Low-Distortion Signal Generation for ADC Testing

Fumitaka Abe, Yutaro Kobayashi, Kenji Sawada, Keisuke Kato, Osamu Kobayashi, Haruo Kobayashi

Gunma University

STARC
Research Objectives

• Use an Arbitrary Waveform Generator (AWG) as low-cost low-distortion signal source for ADC testing
• Validate our 3rd-harmonic-cancelling phase-switching signal generation technique
• Perform analysis, simulation, and experiments using AWGs for ADC testing
Expected Advantage of Our Solution

Conventional Method  Tough LPF requirements

Filter A

$\text{Filter A} \quad \text{Frequency: } 100\text{kHz} \rightarrow 300\text{kHz}$

$\text{Filter B} \quad \text{Frequency: } 300\text{kHz} \rightarrow 900\text{kHz}$

Our Method  Relaxed LPF requirements

Filter C

$\text{Filter C} \quad \text{Frequency: } 100\text{kHz} \rightarrow \frac{1}{2}f_s - f_{in}$

$\text{Filter C} \quad \text{Frequency: } 300\text{kHz} \rightarrow \frac{1}{2}f_s - f_{in}$
Outline

• Background to this research
• Proposed solution
• Problems with proposed solution
• Remedy 1
• Remedy 2
• Experimental results
• Conclusions
Outline

• Background to this research
• Proposed solution
• Problems with proposed solution
• Remedy 1
• Remedy 2
• Experimental results
• Conclusions
Background to this Research

• ADCs are important part of mixed-signal SOCs.

• Need a low-cost, low-distortion signal source for ADC linearity testing.

• #1: Use existing AWGs in testers **low cost**

• #2: Develop a technique that doesn’t require identification of AWG nonlinearity, just a DSP program change.
ADC Testing with Sine Signal

ADC test signal

\[ Z = b_1 Y + b_3 Y^3 \]

Test result

Reference level

Allowable

Freq.

Fundamental

\[ f_{\text{in}} \]

Freq.

ADC linearity test

“Go”

ADC HD3 measurement

“No Go”
Problem with Conventional Method

ADC test signal

\[ Z = b_1 Y + b_3 Y^3 \]

Test signal Generation

\[ Y = a_1 D_{in} + a_3 D_{in}^3 \]

Test result

- fundamental
- HD3

AWG HD3 + ADC HD3

ADC HD3 cannot be measured accurately.

Low quality test
Research Objective

ADC test signal

\[ Z = b_1 Y + b_3 Y^3 \]

Test signal Generation

\[ Y = a_1 D_{in} + a_3 D_{in}^3 \]

only program change

ADC test result

fundamental

HD3

Only ADC HD3

High quality test

AWG HD3 reduction
Outline

- Background to this research
- Proposed solution
- Problems with proposed solution
- Remedy 1
- Remedy 2
- Experimental results
- Conclusion
Conventional Signal Generation with AWG

AWG sampling frequency: \( f_{s(AWG)} = 1/T_s \)

\[
X = A \cos(2\pi f_{in} n T_s)
\]

DAC has 3\(^{rd}\) order nonlinearity
Proposed Signal Generation with AWG

AWG sampling frequency: \( f_{s(\text{AWG})} = 1/T_{s(\text{AWG})} \)

\[ X_0 = 1.15A \cos(2\pi f_{\text{in}} n T_s - \pi/6) \]

\[ X_1 = 1.15A \cos(2\pi f_{\text{in}} n T_s + \pi/6) \]

HD3 is cancelled
Principle of $3^{rd}$ Harmonics Cancellation

Conventional

$\Theta = \pi/3$

Principle of $3^{rd}$ Harmonics Cancellation

Fundamental: $f_{in}$

$3^{rd}$ order non-linear system

Phase rotation by $x3$

$3^{rd}$ harmonics: $3f_{in}$

$\Theta = \pi/3$

$3\Theta = \pi$

Two waves with phase difference $\pi$

are cancelled
Conventional and Phase Switching Signals

**Conventional**

**Waveform**

- Voltage [V]: 1V
- Time [sec]

**Measured Power Spectrum**

- Fundamental: 9.0dBm
- HD3: -68.0dBm

**Phase Switching**

**Waveform**

- Voltage [V]: 1.15V
- Time [sec] \( \pi/3 \)

**Measured Power Spectrum**

- Fundamental: 9.0dBm
- HD3: -78.2dBm
Outline

• Research background
• Proposed solution
• Problems of proposed solution
• Remedy 1
• Remedy 2
• Experimental results
• Conclusion
Conditions of HD3 Cancellation in Cascaded System

Input signal → 3rd nonlinearity → 3rd nonlinearity → 3rd nonlinearity

![Graphs showing normalized frequency and power in dB for input signal, 3rd nonlinearity, and phase switching.](image)

Conventional

Phase switching

HD3’s are not cancelled if attenuate spurious at $f_s/2 - f_{in}$. 

16/41
Problem of Phase Switching Signal Generation

**Ideal**

- Fundamental frequency: $f_{in}$
- Frequency: $f_{in}$

**Nonlinearity Model**

$Y = a_1X + a_3X^3$

**Phase Switching**

- Spurious due to phase switching
- Fundamental frequency: $f_{in}$
- Frequency: $f_{s(ADC)}$

**Reduction of HD3**

- Due to AWG nonlinearity
- Fundamental frequency: $f_{in}$
- Frequency: $f_{s(AWG)}/2 - f_{in}$

**HD3 due to ADC nonlinearity**

- Fundamental frequency: $3f_{in}$
- Frequency: $f_{s(ADC)}$

**Big problem!**
Model for Theoretical Analysis

AWG Input with Phase Switching

\[ D_{in}(nT_s) = \begin{cases} 
A \cdot \sin(2\pi f_{in} nT_s - \frac{\pi}{6}) & \text{n: odd} \\
A \cdot \sin(2\pi f_{in} nT_s + \frac{\pi}{6}) & \text{n: even}
\end{cases} \]

AWG Nonlinearity Model

\[ Y(nT_s) = a_1 D_{in}(n) + a_3 \{D_{in}(n)\}^3 \]

ADC Nonlinearity Model

\[ Z(n) = b_1 Y(nT_s) + b_3 \{Y(nT_s)\}^3 \]

For simplicity \( f_s(AWG) = f_s(ADC) \)

w/o LPF
AWG Output

\[ Y(nT_s) = a_1 D_{in}(n) + a_3 \{D_{in}(n)\}^3 \]

\[ = P \sin(2\pi f_{in} nT_s) \text{ signal} \]

\[ + Q \cos \left( 2\pi \left( \frac{f_s}{2} - f_{in} \right) nT_s \right) \text{ large} \]

\[ + R \cos \left( 2\pi \left( \frac{f_s}{2} - 3f_{in} \right) nT_s \right) \text{ small} \]
Direct Application of Phase Switching Signal

ADC output $Z(n)$ components

\[
\begin{align*}
\alpha_0 & \\
\alpha_{-1}\cos\left(2\pi\left(\frac{f_s}{2} - f_{in}\right)nT_s\right) & \\
\alpha_1\cos\left(2\pi\left(\frac{f_s}{2} + f_{in}\right)nT_s\right) & \\
\alpha_{-3}\cos\left(2\pi\left(\frac{f_s}{2} - 3f_{in}\right)nT_s\right) & \\
\vdots & \\
\end{align*}
\]

By calculation \[\beta_3 = \beta_{-3}\]

$3f_{in}$ and $f_s - 3f_{in}$ components are cancelled

CANNOT measure ADC HD3.
\( Y'(nT_s) = a_1 D_{in}(n) + a_3 \{D_{in}(n)\}^3 \)

\[
= P \sin(2\pi f_{in} nT_s) \\
+ q Q \cos \left( 2\pi \left( \frac{f_s}{2} - f_{in} \right) nT_s \right) \\
+ r R \cos \left( 2\pi \left( \frac{f_s}{2} - 3f_{in} \right) nT_s \right)
\]

0 < q < 1, 0 < r < 1: spurious attenuation
Application of Phase Switching and LPF

ADC output $Z(n)$ components

$$\alpha'_{0}$$

$$\alpha'_{-1}\cos\left(2\pi\left(\frac{f_s}{2} - f_{in}\right)nT_s\right)$$

$$\alpha'_{1}\cos\left(2\pi\left(\frac{f_s}{2} + f_{in}\right)nT_s\right)$$

$$\alpha'_{-3}\cos\left(2\pi\left(\frac{f_s}{2} - 3f_{in}\right)nT_s\right)$$

$$\beta'_{1}\sin(2\pi f_{in}nT_s)$$

$$\beta'_{3}\sin(2\pi3f_{in}nT_s)$$

$$\beta'_{-1}\sin(2\pi(f_s - f_{in})nT_s)$$

$$\beta'_{-3}\sin(2\pi(f_s - 3f_{in})nT_s)$$

$$\beta'_{-5}\sin(2\pi(f_s - 5f_{in})nT_s)$$

By calculation $|\beta'_{3}| \gg |\beta'_{-3}|$

$3f_{in}$ and $f_s - 3f_{in}$ components are NOT cancelled

ADC HD3 can be measured.
Spurious Attenuation Effect

AWG output and low pass filtering

\[ Y(nT_s) = P \sin(2\pi f_{in} nT_s) \]

\[ + q Q \cos\left(2\pi \left(\frac{f_s}{2} - f_{in}\right) nT_s\right) \]

\[ + r R \cos\left(2\pi \left(\frac{f_s}{2} - 3f_{in}\right) nT_s\right) \]

\[ f_s(\text{AWG})/2 - f_{in}\]

spurious reduction

Accurate HD3 measurement

![Graph showing error of \( f_{in} \) amplitude compared to \( 3f_{in} \) amplitude](graph.png)
Spurious Reduction at $f_{s(AWG)}/2 - f_{in}$

MATLAB Simulation Results

Spurious reduction at $f_{s}/2-f_{in}$

HD3 measurement Error

- 10dB: 1%
- 20dB: 0.1%

For accurate ADC HD3 measurement attenuate the spurious at $\frac{f_{s(AWG)}}{2} - f_{in}$
Outline

• Research background
• Proposed solution
• Problems of proposed solution
• Remedy 1
• Remedy 2
• Experimental results
• Conclusion
When Spurious @ $f_{s(\text{AWG})}/2 - f_{\text{in}}$ is Within $f_{s(\text{ADC})}/2$

ADC HD3 can NOT be measured accurately
When Spurious $@ \frac{f_s(AWG)}{2} - f_{in}$ is Beyond $\frac{f_s(ADC)}{2}$

Inside ADC

- $f_{in}$
- $f_s(ADC)/2$
- $f_s(AWG)/2 - f_{in}$

Reproduction of phase switching signal

HD3 cancellation

ADC

Different

ADC HD3 can be measured accurately
Conditions for Accurate ADC HD3 Measurement

\[ \frac{f_s(AWG)}{2} - f_{in} > \frac{f_s(ADC)}{2}, \text{ and/or Spurious Reduction at } \frac{f_s(AWG)}{2} - f_{in} \]

1. Spurious power reduction at \( f_s(AWG)/2 - f_{in} \)
2. \( \frac{f_s(AWG)}{2} - f_{in} > \frac{f_s(ADC)}{2} \)

Change sampling frequency by folding

Accurate measurement of ADC output HD3 with phase switching signal
Outline

• Research background
• Proposed solution
• Problems of proposed solution
• Remedy 1
• Remedy 2
• Experimental results
• Conclusion
ADC 3rd Harmonic Measurement Diagram

- Agilent 33220A
- Oscilloscope, Spectrum Analyzer
- Satisfying Remedy 1
- AD7356 Output
- ADI AD7356 12bit SAR ADC
- CLK 3.478261 MHz
- Evaluation board CED1Z
- PC FFT
- 14bit DAC
- $f_{in} = 200 kHz$
- $f_{s(AWG)} = 10 MHz$
- $f_{s(ADC)} = 3.478261 MHz$

ADC test signal generation
- Conventional
- Phase switching

Satisfying Remedy 2

$$\frac{f_{s(AWG)}}{2} - f_{in} > \frac{f_{s(ADC)}}{2}$$
Experimental Environment for ADC Testing

PC1 for test signal program

Spectrum Analyzer for test signal analysis

Oscilloscope for test signal analysis

AWG 33220A for test signal generation

Common mode noise suppression by a choke coil

EVAL-CED1Z for generating sampling clock, etc.

ADC AD7356 (12bit) 6 samples Device Under Test

Low Pass Filters

PC2 for ADC output analysis

fs(AWG) = 10MHz, fin = 200kHz

fs(ADC) = 3.476261MHz
Analog LPF Design for ADC Testing

Oscilloscope, Spectrum Analyzer

AWG
Agilent 33220A

LPF

Design Implementation Evaluation

DUT
AD7356

Evaluation board

PC
FFT

3.478261 MHz

AD7356 output

..01011..

CLK

digital output

EVAL CED1Z

fundamental @ 200kHz
HD3 @ 600kHz removal

\( f_{in} \quad 3f_{in} \quad f_{in}/2\)

\( fc=250kHz \)
5th order LC Butterworth LPF

fundamental @ 200kHz

\( f_{in} \quad 3f_{in} \quad f_{in}/2\)

\( fc=1MHz, \ 2MHz, \ 2.7MHz, \ 3.7MHz \)
4th order LC Butterworth LPF

Phase switching spurious @ 4.8MHz attenuation
LPF Implementation

Oscilloscope, Spectrum Analyzer

**AWG**
Agilent 33220A

**LPF**

**ADC**
ADI AD7356

**DUT**
digital output

..01011..

**Evaluation board**
AD7356 EVAL CED1Z

**PC**
FFT

**CLK**
3.478261 MHz

**Design Implementation Evaluation**

fc=250kHz

for HD3 reduction

fc=1MHz fc=2MHz fc=2.7MHz fc=3.7MHz

fc=1MHz

for fs/2-fin spurious reduction
LPF Evaluation with Frequency Response Analysis

Oscilloscope, Spectrum Analyzer

DUT

PC

FFT

AD7356 eval board

Evaluation board

Design Implementation Evaluation

AWG

LPF

ADC

Agilent 33220A

ADI AD7356

CLK

AD7356 output

..01011..

0.478261 MHz

-17 dB @ 4.8 MHz

-30 dB @ 4.8 MHz

-54 dB @ 4.8 MHz

-40 dB @ 600 kHz

-100

-80

-60

-40

-20

0

Gain [dB]

Frequency [Hz]

Spurious @ fs/2

HD3

fc=250kHz → -40 dB @ 600 kHz

fc=1 MHz → -54 dB @ 4.8 MHz

fc=2 MHz → -30 dB @ 4.8 MHz

fc=2.7 MHz → -17 dB @ 4.8 MHz

fc=3.7 MHz → -8.0 dB @ 4.8 MHz
Measured Waveforms of ADC Input and Output

Conventional

Phase Switching Signal

Phase switching spurious@4.8MHz attenuation

Fundamental @ 200kHz

Analog Input

Voltage [V]

Time

fs/2-fin Spurious

-8dB

-17dB

-30dB

-54dB

A/D Conversion

Digital output

Voltage [V]

Time

Codes

Sample Number

LPF

HD3 Measurement

Fundamental @ 200kHz
Comparison of Conventional and Proposed Methods

Conventional w/o LPF:
- Input frequency $f_{\text{in}}$:
  - Positive: $-6.94$ dBFS
  - Negative: $-88.1$ dBFS
- 3rd harmonic: $f_{3\text{rd}}$

Phase switching w/ LPF (fc=1MHz):
- Input frequency $f_{\text{in}}$:
  - Positive: $-7.09$ dBFS
  - Negative: $-92.6$ dBFS
- 3rd harmonic: $f_{3\text{rd}}$

Conventional w/ LPF (fc=250kHz):
- 3rd harmonic true ADC HD3:
  - Conventional method: 94.6 dBFS
  - Measured HD3: 88.1 dBFS
  - Error: 6.8%
- Proposed method:
  - Measured HD3: 92.6 dBFS
  - Error: 2.1%

Equations:
1. $\pm f_{\text{s(AWG)}} \pm f_{\text{in}}$
2. $\pm \frac{f_{\text{s}}}{2} \pm f_{\text{in}}$
ADC HD3 Measurement Results

ADC (AD7356) HD3 measurement error reduction is verified

Sample 1
Sample 2
Sample 3
Sample 4
Sample 5
Sample 6

Spurious @ fs/2-fin attenuation [dB]
ADC 3\textsuperscript{rd} harmonics detection error [%]
Outline

• Research background
• Proposed solution
• Problems of proposed solution
• Remedy 1
• Remedy 2
• Experimental results
• Conclusion
Conclusions

- Low distortion sine signal generation
- Without AWG hardware modification
- Just AWG program change
  and a simple analog LPF
- Verified with
  AWG (Agilent 33220)
  6 samples of 12bit SAR ADC (AD7356)

Greatly improved quality of ADC Linearity testing
at virtually no extra cost.
Future Work

- Generalization to other types of low distortion sinusoidal signal generation
  - HD2, HD2&HD3 cancellation for 1-tone
  - IMD3 cancellation for 2-tone
- We have partially verified these.
- Detailed theoretical analysis, simulations, and experiments are underway.