Evaluation of Code Selective Histogram Algorithm for ADC Linearity Test

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Outline

- Background and Objective
- ADC Test with Histogram Method
- Code Selective Histogram Method
- Evaluation of Code Selective Histogram Algorithm
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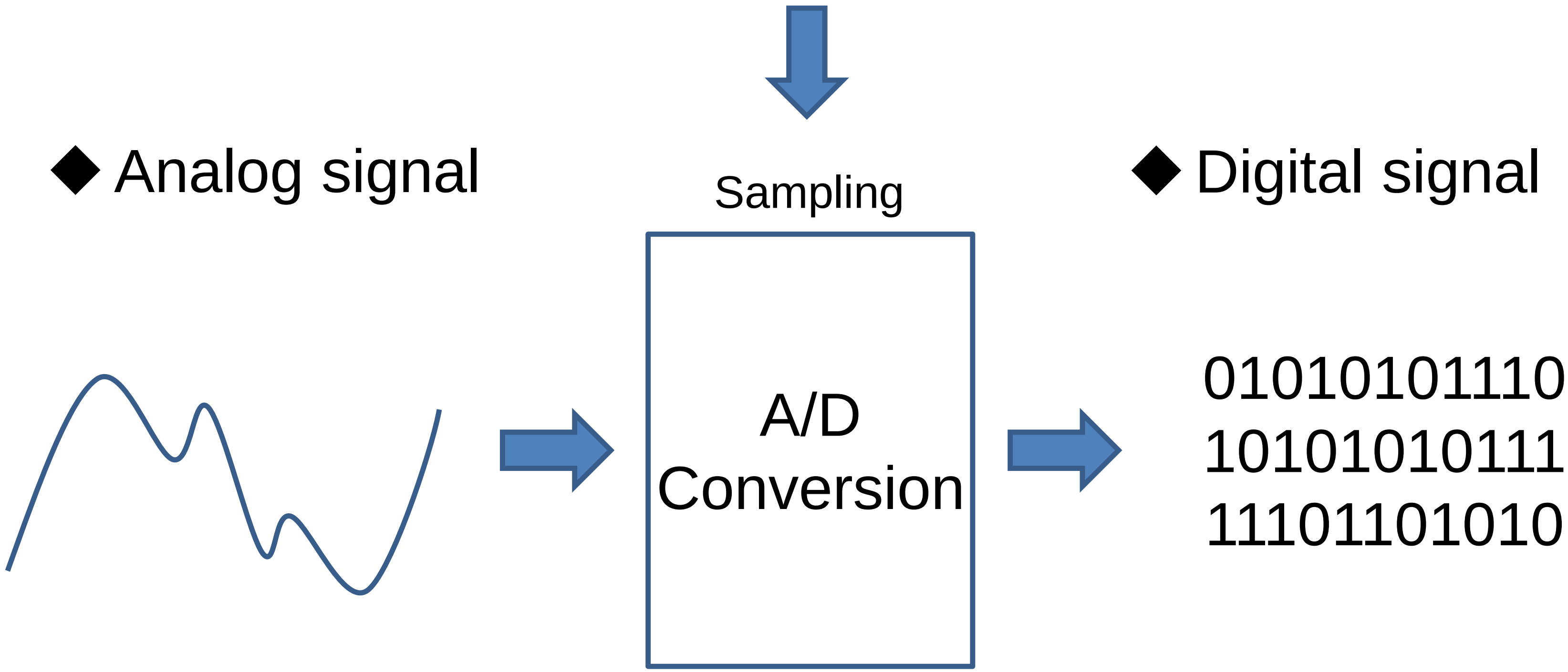
Background

IoT era is coming !

ADC is a key component



High quality & low cost ADC test is required

Research Objective & Approach

SAR ADC linearity test ⇨ long time

- low-speed sampling
- high-resolution

☹ Test cost is proportional to test time

This Work

ADC linearity test with histogram method:
Test linearity for specific vulnerable codes
Code selective histogram method
with two-tone sine wave

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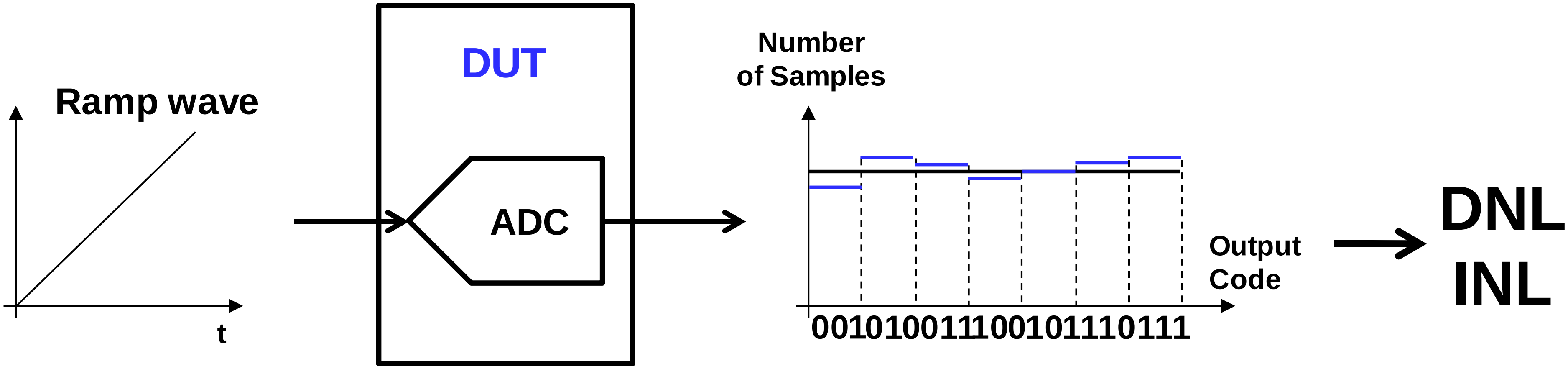
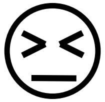
Conventional Linearity Testing 1

■Histogram method (Ramp wave input)

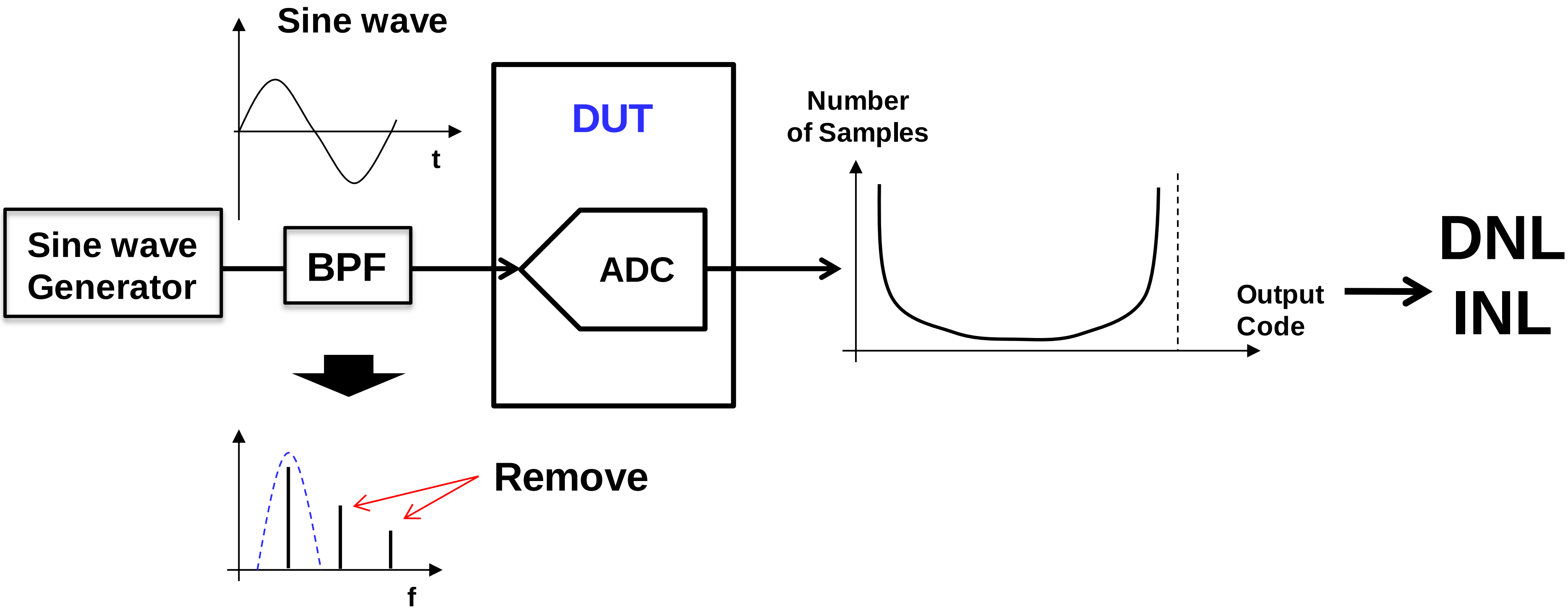


- ADC output histograms for all bins are equal if ADC is perfectly linear
- Highly linear ramp signal generation is difficult (limitation up to 14-bit ADC)



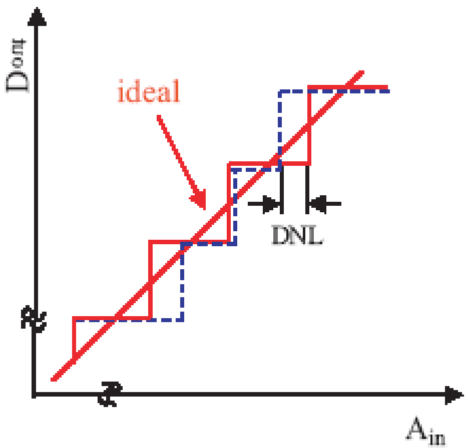
Conventional Linearity Testing 2

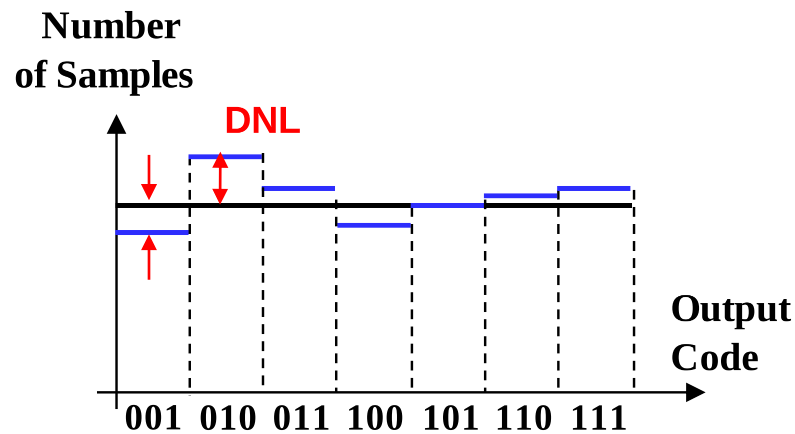
■Histogram method(Single sine wave input)

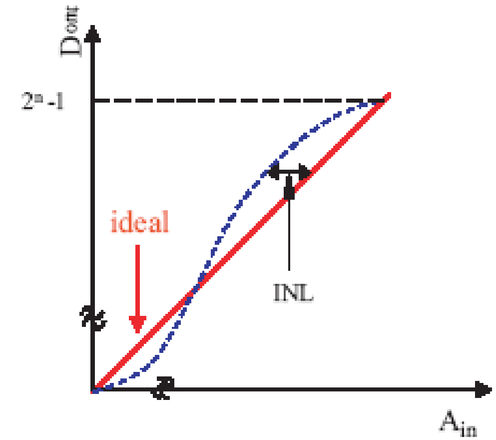


- Low distortion sine using an analog filter
- Number of samples is small around middle
  - ➡ Many samples required

DNL & INL







- Important ADC testing items

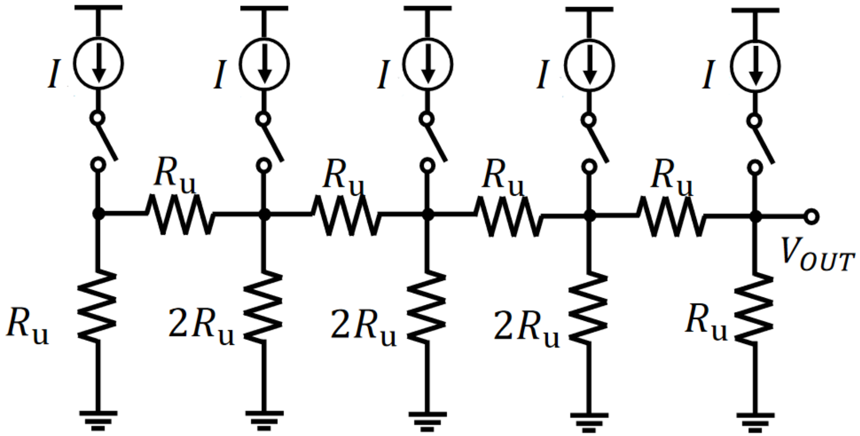
DNL : Difference between actual step width and ideal value

INL : Deviation from ideal conversion line

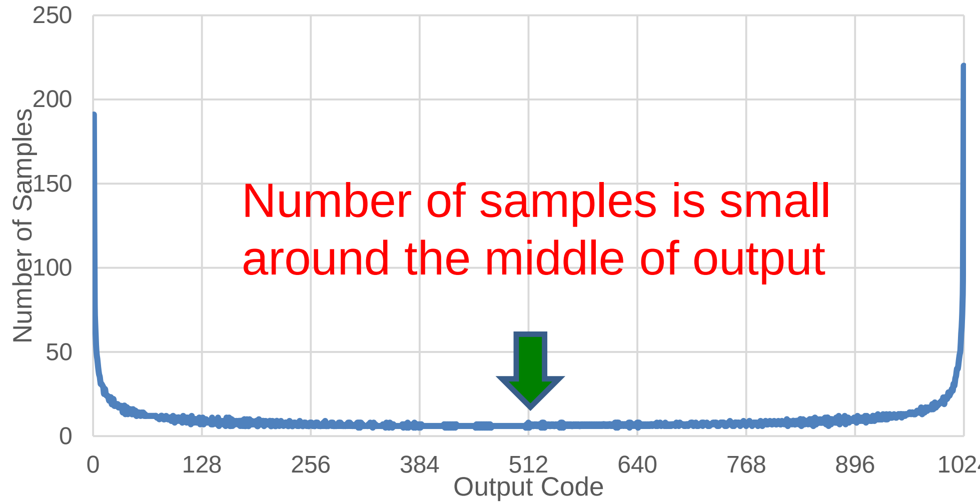
$$INL(k) = \sum_{i=1}^{k} DNL(i)$$

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, …

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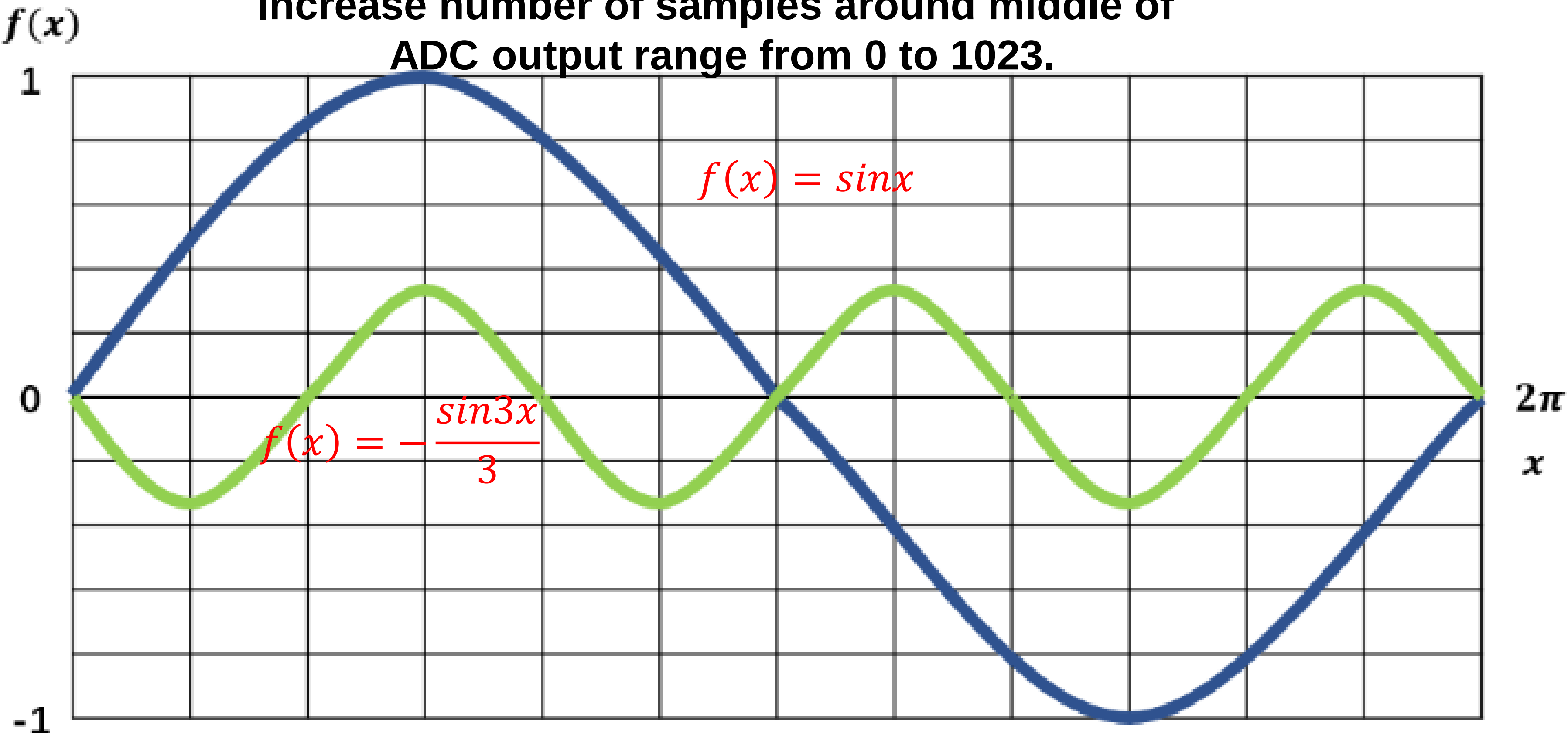
[1] Yujie Zhao, *et al.:* "Revisit to Histogram Method for ADC Linearity Test: Examination of Input Signal and Ratio of Input and Sampling Frequencies", Journal of Electronic Testing: Theory and Applications, Springer (March 2022)

Multiple Sine Waves Combination

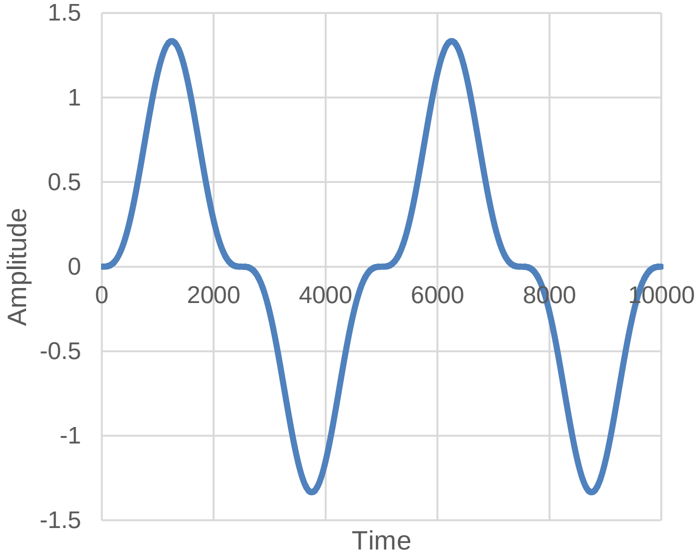
Increase number of samples around middle of ADC output range from 0 to 1023.



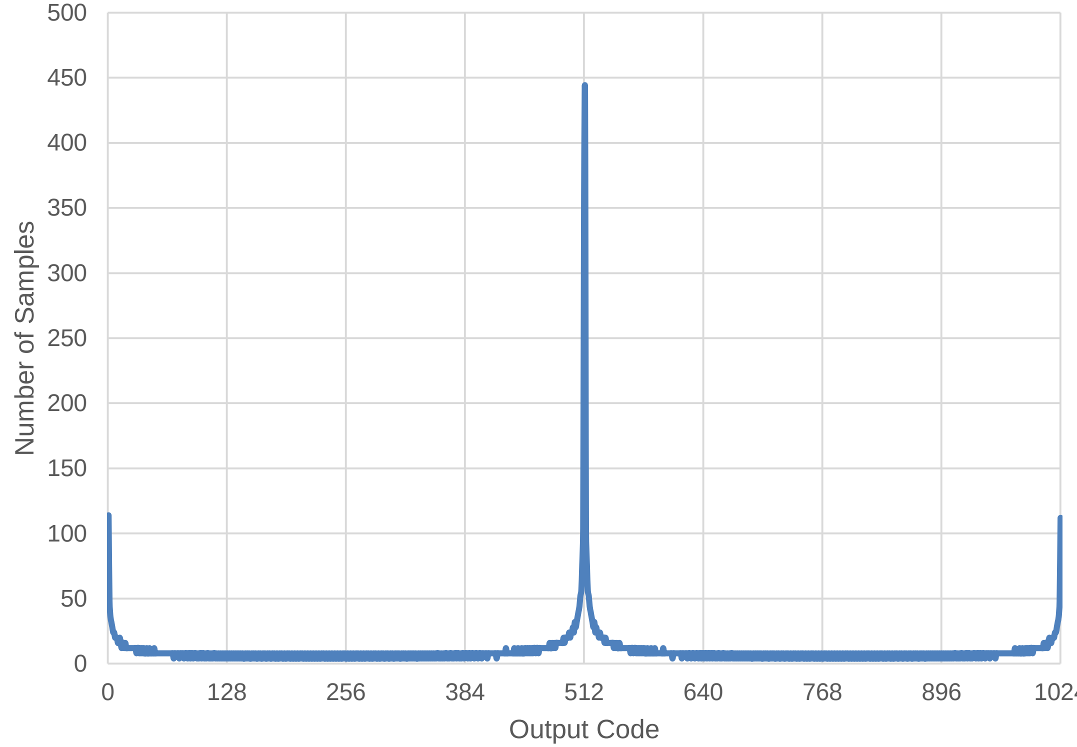
Smaller slope of input signal → More samples in histogram

Input signal slope reduction at target amplitude positions by combining sine waves.

Result of Multiple Sine Waves



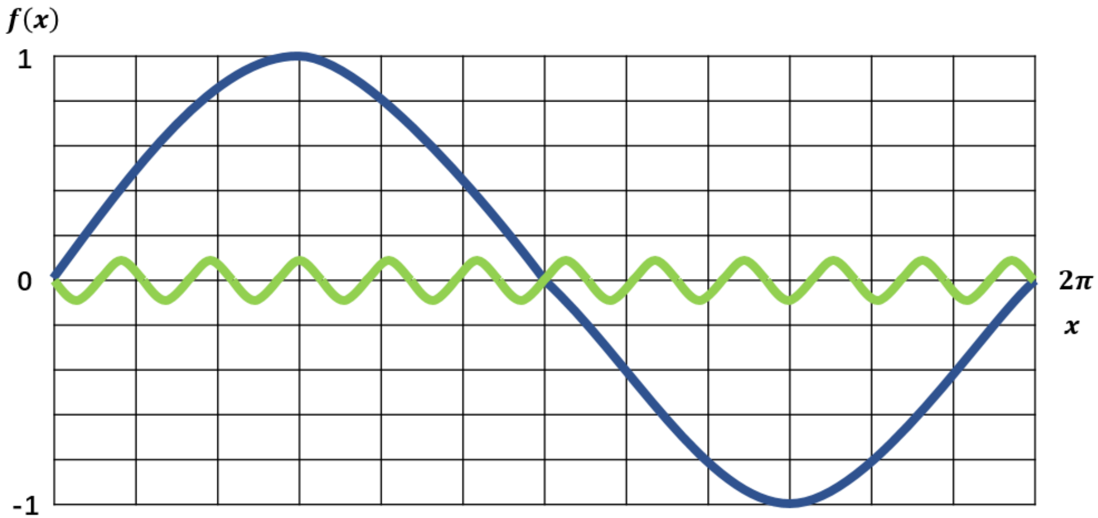
$$f(x) = sinx - \frac{sin3x}{3}$$

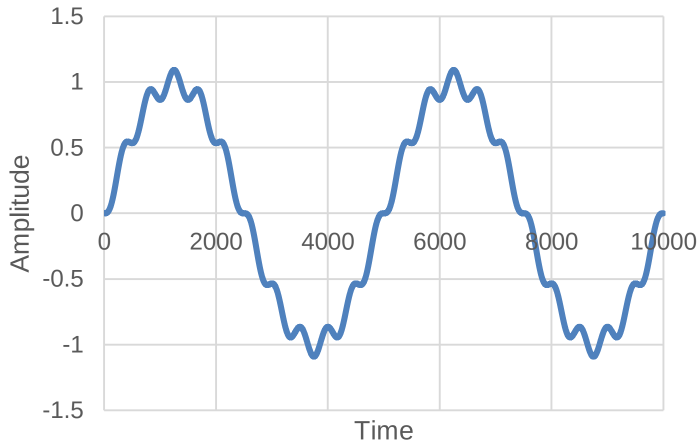


Number of samples around middle (digital output 512)

Increased.

Result of Other Codes



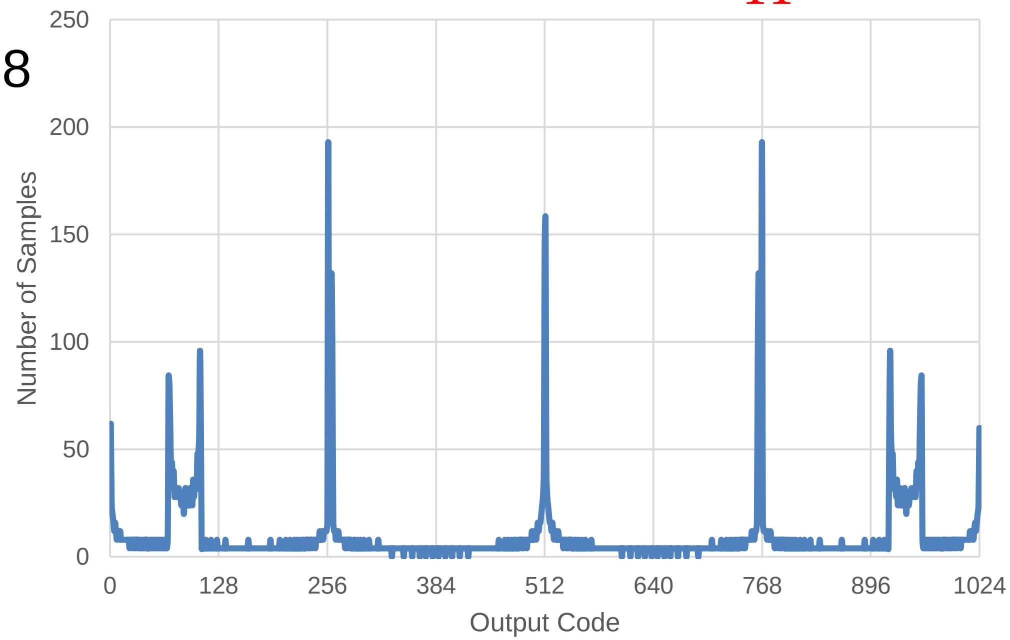


$$f(x) = \sin x - \frac{\sin 11x}{11}$$

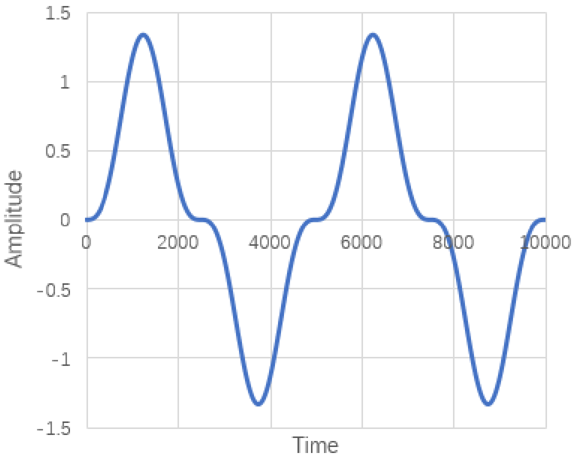
Increase histograms at 256 and 768 in output range from 0 to 1023.

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

Try to use 11.

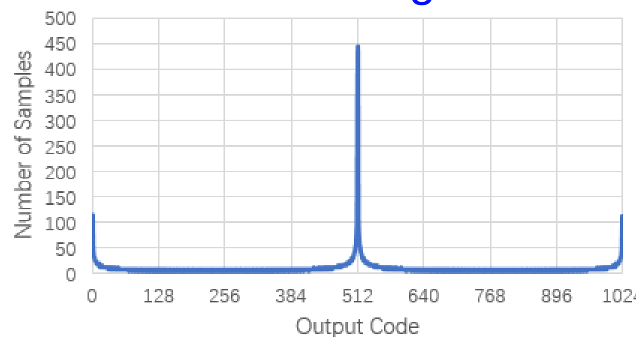


Problem of Two-Tone Input Signal



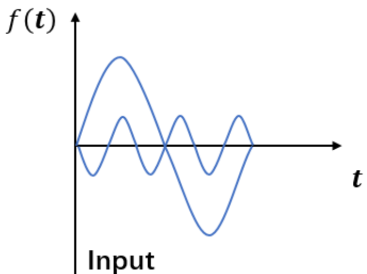
DUT

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.

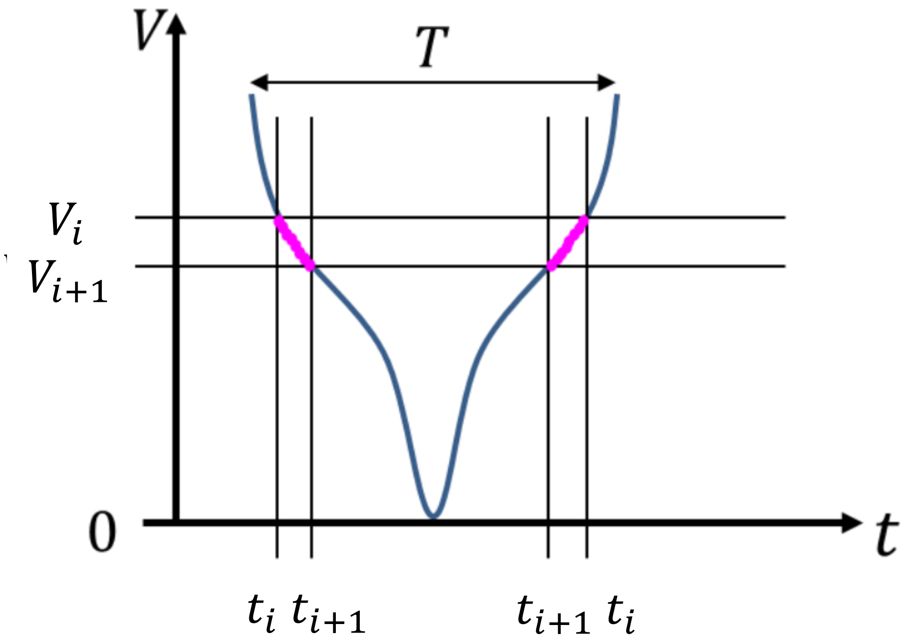
Outline

Applicable Input Waveforms

Periodic function

$$V = f(\mathrm{t})$$
$$\mathrm{t} = f^{-1}(V)$$

Two points where $f'(\mathrm{t}) = 0$
(slope is 0) in one cycle (T)



Probability of existing between waveform voltages V_i and V_{i+1} is

$$p[i] = \frac{2(\mathrm{t}_{i+1} - \mathrm{t}_i)}{T}$$

$$p[i] = \frac{2\left(f^{-1}(V_{i+1}) - f^{-1}(V_i)\right)}{T}$$

DNL&INL Calculation Method

	…	i-1	i	i+1	…
V		$V_{\mathrm{i}-1}$	V_{i}	$V_{\mathrm{i}+1}$	
DNL		DNL[i-1]	DNL[i]	DNL[i+1]	
P		p[i-1]	p[i]	p[i+1]	

Cumulative distribution function

$$PI[i] = \sum_{k=0}^{i} p[k] = \frac{2}{T} f^{-1}(V_{i+1})$$

$$V_{i+1} = f\left(\frac{T}{2} PI[\mathrm{i}]\right)$$

$$\Delta = \frac{V_{2^n-1} - V_1}{2^n - 2}$$

$$DNL[i] = \frac{V_{i+1} - V_i}{\Delta} - 1[LSB]$$

$$INL[i] = \sum_{k=1}^{i} DNL[k]$$

DNL of an n-bit ADC is

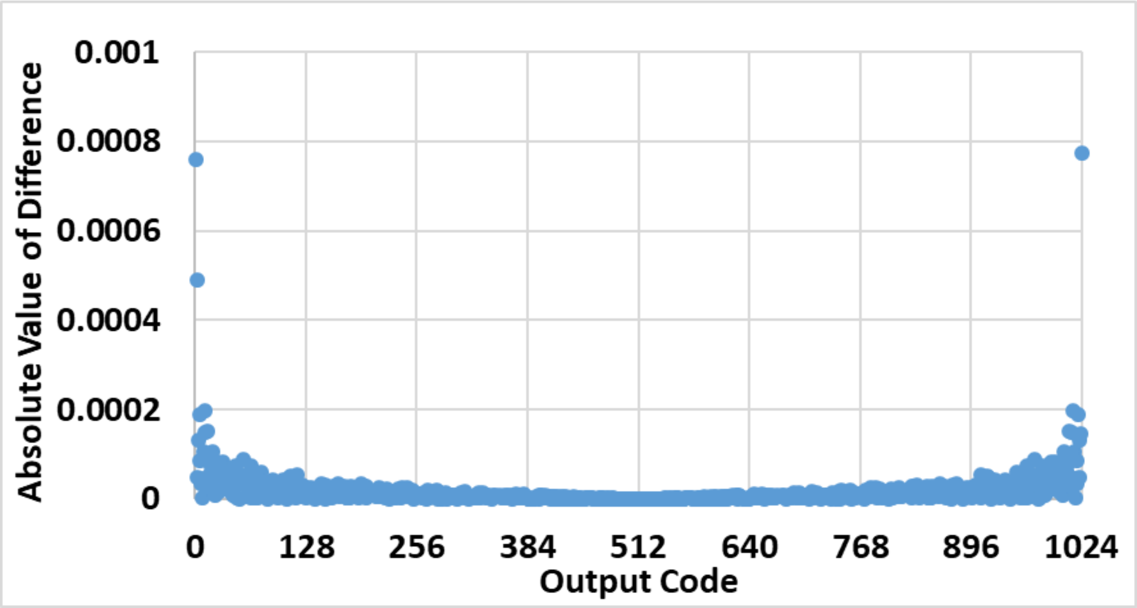
$$DNL[i] = (2^n-2) \cdot \frac{f\left(\frac{T}{2} PI[i]\right) - f\left(\frac{T}{2} PI[i-1]\right)}{f(\frac{T}{2} PI[2^n-2]) - f\left(\frac{T}{2} PI[0]\right)} - 1$$

$$INL[i] = (2^n-2) \cdot \frac{f\left(\frac{T}{2} PI[i]\right) - f\left(\frac{T}{2} PI[0]\right)}{f(\frac{T}{2} PI[2^n-2]) - f\left(\frac{T}{2} PI[0]\right)} - i$$

$$i = 1,2, \dots, 2^n - 1$$

$DNL[0]$ and $INL[0]$ set to 0

Proposed Method and Ideal (Sine)



$$DNL_{ABS} = \left| DNL_{Propose} - DNL_{Ideal} \right|$$

Absolute difference between DNLs calculated from the proposed method and the ideal histogram

0.0002 LSB or less

ADC DNL Setting of Evaluation

10bit ideal ADC
Resolution N=1024
Total number of samples M= 2^{16}

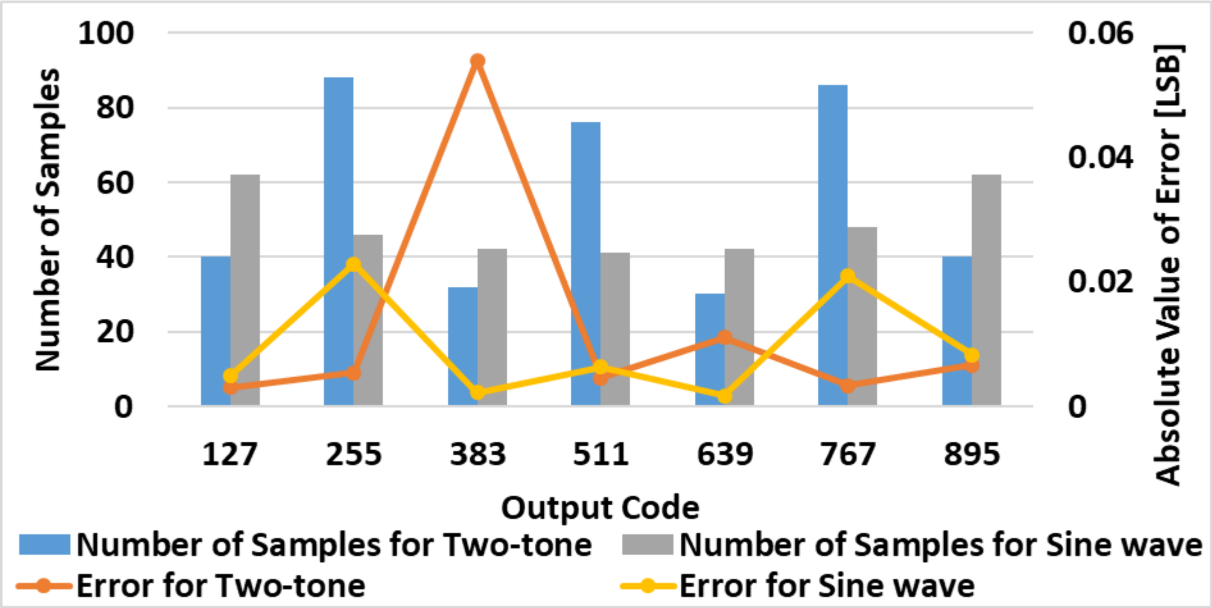
$$f_{11}(t) = sin(t) - \frac{sin(11t)}{25}$$

Compare proposed wave $f_{11}(t)$ and sine wave
are used as test signals

Undistorted ADC

Distorted:
0.5 LSB → 511
-0.3, -0.3 LSB → 255, 767
0.1 LSB → 127, 383, 639, 895

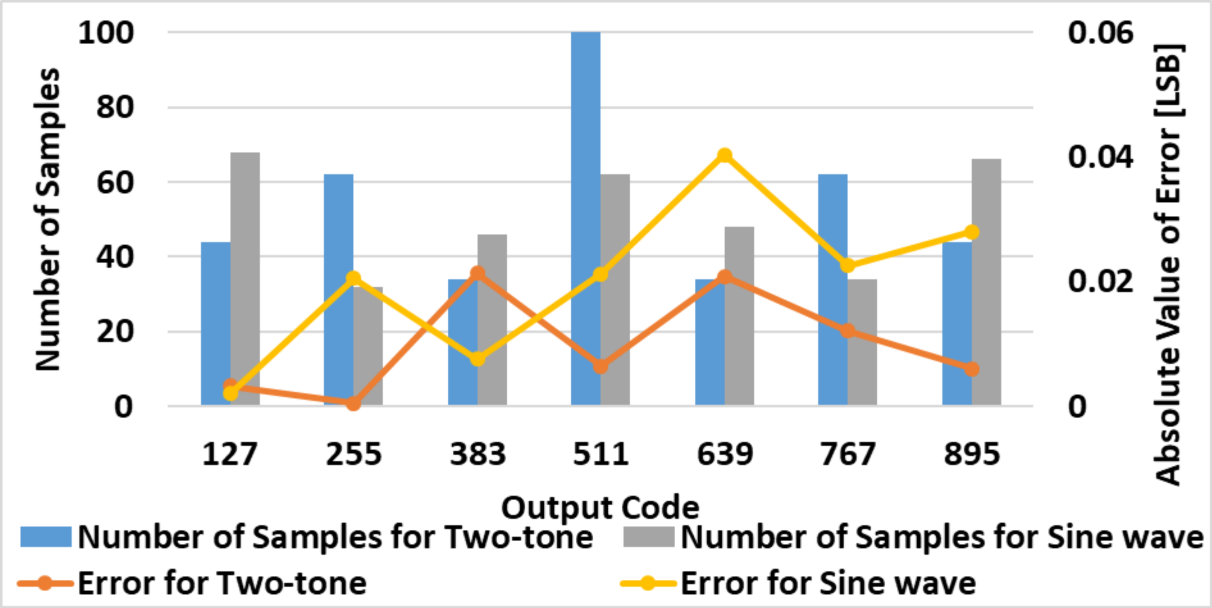
Evaluation Result of Undistorted ADC



As expected, number of samples near 255,767 and 511 increased

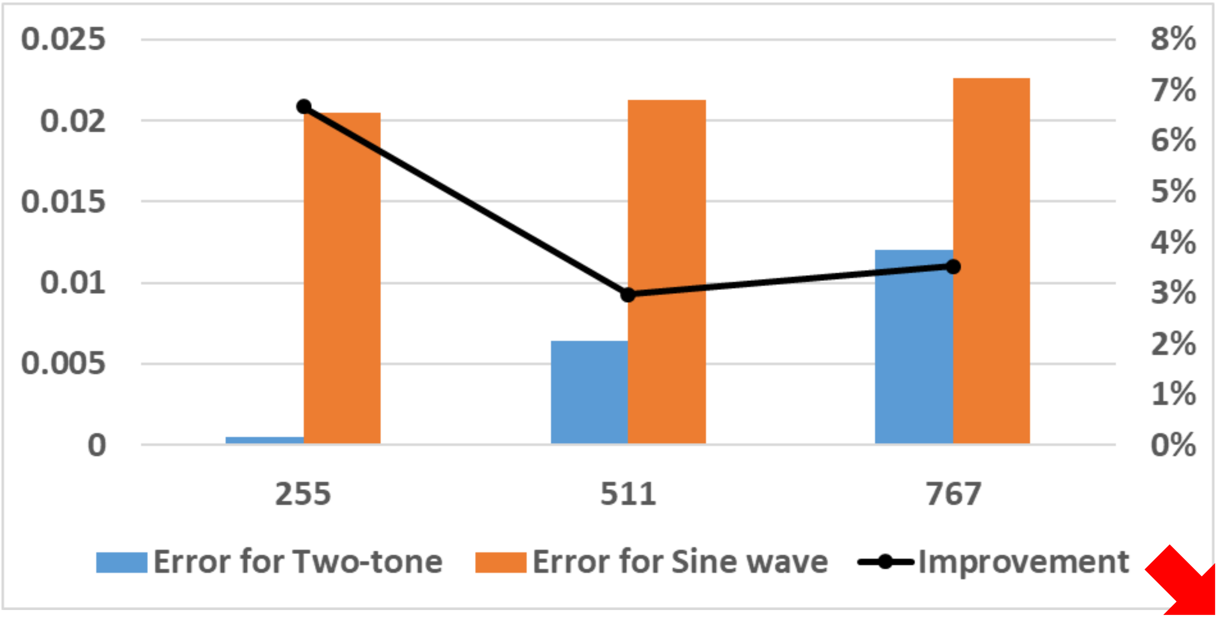
DNL accuracy improved
(127,383,639,895 decrease)

Evaluation Result of Distorted ADC



Same as undistorted result, number of samples near 255,767 and 511 increased, DNL accuracy improved

DNL Accuracy of Distorted ADC



Output code	Added DNL	Number of Samples for Two-tone	Error for Two-tone	Number of Samples for Sine wave	Error for Sine wave	$\frac{E_{Sin} - E_{Two}}{\lvert DNL_{Add} \rvert}$
255	-0.3	62	0.000475	32	0.020511	6.67%
511	0.5	114	0.006441	62	0.021264	2.96%
767	-0.3	62	0.012022	34	0.022598	3.52%

Error compared to added DNL,
the result of two-tone waveform is more accurate

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Conclusion

Sine wave histogram method
Specific codes
(like middle of output range)
Number of samples : less

⇨

Proposed method
Specific codes
Number of samples increase
Improve testing accuracy

Using code selective method,
DNL accuracy of specific code is improved by about 2%~7%.

Next work

- Calculate DNL results of other waveforms
  (other specific codes) and compare with sine wave.
  Expand code range of evaluation,
  get variation near specific codes

Thanks for your attention.

Cost is more important than quality.
But quality is the best way to reduce cost.

Prof. Gen'ichi Taguchi
1924-2012