Algorithms for Generating Low-Distortion Single-Tone and Two-Tone Sinewaves Using an Arbitrary Waveform Generator

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Research Goal

Generating low-distortion sinewaves for ADC linearity testing using low-cost AWG

Conventional method

Proposed method
Contents

• Research Goal
• ADC Linearity Test
• Conventional Test Method
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• Experimental Results
• Conclusions
Signal Generation with AWG

**AWG (Arbitrary Waveform Generator) = DSP + DAC**

- **DSP** generates digital signal.
- **DAC** converts it to analog signal.

**Single-tone and two-tone analog signals for ADC testing**

**DAC has nonlinearity**
Spurious Components due to DAC Nonlinearity

Digital input $X$ \quad DAC \quad Analog input $Y$

Ideal DAC output $Y = a_1 X$

Actual DAC output $Y = a_1 X + a_2 X^2 + a_3 X^3 + a_4 X^4 \ldots$

DAC Nonlinearity \quad Spurious components
Use differential signals to cancel even harmonics.

Next focus on removing third-order harmonics.
Third-order Nonlinearity Distortion Components

Single-tone input

Two-tone input

IM3 components are difficult to remove with analog filter
ADC Linearity Test (Single-tone Input)

Proposed method relaxes requirements for analog LPF

Use simple analog LPF to remove HD3 (& higher harmonics)

ADC distortion can be measured & tested accurately.
Communication ⇒ Narrow band, high frequency

IM3 ($2f_1-f_2, 2f_2-f_2$) components in input signal are
- within signal band
- difficult to remove by analog BPF.
Use proposed method to cancel IM3 in analog input.

ADC distortion (IM3) can be measured & tested accurately.
Contents

• Research Goal
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• Conventional Test Method
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Conventional Single-tone Generation

\[ Y = aX + bX^3 \]

\[ X = A \sin(2\pi f_{\text{in}}t) \]

\[ Y = aA \sin(2\pi f_{\text{in}}t) + b(A\sin(2\pi f_{\text{in}}t))^3 \]

- HD3 appears
Conventional Two-tone Generation

\[ X = A \sin(2\pi f_1 t) + B \sin(2\pi f_2 t) \]

\[ Y = a x + b x^3 \]

- IM3 appears
Contents

• Proposed Test Method
  - Single-tone Generation
  - Two-tone Generation
  - Algorithm Generalization
Proposed Method

Interleave $X_1, X_2$ by one clock and generate Din

Feed Din to DAC

Cancel distortion components of output $Y$

- Requires only DSP program change
- Spurious components are far from signal band
Contents

• Proposed Test Method
  - Single-tone Generation
  - Two-tone Generation
  - Algorithm Generalization
Principle of Proposed Method

\[ Y = a X + b X^3 \]

\[ \text{Din} = A \sin(2\pi f_{\text{in}} t + \pi/6) \quad \text{Din} = A \sin(2\pi f_{\text{in}} t - \pi/6) \]

Distortion around fs/2

Input Din

Output Y
Proposed Method (Single-tone)

\[ \text{Input Din} = A \sin(2\pi f_{in} t + \pi/6) \quad \text{or} \quad \text{Input Din} = A \sin(2\pi f_{in} t - \pi/6) \]

\[ \text{Output Y} = aX + bX^3 \]

Fundamental \( f_{in} \) power reduction by 1.25dB
Simulation Condition (Single tone)

\[ Y = aX + bX^3 \]

Input signal \( X_1 \):
\[ \sin(2\pi f_{\text{in}} t + \pi/6) \]

Input signal \( X_2 \):
\[ \sin(2\pi f_{\text{in}} t - \pi/6) \]

1\(^{st}\) coeff. \( a(\text{DAC}) \):
1.0

3\(^{rd}\) coeff. \( b(\text{DAC}) \):
-0.005

Input freq. \( f_{\text{in}} \):
51

Sampling freq. \( f_s \):
1024
Spurious due to interleave
• Proposed Test Method
  - Single-tone Generation
  - Two-tone Generation
  - Algorithm Generalization
Proposed Method (Two-tone signal)

\[ \text{Din} = A \sin(2\pi f_1 t + \pi/6) + B \sin(2\pi f_2 t - \pi/6) \]

\[ \text{Din} = A \sin(2\pi f_1 t - \pi/6) + B \sin(2\pi f_2 t + \pi/6) \]
Simulation Condition (Two tone)

\[ Y = aX + bX^3 \]

Input signal \( X_1 \):
\[ \sin(2\pi f_1 t + \pi/6) + \sin(2\pi f_2 t - \pi/6) \]

Input signal \( X_2 \):
\[ \sin(2\pi f_1 t - \pi/6) + \sin(2\pi f_2 t + \pi/6) \]

1st coeff. \( a \) (DAC):
1

3rd coeff. \( b \) (DAC):
-0.005

Input freq. \( f_1 \):
51

Input freq. \( f_2 \):
81

Sampling freq. \( f_s \):
1024
Output Power Spectrum (Two-tone Input)

\[
20 \log |Y| [\text{dB}]
\]

Normalized Frequency \( f/f_s \)

Spurious due to interleave
Contents

• Proposed Test Method
  - Single-tone Generation
  - Two-tone Generation
  - Algorithm Generalization
Algorithm Generalization

① HD2 cancellation
② HD2 & HD3 cancellation
③ HD3, HD5 & HD7 cancellation
HD2 Cancellation

**Fundamental**

2-way interleave cancels HD2

\[
X_1 = \text{Asin}(2\pi f_{in} t + \pi/4) \\
X_2 = \text{Asin}(2\pi f_{in} t - \pi/4)
\]
HD2, HD3 Cancellation

4-way interleave cancels HD2 & HD3

\[ X_1 = \text{Asin}(2\pi f_{\text{in}} t - \pi/4 - \pi/6) \quad X_2 = \text{Asin}(2\pi f_{\text{in}} t - \pi/4 + \pi/6) \]

\[ X_3 = \text{Asin}(2\pi f_{\text{in}} t + \pi/4 - \pi/6) \quad X_4 = \text{Asin}(2\pi f_{\text{in}} t + \pi/4 + \pi/6) \]
Even Harmonic Cancellation

Differential structure cancels HD2 $\cdot$ HD4 $\cdot$ HD6 $\cdot$ HD8

fundamental

$f_{in}$ $2f_{in}$ $3f_{in}$ $4f_{in}$ $5f_{in}$ $6f_{in}$ $7f_{in}$ $8f_{in}$

HD2 HD3 HD4 HD5 HD6 HD7 HD8
HD3, HD5, HD7 cancellation

Differential structure cancels HD2・HD4・HD6・HD8

Proposed method cancels HD3・HD5・HD7

8-interleave cancels HD3, HD5 & HD7
Contents

• Research Purpose
• ADC Linearity Test
• Conventional Test Method
• Proposed Test Method
• Experimental Results
• Conclusion
Experimental Verification

- Only DSP algorithm change in conventional AWG
- Single-tone generation with HD3 cancellation

\[
Y = aX + bX^3
\]

\[
\text{Din} = A \sin(2\pi f_{in} t + \pi/6)
\]

\[
\text{Din} = A \sin(2\pi f_{in} t - \pi/6)
\]
Experiment Instrumentation

AWG (Agilent 33120A)

- Max. Sampling frequency (Hz): 40M
- Resolution (bit): 12
- Linearity: $\Delta$

Spectrum Analyzer (HP ESA-L1500A)

- Frequency range (Hz): 9k~1.5G
- Max amplitude (Vpp): 19.8
Experiment Condition

Conventional

Proposed

input $X = A \sin(2\pi ft)$

input $Din = A \sin(2\pi ft \pm \pi/6)$
Experiment Results  (fs= 10MHz, Input amplitude 1.3Vpp)

Conventional

Proposed

Fundamental
(1MHz): 6.31dBm

HD3 (3MHz): -65dBm

1.09dB reduction

5.12dBm

11.5dB

-76.5dBm (Noise floor level)
Experimental Results: HD3  (fs=10MHz)

Almost noise floor

Fundamental component power level [dBm]

HD3 power level [dB]

HD3 (Conventional)
HD3 (Proposed)

Noise floor level
Experimental Results: HD3 reduction (fs=10MHz)

Power reduction [dB]

Fundamental component power level [dBm]

- **Fundamental**
- **HD3**
Conclusions

- Low-distortion signal generation with AWG
- Single-tone: HD3 cancellation
- Two-tone: IM3 cancellation
- Algorithm generalization
- Only program change
- No hardware change.
- No need for AWG nonlinearity identification
- Theoretical analysis, simulation and experiment all verify the effectiveness of the proposed method

Low-cost, high-quality testing of ADC is possible
• Proposed signal generation method
  - Distortion components close to signal band are reduced
  - Distortion components far from signal band may appear.

**Distortion-shaping**

Similar to but different from noise-shaping