High-Frequency Low-Distortion Signal Generation Algorithm with Arbitrary Waveform Generator

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Abstract
This paper describes analysis and simulation verification of a high-frequency low-distortion signal generation method with an arbitrary waveform generator (AWG). Our previously proposed phase-switching method was limited to low-distortion but low-frequency signal generation, and therefore it cannot be used directly for high-frequency signal generation. We propose here a method for generating a low-distortion high-frequency signal with an AWG (i.e., the frequency close to the Nyquist frequency of the AWG), and show its theoretical analysis and simulation results. With this proposed method, 3rd order harmonics of the generated signal are suppressed simply by changing the AWG program (or waveform memory contents)—AWG nonlinearity identification is not required—and spurious components, generated far from the signal band, are relatively easy to remove using an analog filter.

Keyword: ADC Testing, Low Distortion Signal Generation, Distortion Shaping, Arbitrary Waveform Generator, Third-order Harmonics

1. Introduction

LSI production testing is becoming important in the semiconductor industry, because its testing cost is increasing while its silicon cost per transistor is decreasing [1]. Analog-to-Digital Converters (ADCs) are important key components in mixed-signal SoCs, and here we consider their testing at low cost with high quality.

An AWG consists of a DSP (or waveform memory) and a DAC. We can use AWGs to generate arbitrary analog waveforms simply by changing the DSP program, and Automatic Test Equipment (ATE) uses AWGs for their flexibility. However, due to AWG nonlinearities, sinusoidal signals generated by AWGs include harmonics that degrade the accuracy of ADC testing when AWGs are used as ADC input signal sources.

We have previously proposed methods for generating low-distortion (especially low 3rd harmonic distortion) signals simply by changing the AWG program, without AWG nonlinearity identification [2,3,4]. However they are limited to low-frequency signal generation. In this paper we extend the previously proposed methods for high frequency signal generation (i.e. up to approximately the Nyquist frequency ($f_s/2$) of the DAC in the AWG, where fs is a sampling frequency of the DAC). Its principle, theoretical analysis and simulation results are presented.

2. Low Distortion Signal Generation for ADC Testing

The AWG generates an analog signal through a DAC whose digital input is provided from DSP (or waveform memory). Hence the nonlinearity of the DAC causes harmonic distortion, and then we propose methods to cancel the DAC nonlinearity effects with the DSP program change as a pre-distortion [2,3,4], previously for low-frequency and here for high-frequency signal generations.

2.1. Previous Low-Frequency Low-Distortion Sinusoidal Wave Generation Technique.

Eq.1 shows a conventional (direct) sinusoidal signal generation method with AWG, where D_{in} is a digital input signal to the DAC from DSP inside the AWG.

$$\mathbf{D_{in}=A\sin(2\pi f_{in} n T_s).} \quad (1)$$

Eq.2 shows a low distortion signal generation algorithm with the previously proposed phase switching method using the AWG [2 3, 4].

$$\mathbf{D_{in}}=\begin{cases} \mathbf{X_0=A\sin(2\pi f_{in} n T_s+\varphi_0)} & \mathbf{n:even} \\ \mathbf{X_1=A\sin(2\pi f_{in} n T_s+\varphi_1).} & \mathbf{n:odd} \end{cases} \quad (2)$$

$$\boldsymbol{\varphi_x=\varphi_0-\varphi_1=(2m-1)\pi/N.} \quad \boldsymbol{m=0,1,2,\ldots} \quad (3)$$

Here, n is an integer, and T_s is a sampling period. The DSP output signal D_{in} consists of X_0 and X_1, and they are interleaved every one clock cycle (Fig.1). Signals having a phase difference φ_x reduce the Nth-order harmonics.

We consider here the case that 3rd order distortion is dominant in the DAC and ADC (Fig.2), and we use a simple model as follows:

$$\boldsymbol{Y(nT_s)=a_1D_{in}+a_3D_{in}^3} \quad (4)$$

$$\boldsymbol{Z(nT_s)=b_1Y+b_3Y^3} \quad (5)$$

Here *Y* is the AWG output and *Z* is the output of an ADC under test (Fig.2). Numerical simulation results are shown in Fig.3 and Fig.4 by using Eq.1, Eq.2 and Eq.4 (where $a_1=1.0, a_3=-0.005$, $f_{in}/f_s=121/8192$, $A=1.0$, $\varphi_0=\pi/6$, $\varphi_1=-\pi/6$). We see in Fig.4 that the phase-switching signal generation method cancels the power of the 3rd harmonics of the AWG, but it generates a high frequency spurious signals at $f_s/2-f_{in}$ and $f_s/2-3f_{in}$. We call this function as *distortion shaping* [2, 3, 4], because the distortion components move from low to high frequency bands. We can obtain low distortion signals by attenuating the spurious around fs/2 with an analog low pass filter (LPF). However this previously proposed method is limited to the use of only the low-frequency signal generation.

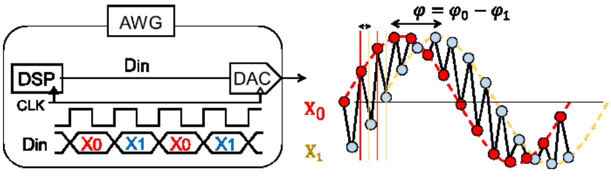

Fig.1 Phase switching signal generation method.

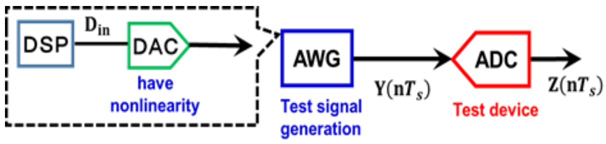

Fig2. ADC linearity testing system.

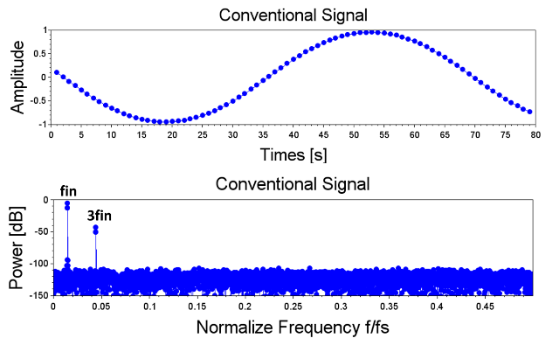

Fig3. AWG output signal waveform and spectrum with the conventional signal generation method (Eq.1).

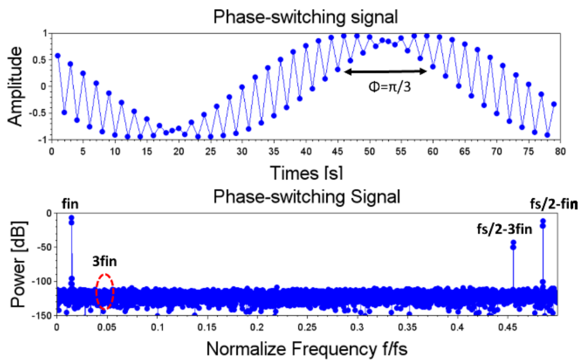

Fig.4 Low-frequency AWG output signal waveform and spectrum with the previously proposed method (Eqs.2, 3).

2.2. Proposed High-Frequency Low-Distortion Signal Generation Technique

Note that 3rd order harmonics distortion from the AWG is folded back by aliasing when the AWG generates a signal in the vicinity of half the sampling frequency (Fig.5). In the previous section, the conventional phase switching technique is described as limited to the use of only the low frequency signal generation.

We propose here to generate a low distortion signal around the Nyquist frequency, by using a phase difference φ_y:

$$\boldsymbol{\varphi_y = \varphi_0 - \varphi_1 = 2m\pi/N} \qquad (6)$$

For example, consider the case of 3rd-order cancellation method. For the low-frequency signal generation (Eq.5), $\boldsymbol{\varphi_x = \pi/3}$, and the AWG output sinusoidal signal frequency is $\mathbf{f_{in}}$. On the other hand, for the high-frequency signal generation (Eq.6), $\boldsymbol{\varphi_y = 2\pi/3}$, and the AWG output sinusoidal signal frequency is $\mathbf{f_{out} = f_s/2 - f_{in}}$ (Fig.6).

Numerical simulation results with Eq. 6 are shown in Fig.6 (where $a_1 = 1.0, a_3 = -0.005$, $f_{in}/f_s = 121/8192$, $A = 1.0, \varphi_0 = \pi/3$, $\varphi_1 = -\pi/3$). We see that compared to the low-frequency signal generation algorithm, the proposed high-frequency signal generation method generates a high frequency signal of $\mathbf{f_{out} = f_s/2 - f_{in}}$ and removes 3rd-order image signal of $\mathbf{3f_{out} = 3(f_s/2 - f_{in})}$.Note that $\mathbf{f_{in}}$ and $\mathbf{3f_{in}}$ can be reduced with an analog high pass filter (HPF).

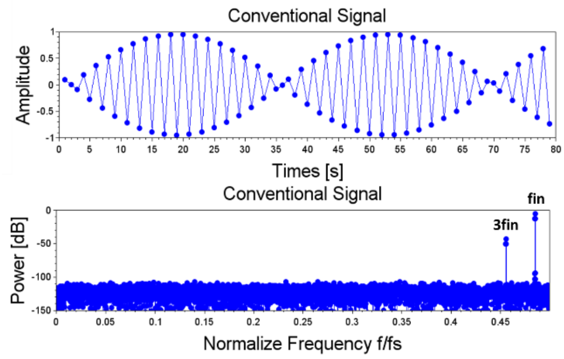

Fig5. AWG output signal waveform and spectrum at high frequency with the conventional method (Eq.1)

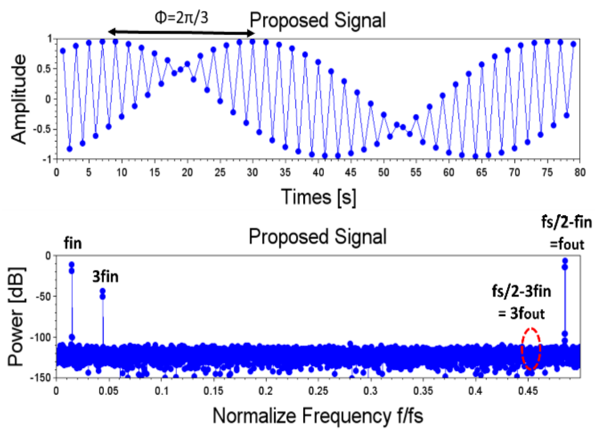

Fig6. AWG output signal waveform and spectrum at high frequency with the newly proposed method (Eq.6).

2.3. Unified Principle of Low-Frequency and High-Frequency Low-Distortion Signal Generation Methods

We consider here the unified principle of both the low-frequency and high-frequency low-distortion signal generation methods with the phase switching technique. Third-order harmonic component is generated by inputting a sinusoidal signal to the system that having 3rd order nonlinearity. Since the phase switching method interleaves two signals having the same amplitude and frequency but different phases for each clock T_s ($T_s \equiv 1/f_s$), an image signal is also generated around $f_s/2$, and then four frequency components are produced; fundamental component f_{in}, its 3rd order distortion component $3f_{in}$, image signal $f_s/2$-f_{in}, and 3rd order image signal $f_s/2$-$3f_{in}$ (Fig.7). The 3rd harmonic components of the two input signals are cancelled with the reverse phase (φ_x), and also the 3rd order image signals of the two input signals are cancelled with the same phase (φ_y) (Fig.8).

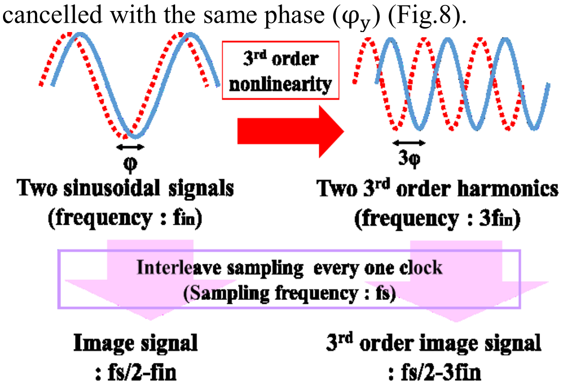

Fig.7. Frequency components appearing with the phase switching technique.

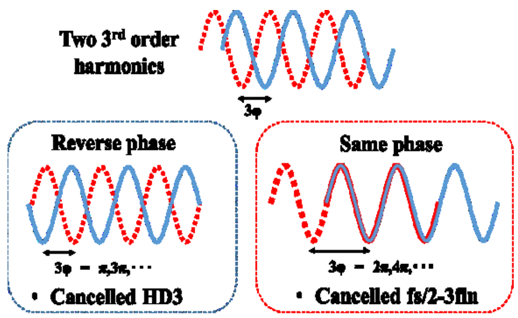

Fig.8. HD3 components cancellation using the phase difference.

3. HD3 Measurement of ADC Under Test

3.1 Problem and Remedy

Fig.9 shows the simulated output spectrum of ADC with 3rd order nonlinearity for the input signal generated by the proposed high-frequency phase switching method. We see that $\mathbf{3f_{out}}$ component is cancelled; this means that the proposed high-frequency signal generation method cancels not only AWG 3rd order nonlinearity effects of the AWG but also that of the ADC; thus the proposed method cannot test the ADC 3rd-order nonlinearity. This is exactly the same problem as the previously proposed low-frequency signal generation method [2].

However, we will show in simulation that its remedy is also the same as [2]. After the AWG output (i.e., before the ADC input), we place a simple analog HPF and reduces low-frequency spurious. Then $\mathbf{3f_{out}}$ component due to the ADC 3rd-order nonlinearity appears (Fig.10) and thus the 3rd-order nonlinearity of the ADC under test can be measured.

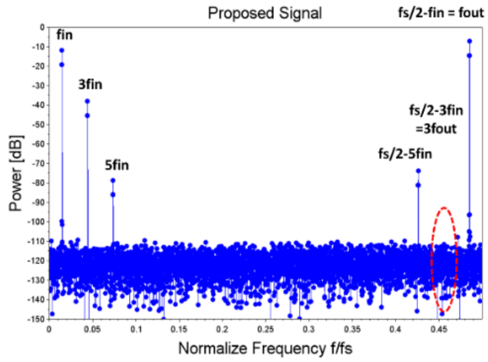

Fig9. ADC output spectrum of high frequency with phase-switching method.

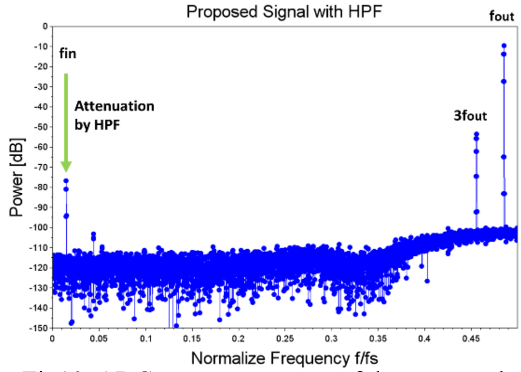

Fig10. ADC output spectrum of the proposed high-frequency phase-switching method, and $\mathbf{3f_{out}}$ component recovers.

3. 2 Theoretical Analysis

In this subsection, we show theoretical analysis of the problem and its remedy (adding a simple analog HPF) of the proposed high-frequency low-distortion signal generation method.

A. AWG modeling

We have analyzed the phase switching signals by using a mathematical model (Eq. 7) to find reasons reducing harmonic distortion by utilizing the phase switching technique. We obtain AWG output as Eq.7 from Eq.2, Eq.4 and Eq.6. We see that the HD3 image ($f_s/2$-$3f_{in}$) component is cancelled in Eq.7.

$$\begin{aligned}\mathbf{Y(nT_s)} &= \boldsymbol{\alpha} * \mathbf{P\,sin(2\pi f_{in} nT_s)} \\ &+ \boldsymbol{\beta} * \mathbf{Q\,cos(2\pi(3f_{in})nT_s)} \\ &+ \mathbf{R\,cos}\left(\mathbf{2\pi}\left(\frac{\mathbf{f_s}}{\mathbf{2}} - \mathbf{f_{in}}\right)\mathbf{nT_s}\right). \end{aligned} \quad (7)$$

$$\mathbf{P} \equiv -\frac{1}{2}\left(\mathbf{a_1 A} + \frac{3}{4}\mathbf{a_3 A^3}\right), \mathbf{Q} \equiv -\frac{1}{4}\mathbf{a_3 A^3},$$
$$\mathbf{R} \equiv \frac{\sqrt{3}}{2}\left(\mathbf{a_1 A} + \frac{3}{4}\mathbf{a_3 A^3}\right).$$

We consider the case that an analog HPF following the AWG attenuates (f_{in}) component by α and ($3f_{in}$) component by β (0≤α,β≤1).

B. Theoretical analysis for high frequency low distortion signal generation method

We assume here f_s(AWG) = f_s(ADC) for simplicity, and we model the ADC under test as in Eq.5. Then the ADC output can be calculated as follows;

$$\begin{aligned}
&Z(nT_s) \\
&= \left\{b_1 R + \frac{3}{4} b_3 R(R^2 + \alpha^2 P^2 + 2\alpha\beta PQ \right. \\
&\left. + 2\beta^2 Q)\right\} \cos\left\{2\pi\left(\frac{f_s}{2} - f_{in}\right) nT_s\right\} \\
&+ \left\{\frac{1}{4} b_3 R\,(R^2 - 3\alpha^2 P^2)\right\} \cos\left\{2\pi\left(\frac{f_s}{2} - 3f_{in}\right) nT_s\right\} \\
&- \frac{3}{4}\beta b_3 QR(2\alpha P + \beta Q) \cos\left\{2\pi\left(\frac{f_s}{2} - 5f_{in}\right) nT_s\right\} \\
&- \frac{3}{4}\beta^2 b_3 Q^2 R \cos\left\{2\pi\left(\frac{f_s}{2} - 7f_{in}\right) nT_s\right\} \\
&+ \left\{\alpha b_1 P + \frac{3}{4} b_3\{\alpha^3 P^3 + \beta Q R^2 - \alpha^2 \beta P^2 Q \right. \\
&\left. + \alpha P(R^2 + 2\beta^2 Q^2)\}\right\} \sin\{2\pi(f_{in}) nT_s\} \\
&+ \left\{\beta b_1 Q + \frac{b_3}{4}(3\alpha P R^2 - \alpha^3 P^3 + 6\beta Q R^2 \right. \\
&\left. + \alpha^2 \beta P^2 Q + 3\beta^3 Q^3)\right\} \sin\{2\pi(3f_{in}) nT_s\} \\
&+ \frac{3}{4}\beta b_3 Q\{R^2 + \alpha P(\beta Q - \alpha P)\} \sin\{2\pi(5f_{in}) nT_s\} \\
&- \frac{3}{4}\alpha\beta^2 b_3 P Q^2 \sin\{2\pi(7f_{in}) nT_s\} \\
&- \frac{1}{4}\beta^3 b_3 Q^3 \sin\{2\pi(9f_{in}) nT_s\}
\end{aligned} \qquad (8)$$

In the signal generated with the proposed method, 3rd order harmonic is equal to $f_s/2\text{-}3f_{in}$. Then the coefficient of $\cos\{2\pi(f_s/2 - 3f_{in})nT_s\}$ term is given by

$$\begin{aligned}
&\frac{1}{4} b_3 R\,(R^2 - 3\alpha^2 P^2) \\
&= -\frac{3\sqrt{3}}{32} b_3 A^2 \left(a_1 A + \frac{3}{4} a_3 A^3\right)(\alpha^2 - 1).
\end{aligned} \qquad (9)$$

Eq.9 shows the amplitude of the image signal $f_s/2\text{-}3f_{in}$ component to the 3rd order harmonic distortion with phase switching varies by α. When we don't reduce the spurious (i.e., α = 1), the amplitude of the $f_s/2\text{-}3f_{in}$ components is cancelled.

Fig.11 shows numerical calculation results of the error of $[\boldsymbol{f_{out}\ Amplitude}]/[\boldsymbol{3f_{out} Amplitude}]$ between the phase switching signal input with attenuation α and the ideal sinusoidal input cases for $a_1 = b_1 = 1, a_3 = b_3 = -0.005, \beta = 1$. We see that when the smaller α is, the smaller error is. As an example, the measurement error of HD3 can be 1.7% at α = 0.1 (i.e., attenuation by a factor of 1/10 with a HPF which is not difficult).

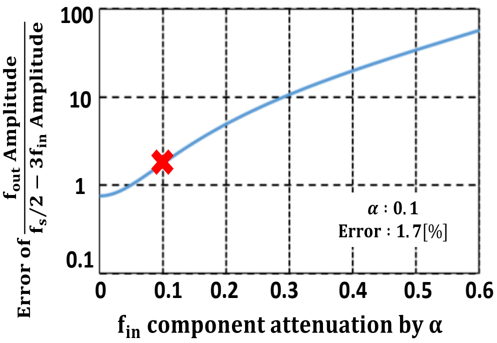

Fig.11. Error of the measurable f_{out} and 3rd order spurious amplitude ratio with proposed method.

4. Conclusion

We have proposed a high-frequency low-distortion signal generation algorithm with the AWG using the phase switching technique, by extending the previously proposed low-frequency signal generation algorithm. The proposed method does not need the AWG nonlinearity identification. It needs only a simple analog HPF. Its principle, theoretical analysis and simulation results are shown.

We close this paper by remarking that the 3rd-order image cancellation is discussed here, however, cancellation of the 2nd-order, or another order image signal as well as their combination is also possible; similar arguments were already discussed for the previously proposed low-frequency signal generation methods [3].

Acknowledgments

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