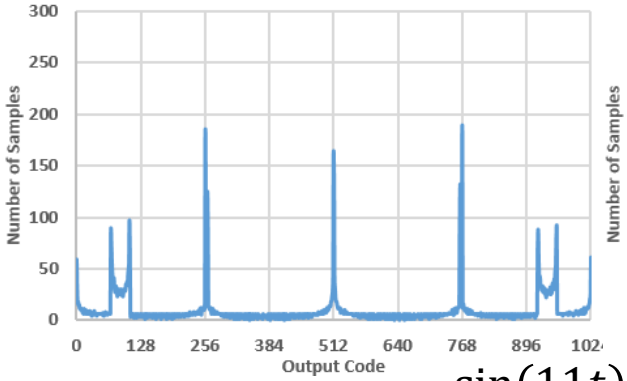
$$g_{3,3}(t) = \sin(t) - \frac{\sin(3t)}{3}$$



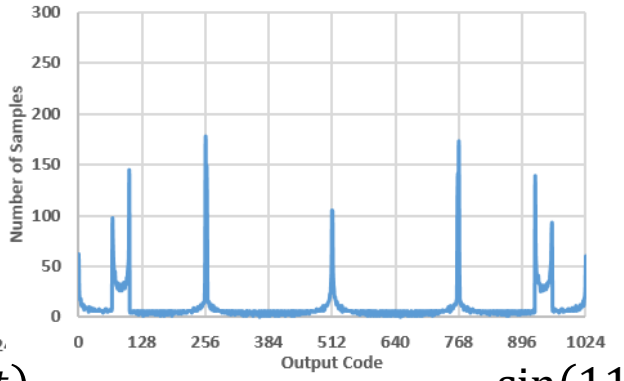
$$g_{3,3.5}(t) = \sin(t) - \frac{\sin(3t)}{3.5}$$



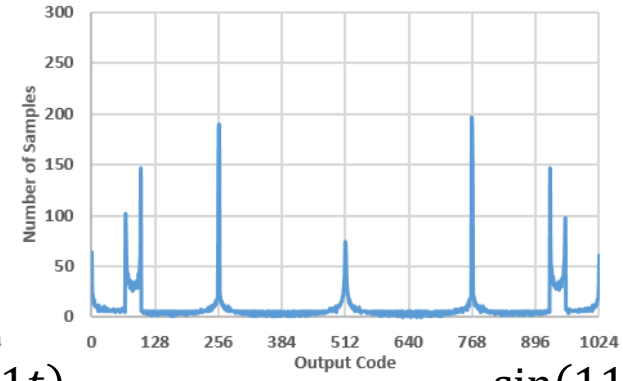
$$g_{3,4}(t) = \sin(t) - \frac{\sin(3t)}{4}$$



$$g_{11,11}(t) = \sin(t) - \frac{\sin(11t)}{11}$$



$$g_{11,11.5}(t) = \sin(t) - \frac{\sin(11t)}{11.5}$$

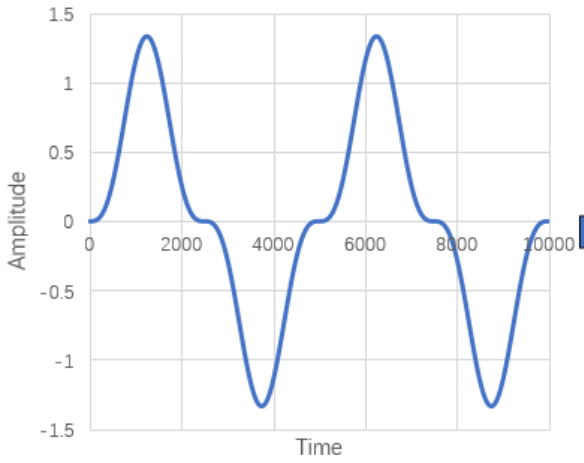


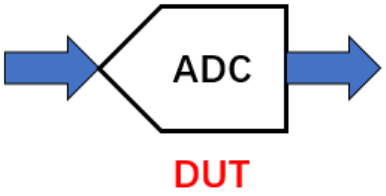
$$g_{11,12}(t) = \sin(t) - \frac{\sin(11t)}{12}$$

$$f(x) = sin(\omega_1 x) - \frac{sin(\omega_2 x)}{k}$$

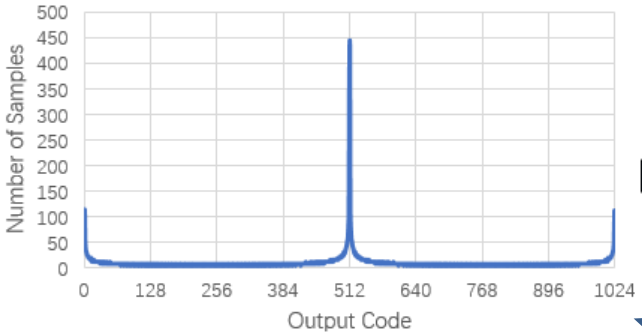
k increases → Histogram peaks spread.

Problem of Two-Tone Input Signal



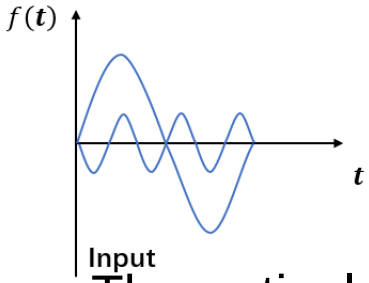


Actual histogram



DNL
INL

PDF is required to calculate the ideal histogram for DNL.



Proposed signal ➡ No inverse function

Theoretical derivation of probability density function (PDF) ➡ difficult

Histogram method requires explicit PDF.

➡ Alternatively, PDF obtained by simulation can be used.

Outline

- Background and Objective
- ADC Test with Histogram Method
- Sine Wave Histogram and Waveform Missing
- Combine Multiple Sine Waves
- General Two-Tone Input Signal Configuration
- **Conclusion**

Conclusion

- Focused ADC output histogram on specific codes by a two-tone wave with simple synthesis method for short time ADC linearity testing.
- Simulation results verified the proposed code selective histogram method.
- Addressed problem of the proposed method

Future work:

To investigate the ratio between input frequency and sampling frequency to control the sampling points spread for efficient waveform sampling, such as metallic ratios (golden ratio, silver ratio,…), prime number ratios.

Start with the simplest and reach the complex.

René Descartes

Thanks for your attention.