High-Frequency Low-Distortion One-Tone and Two-Tone Signal Generation Using Arbitrary Waveform Generator

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Abstract - This paper describes algorithms and simulation verification of low-distortion sinusoidal signal generation methods with harmonics and image cancellation using an arbitrary waveform generator. We show high-frequency sinusoidal signal generation algorithms with HD3 image cancellation, HD3 & HD5 images cancellation, and point out that even harmonics images (such as HD2 image) is not required because they are far from the signal frequency. Also we show high-frequency two-tone signal generation with IMD3 suppression. With these methods, distortion components close to the signal are suppressed simply by changing the DSP program—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, Arbitrary Waveform Generator

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]. ADC 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 the Arbitrary Waveform Generators (AWG) to generate arbitrary analog waveforms simply by changing the DSP program, and Automatic Test Equipment (ATE) uses AWGs thanks to 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.

This paper presents methods for generating a low-distortion high-frequency one-tone and two-tone signals with image and IMD suppression simply by changing the AWG program, without AWG nonlinearity identification. Here we show that its simultaneous HD3 and HD5 image suppressions are possible, and that HD2 image is far from the signal component. Also high-frequency two-tone signal generation with IMD3 suppression is shown. Their principle, theoretical analysis and simulation results are presented.

The reference [2] shows a low-distortion one-tone signal generation algorithm with the AWG nonlinearity compensation, but it requires AWG nonlinearity identification. On the other hand, we have investigated the phase switching algorithm for one-tone and two-tone signal generation which does not require AWG nonlinearity identification. For the low-frequency signal generation, the references [3] [4] [5] show its algorithms, experimental results at laboratory level and ATE application results, respectively. The reference [6] shows the two-tone case. For the *high-frequency* signal generation, the reference [7] shows only HD3 image cancellation algorithm of one-tone signal. In this paper, we show *high-frequency* signal generation with multiple-image cancellation and also *high-frequency* two-tone signal generation with IMD3 suppression.

Note that here *high frequency* means "up to approximately the Nyquist frequency ($f_s/2$) of the DAC in the AWG, where fs is a sampling frequency of the DAC". HD stands for harmonic distortion, and IMD stands for intermodulation distortion.

2. One-Tone Signal Generation

The AWG generates an analog signal through a DAC whose digital input is provided from DSP. 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 pre-distortion.

The direct sinusoidal signal generation method with AWG uses the following, where D_{in} is a digital input signal to the DAC from DSP inside the AWG.

$$D_{in} = A\sin(2\pi f_{in} nT_s) \quad (1)$$

For the low-distortion signal generation with the AWG, our phase switching method uses the following:

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

For low-frequency generation

$$\varphi_x = \varphi_0 - \varphi_1 = (2m-1)\pi/N. \quad (3)$$

For high-frequency generation

$$\varphi_y = \varphi_0 - \varphi_1 = 2m\pi/N. \quad (4)$$

Here $m = 0,1,2,\ldots$, and n is an integer, while 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, or φ_y reduce the Nth-order harmonics or image.

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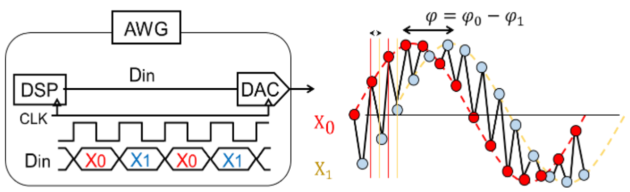

Fig. 1 Phase switching signal generation method.

2.1 HD3 Image Cancellation

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

$$Y(nT_s) = a_1 D_{in} + a_2 D_{in}^2 + a_3 D_{in}^3 \quad (5)$$

$$Z(nT_s) = b_1 Y + b_2 Y^2 + b_3 Y^3 \quad (6)$$

Here Y is the AWG output and Z is the output of an ADC under test.

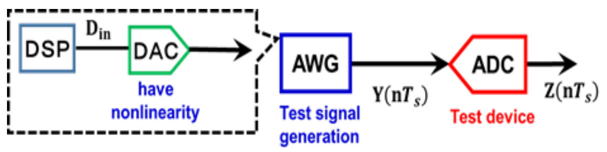

Fig. 2. ADC linearity testing system.

In case of high-frequency sinewave generation, Fig. 3 shows the simulated AWG output power spectrum with the direct method (Eq. 1), and Fig. 4 shows the one with 3rd-order image cancellation method (Eqs. 2, 4). Where $a_1 = 1, a_2 = 0, a_3 = 1, f_{in}/f_s = 50/1024$, A $= 1, \varphi_0 = \pi/3$, $\varphi_1 = -\pi/3$.

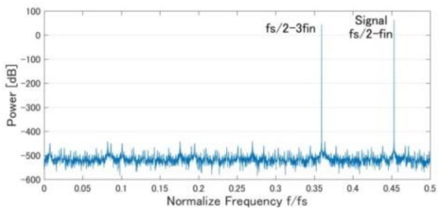

Fig. 3. Y(nTs) spectrum with the direct high-frequency signal generation with AWG 3rd-order distortion (using Eq.1).

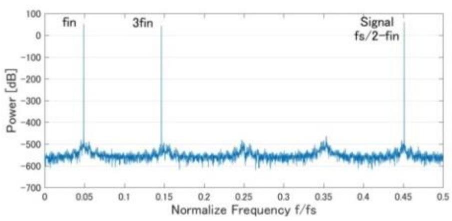

Fig. 4. Y(nTs) spectrum with the phase-switching high-frequency signal generation with AWG 3rd-order distortion (using Eqs. 2, 4).

2.2 HD2 Image Cancellation

Consider the HD2 cancellation method. For the high-frequency signal generation (Eqs. 2, 4), $\varphi_y = \pi$ and the AWG output sinusoidal signal frequency is $f_{out} = f_s/2 - f_{in}$. Numerical simulation results with Eqs. 2, 4 are shown in Fig.5 (where $a_1 = 1, a_2 = 1, a_3 = 0, f_{in}/f_s = 50/1024$, A $= 1, \varphi_0 = \pi/2$, $\varphi_1 = -\pi/2$). We see that the high-frequency signal generation method generates a signal of $f_{out} = f_s/2 - f_{in}$ and there are no HD2 image components close to this signal frequency in Fig. 5 even without phase switching; we do not need HD2 image cancellation for high frequency generation.

This statement is valid in all even-order image cases for the *high-frequency* signal generation.

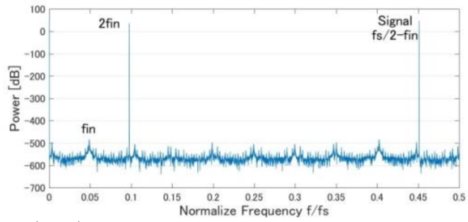

Fig.5. Y(nTs) spectrum with the phase-switching high-frequency signal generation with AWG 2nd-order distortion (using Eqs. 2, 4)).

2.3 Multiple-Image Cancellation

Now we consider the case that the AWG has 3rd and 5th order distortions and we consider to cancel their effects to generate a low-distortion high-frequency sine signal. Consider the case that the AWG has 3rd and 5th-order distortions:

$$Y(nT_s) = a_1 D_{in} + a_3 D_{in}^3 + a_5 D_{in}^5 \quad (7)$$

Then let

$$D_{in} = \begin{cases} X_0 = A\sin(2\pi f_{in} nT_s - \varphi_a - \varphi_b) & n = 4k \\ X_1 = A\sin(2\pi f_{in} nT_s - \varphi_a + \varphi_b) & n = 4k+1 \\ X_2 = A\sin(2\pi f_{in} nT_s + \varphi_a - \varphi_b) & n = 4k+2 \\ X_3 = A\sin(2\pi f_{in} nT_s + \varphi_a + \varphi_b) & n = 4k+3 \end{cases} \quad (8)$$

$$\varphi_a = \frac{\pi}{6}, \quad \varphi_b = \frac{\pi}{5}. \quad (9)$$

Also for the simulation conditions, we set

$$f_{in}/f_s = 20/1024$$

$$A = 1, a_1 = 1, a_3 = 0.3, a_5 = 0.3$$

Fig. 6 shows the power spectrum with the direct method. Fig. 7 shows the one with the proposed method with Eqs. 7, 8; we see that the spurious components at the vicinity of the signal component (fs/2 – fin) are removed.

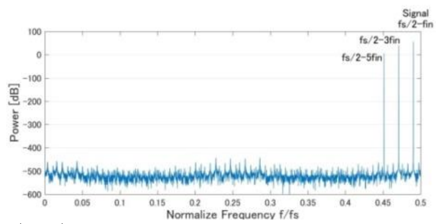

Fig. 6. Y(nTs) spectrum with the direct high-frequency signal generation method with AWG 3rd and 5th-order distortions. (using Eq.1).

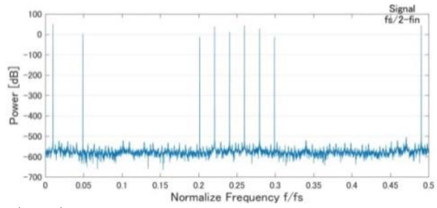

Fig. 7. Y(nTs) spectrum with the phase-switching high-frequency signal generation method with DAC HD3, HD5 (using Eqs. 2, 3, 6).

3. Two-tone Signal Generation

Two-tone signal testing is frequently used in ADC testing for such as communication applications. When the 3rd-order nonlinearity is dominant in the AWG and f_{out1}, f_{out2} are used, IMD3 components ($2f_{out1}$-f_{out2}, $2f_{out2}$-f_{out1}) are serious because they are close to the signals (f_{out1}, f_{out2}) and are difficult to remove with an analog filter. Then we consider to apply the phase switching algorithm. Suppose that the AWG has 3rd-order distortion. Suppose the following:

$$Y(nT_s) = a_1 D_{in} + a_3 D_{in}^3 \qquad (10)$$

For the direct method, we use

$$D_{in} = A\sin(2\pi f_1{}' nT_s) + B\sin(2\pi f_2{}' nT_s) \qquad (11)$$

Simulation conditions are as follows:

$$f_1/f_s = 31/1024, \qquad f_2/f_s = 47/1024$$
$$f_1'/f_s = (f_s/2 - f_1)/f_s = 481/1024$$
$$f_2{}'/f_s = (f_s/2 - f_2)/f_s = 465/1024$$
$$A = 1, B = 1, a_1 = 1, a_3 = 1.$$

Then the output spectrum is shown in Fig. 10.

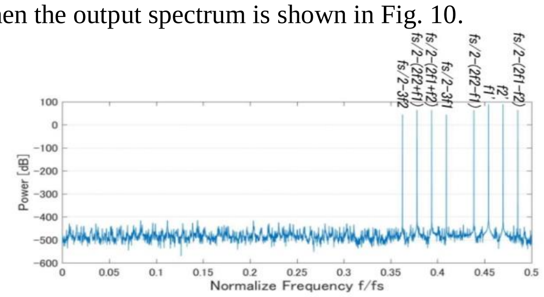

Fig. 8 Y(nTs) spectrum with the direct high-frequency two-tone signal generation method with AWG 3rd-order distortion (using Eq. 10)

On the other hand, let us consider the high-frequency two-tone phase switching algorithm:

$$D_{in} = \begin{cases} X_0 = A\sin(2\pi f_1 nT_s + \varphi_0) + A\sin(2\pi f_2 nT_s - \varphi_0) & n\text{: even} \\ X_1 = A\sin(2\pi f_1 nT_s - \varphi_0) + A\sin(2\pi f_2 nT_s + \varphi_0) & n\text{: odd} \end{cases} \qquad (11)$$

$$\varphi_0 = \frac{\pi}{3} \qquad (12)$$

The output power spectrum is shown in Fig. 9, and we see that the IMD3 components are cancelled.

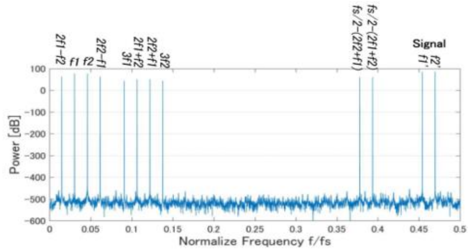

Fig. 9 Y(nTs) spectrum with the phase-switching high-frequency two-tone signal generation method with 3rd order distortions.

4. Conclusion

We have described our high-frequency low-distortion one-tone and two-tone generation algorithms with an AWG using the phase switching technique. It does not need the AWG nonlinearity identification, but need only a simple analog HPF. Simulation results show their effectiveness.

For future work:

(1) We evaluate the *high-frequency* phase switching algorithms at laboratory level and ATE application level, as was done for the *low-frequency* ones [4][5].

(2) We have developed the low-frequency (close to DC) and high-frequency (close to fs/2) phase switching algorithms. Then we will develop the *mid-frequency* (close to fs/4) phase switching algorithm.

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