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

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Gunma University
Semiconductor Technology Academic Research Center
• Research Goal
• ADC Linearity Test
• Conventional Test Method
• Proposed Test Method
• Experimental Results
• Conclusions
Research Goal

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

Conventional method

Proposed method
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Signal Generation with AWG

**AWG** (Arbitrary Waveform Generator)

- 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 $X$ ➔ DAC ➔ Analog input $Y$

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

- **Spurious components**
  - $f_{in}$
  - $2f_{in}$
  - $3f_{in}$
  - $4f_{in}$

**DAC Nonlinearity** ➔ **Spurious components**
Use differential signals to cancel even harmonics.

\[ Y = a_1 X + a_2 X^2 + a_3 X^3 + a_4 X^4 \]

\[ \Delta Y = Y_1 - Y_2 \]

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

Single-tone input

HD • • • Harmonic Distortion

Two-tone input

IM • • • Intermodulation

IM3 components are difficult to remove with analog filter

\[ f_{in}, \quad 3f_{in}, \quad f_1, \quad f_2, \quad 2f_1 - f_2, \quad 2f_1 + f_2, \quad 2f_2 - f_1, \quad 2f_2 + f_1, \quad 3f_1, \quad 3f_2, \quad 3f_3 \]
ADC Linearity Test (Single-tone Input)

Can use analog LPF to remove HD3 (& higher harmonics)

ADC distortion can be measured & tested accurately.
Communication Application ADC Test (Two-tone Input)

Communication ⇒ Narrow band, high frequency

\[ Y = aX + bX^3 \]

IM3 \((2f_1-f_2, 2f_2-f_2)\) components in input signal are
- within signal band
- difficult to remove by analog BPF.
Communication Application ADC Test (Two-tone Input)

Communication $\Rightarrow$ Narrow band, high frequency

Y = aX + bX^3

Use proposed method to cancel IM3 in analog input.

ADC distortion (IM3) can be measured & tested accurately.
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Conventional Single-tone Generation

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

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

\[ Y = aX + bX^3 \]

- HD3 appears
Simulation Condition (Single-tone)

Y = aX + bX^3

**Input signal X**: \( \sin(2\pi f_{in} t) \)

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st coeff. a (DAC)</td>
<td>1.0</td>
</tr>
<tr>
<td>3rd coeff. b (DAC)</td>
<td>-0.005</td>
</tr>
<tr>
<td>Input freq. fin</td>
<td>51</td>
</tr>
<tr>
<td>Sampling freq. fs</td>
<td>1024</td>
</tr>
</tbody>
</table>

Output power spectrum is obtained by FFT.

Normalized Frequency \( f/fs \)

**Diagram**: Diagram showing the flow from DSP to DAC with input signal, coefficients, and output power spectrum.
Conventional Two-tone Generation

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

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

\[ f = f_1, f_2 \]

\[ f = 2f_1 - f_2, 2f_2 - f_1, 2f_1 + f_2, 2f_2 + f_1, 3f_1, 3f_2 \]

\[ \text{IM3 appears} \]
Simulation Condition (Two-tone)

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

<table>
<thead>
<tr>
<th>Input signal X</th>
<th>( \sin 2\pi f_1 t + \sin 2\pi f_2 t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1\textsuperscript{st} coeff. ( a(DAC) )</td>
<td>1</td>
</tr>
<tr>
<td>3\textsuperscript{rd} coeff. ( b(DAC) )</td>
<td>-0.005</td>
</tr>
<tr>
<td>Input freq. ( f_1 )</td>
<td>51</td>
</tr>
<tr>
<td>Input freq. ( f_2 )</td>
<td>81</td>
</tr>
<tr>
<td>Sampling freq. ( f_s )</td>
<td>1024</td>
</tr>
</tbody>
</table>
Output Power Spectrum (Two-tone Input)

\[20 \log |Y| [dB] \]

Normalized Frequency \( f/f_s \)
• Proposed Test Method
  - Single-tone Generation
  - Two-tone Generation
  - Algorithm Generalization
Proposed Method

\[ Y = aX + bX^3 \]

Interleave \( X_1 \) and \( X_2 \) by one clock and generate \( \text{Din} \)

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

Feed \( \text{Din} \) to DAC

Cancel distortion components of output \( Y \)
Principle of Proposed Method

DAC

DSP

Input Din

Output Y

c

ck

ck

Din = Asin(2\pi f_{in}t + \pi/6)

Din = Asin(2\pi f_{in}t - \pi/6)

Distortion around fs/2

3f_{in}
Proposed Method (Single-tone)

Input Din

Y = a X + b X^3

Din = Asin(2πf_{in}t + π/6)  Din = Asin(2πf_{in}t - π/6)

Din = 0.87Asin2πf_{in}t + 0.5Acos2π(1/2fs-f_{in})t

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

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

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

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

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

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

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

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

- **Normalized Frequency** \( f/f_s \)
  - \( f_{\text{in}} \)
  - \( \frac{f_s}{2} - f_{\text{in}} \)
  - \( \frac{f_s}{2} - 3f_{\text{in}} \)

- **Spurious due to interleave**

- **20log|Y|[dB]**
  - Scale from -100 to 20 dB
• Proposed Test Method
  - Single-tone Generation
  - Two-tone Generation
  - Algorithm Generalization
Proposed Method (Two-tone signal)

\[ Y = aX + bX^3 \]

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

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

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

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. \( fs \):
1024
Output Power Spectrum (Two-tone Input)

20\log|Y| [dB]

Normalized Frequency \( f/fs \)

Spurious due to interleave
• **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
2-way interleave cancels HD2.

\[ X_1 = A \sin(2\pi f_{in} t + \pi/4) \quad X_2 = A \sin(2\pi f_{in} t - \pi/4) \]
4-way interleave cancels HD2 & HD3.

\[ X_1 = \text{Asin}(2\pi f_{in} t - \pi/4 - \pi/6) \]
\[ X_2 = \text{Asin}(2\pi f_{in} t - \pi/4 + \pi/6) \]
\[ X_3 = \text{Asin}(2\pi f_{in} t + \pi/4 - \pi/6) \]
\[ X_4 = \text{Asin}(2\pi f_{in} t + \pi/4 + \pi/6) \]
Even Harmonic Cancellation

Differential structure cancels HD2 • HD4 • HD6 • HD8
HD3, HD5, HD7 cancellation

Differential structure cancels HD2 • HD4 • HD6 • HD8

Proposed method cancels HD3 • HD5 • HD7

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Experimental Verification

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

**AWG (Agilent 33120A)**
- Max. Sampling frequency (Hz): 40M
- Resolution (bit): 12
- Linearity: Δ

**Spectrum Analyzer (HP ESA-L1500A)**
- Frequency range (Hz): 9k~1.5G
- Max amplitude (Vpp): 19.8
Experiment Condition

Conventional

DSP \rightarrow DAC

\text{input} \quad X = A \sin(2\pi ft)

Proposed

DSP \rightarrow DAC

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

Conventional

Fundamental (1MHz): 6.31dBm
HD3 (3MHz): -65dBm

Proposed

Fundamental (1MHz): 5.12dBm
HD3 (3MHz): -76.5dBm (Noise floor level)

1.09dB reduction
11.5dB
Experimental Results: HD3  (fs=10MHz)

- Fundamental component power level [dBm]
- Noise floor level

HD3 power level [dB]

HD3 (Conventional)
HD3 (Proposed)
Experimental Results: HD3 reduction (fs=10MHz)

- Fundamental component power level [dBm]
- HD3 Power reduction [dB]
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**