Low-Distortion One-Tone and Two-Tone Signal Generation Using AWG Over Full Nyquist Region

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Abstract - This paper describes algorithms, simulation and experiment verifications of a novel harmonic distortion suppression technique for an arbitrary waveform generator (AWG). It can automatically suppress the harmonics and the image components over a full Nyquist region of the AWG by preprocessing the sinusoidal waveform digital data using "phase switching method". We show this technique can apply to cancel the harmonics from mid-frequency regions. Also we show two-tone signal generation with IMD suppression. With these methods, distortion components close to the signal are suppressed simply by changing DSP 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: Analog/Mixed-Signal IC Testing, Low Distortion Signal Generation, Arbitrary Waveform Generator, Sine Wave, Two-Tone Signal

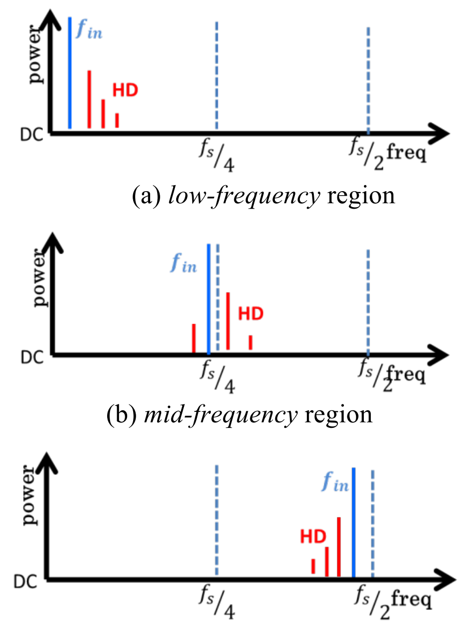
1. Introduction

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]. Especially low-cost and high-quality testing of analog/mixed-signal circuits are important.

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

This paper presents methods for generating a low-distortion one-tone and two-tone signals with harmonics, images and IMD suppression from low, mid frequency regions. Table I clarifies the position of this paper in this field.

As shown in the Fig.1, the regions where harmonics appear near the fundamental wave can be divided into three: "*low-frequency*", "*mid-frequency*" and "*high-frequency*" regions.



(a) *low-frequency* region

(b) *mid-frequency* region

(c) *high-frequency* region

Fig.1 Regions where harmonics appear near the fundamental wave

Note that here *mid-frequency* means *"the frequency region around fs/4"*, and *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". Also HD stands for harmonic distortion, and IMD stands for intermodulation distortion.

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][7] shows the two-tone case. For the *high-frequency* signal generation, the reference [8] shows only HD3 image cancellation algorithm of one-tone signal. The paper [9] shows *high-frequency* single-tone and two-tone signals generation with image and IMD suppression. This paper

978-1-5386-5180-3/18/$31.00 ©2018 IEEE
DOI 10.1109/ITC-Asia.2018.00026

shows *mid-frequency* single-tone and two-tone signals generation with image and IMD suppression

Then with this paper and the references [3-9], low-distortion one-tone and two-tone signal generation using AWG over full Nyquist region becomes possible.

Table I Overview of our phase switching methods

	Low frequency	*Mid frequency*	*High frequency*
Single-tone	[3,4, 5]	This paper	[8]
Two-tone	[3, 6, 7]	This paper	[8, 9]

2. Theory of Phase-Switching Method and *Low-Frequency* 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.

2.1 Single-Tone Signal Generation

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.

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

For the low-distortion signal generation with the AWG [3-5], our phase switching method uses the following:

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

For low-frequency generation

$$\varphi = \varphi_0 - \varphi_1 = (2m-1)\pi/N \tag{3}$$

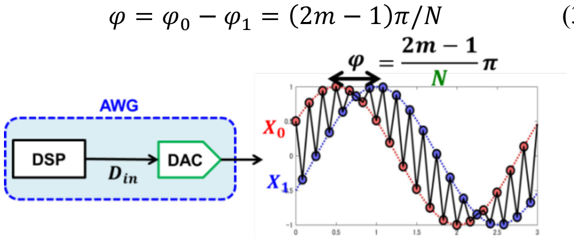


Fig.2 Phase-switching method

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 (Fig.2).

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

$$Y(nT_s) = a_1 D_{in} + a_3 D_{in}^3 \tag{4}$$

Here, considering the 3rd order harmonics (HD3), X_0 and X_1 are as shown in equations (5) and (6).

$$a_1 X_0 + a_3 X_0^3 = \frac{4a_1 A + 3a_3 A^3}{4}\sin(2\pi f_{in} nT_s + \varphi_0) - \frac{a_3 A^3}{4}\sin(2\pi \cdot 3 f_{in} nT_s + 3\varphi_0) \tag{5}$$

$$a_1 X_1 + a_3 X_1^3 = \frac{4a_1 A + 3a_3 A^3}{4}\sin(2\pi f_{in} nT_s + \varphi_1) - \frac{a_3 A^3}{4}\sin(2\pi \cdot 3 f_{in} nT_s + 3\varphi_1) \tag{6}$$

The interleave operation can be expressed by the following equation:

$$\begin{aligned} Y(nT_s) &= \frac{1}{2}\left\{1 + \cos\left(2\pi \cdot \frac{f_s}{2} nT_s\right)\right\}(a_1 X_0 + a_3 X_0^3) + \frac{1}{2}\left\{1 - \cos\left(2\pi \cdot \frac{f_s}{2} nT_s\right)\right\}(a_1 X_1 + a_3 X_1^3) \\ &= \frac{4a_1 A + 3a_3 A^3}{8}\left(e^{j\varphi_0} + e^{j\varphi_1}\right)\sin(2\pi f_{in} nT_s) - \frac{a_3 A^3}{8}\left(e^{j3\varphi_0} + e^{j3\varphi_1}\right)\sin(2\pi \cdot 3 f_{in} nT_s) \\ &\quad - \frac{4a_1 A + 3a_3 A^3}{8}\left(e^{j\varphi_0} - e^{j\varphi_1}\right)\sin\left(2\pi\left(\frac{f_s}{2} - f_{in}\right)nT_s\right) \\ &\quad + \frac{a_3 A^3}{8}\left(e^{j3\varphi_0} - e^{j3\varphi_1}\right)\sin\left(2\pi\left(\frac{f_s}{2} - 3f_{in}\right)nT_s\right) \end{aligned} \tag{7}$$

To cancel 3rd order harmonics, φ_0 and φ_1 have to satisfy the following condition:

$$e^{j3\varphi_0} + e^{j3\varphi_1} = 0 \tag{8}$$

$$\varphi_0 - \varphi_1 = \frac{(2m-1)\pi}{3} \quad (m = 1,2,3\ldots) \tag{9}$$

In brief, it takes the following values:

$$\varphi_0 = \frac{\pi}{6}, \qquad \varphi_1 = -\frac{\pi}{6} \tag{10}$$

If the phase difference is determined by the above method, it is possible to create a waveform that removes only arbitrary harmonic components.

Also for the simulation conditions, we set

$$f_{in}/f_s = 3/200$$

$$A = 1, \qquad a_1 = 1, \qquad a_3 = -0.01$$

Figs 3, 4 show simulation results for the direct and phase switching methods respectively, and we see in Fig 3 that HD3 component is removed by the phase switching. Spurious appears on the high frequency side, but it is removed with an analog filter. Rather than directly filtering the third harmonic, setting order and design of the filter is simplified.

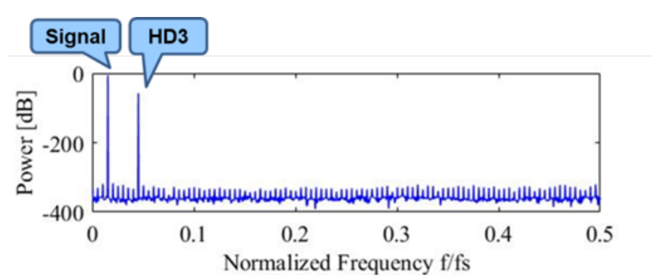


Fig.3. $Y(nT_s)$ spectrum with the direct *low-frequency* signal generation method with AWG 3rd -order distortions. (using Eq.1).

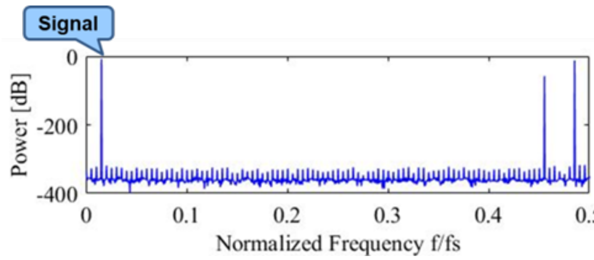


Fig.4 $Y(nT_s)$ spectrum with the phase-switching *low-frequency* signal generation with AWG 3rd-order distortion(using Eq.2).

2.2 Multiple Harmonics suppression

Now we consider the case that the AWG has 3rd and 5th order distortions (Eq. 11) and we consider to cancel their effects to generate a low-distortion sine signal.

$$Y(nT_s) = a_1 D_{in} + a_3 D_{in}^3 + a_5 D_{in}^5 \qquad (11)$$

Then let

$$D_{in} = \begin{cases} X_0 = A\sin(2\pi f_{in} nT_s - \varphi_a - \varphi_b) & n = 4k \\ X_1 = A\sin(2\pi f_{in} nT_s + \varphi_a - \varphi_b) & n = 4k+1 \\ X_2 = A\sin(2\pi f_{in} nT_s - \varphi_a + \varphi_b) & n = 4k+2 \\ X_3 = A\sin(2\pi f_{in} nT_s + \varphi_a + \varphi_b) & n = 4k+3 \end{cases} \qquad (12)$$

$$\varphi_a = \frac{\pi}{6}, \quad \varphi_b = \frac{\pi}{10}$$

Also for the simulation conditions, we set

$$f_{in}/f_s = 1/200$$

$$A = 1, \qquad a_1 = 1, \qquad a_3 = -0.01, \qquad a_5 = -0.001$$

Fig. 5 shows the power spectrum with the direct method. Fig. 6 shows the one with the proposed method with Eq. 12; we see that there are no harmonics around the fundamental signal.

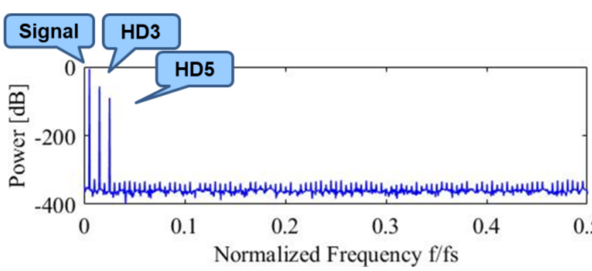


Fig.5 $Y(nT_s)$ spectrum with the direct *low-frequency* signal generation method with AWG 3rd and 5th-order distortions. (using Eq.1).

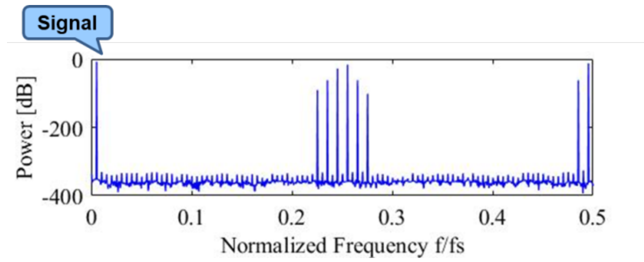


Fig.6 $Y(nT_s)$ spectrum with the phase-switching *low-frequency* signal generation with AWG 3rd and 5th-order distortion (using Eq. 12).

2.3 Two-Tone Signal Generation

Two-tone signal testing is frequently used for testing of communication application circuits. 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:

$$Y(nT_s) = a_1 D_{in} + a_3 D_{in}^3 \qquad (13)$$

For the direct method, we use

$$D_{in} = A\sin(2\pi f_1 nT_s) + B\sin(2\pi f_2 nT_s) \qquad (14)$$

Simulation conditions are as follows:

$$f_1/f_s = 3/200, \qquad f_2/f_s = 4/200$$

$$A = 1, \qquad B = 1, \qquad a_1 = 1, \qquad a_3 = -0.01$$

Then the output spectrum is shown in Fig.7.

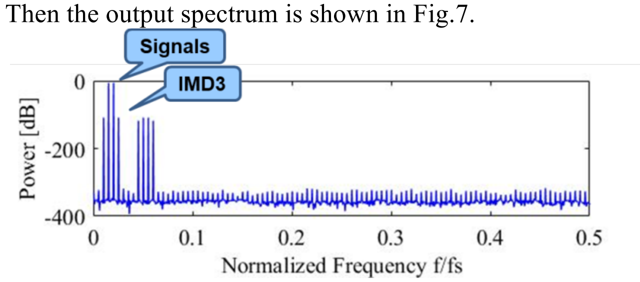


Fig.7. $Y(nT_s)$ spectrum with the direct *low-frequency* two-tone signal generation method with AWG 3rd-order distortion (using Eqs. 13)

We proposed to use Eqs. (15), (16) for a *low-frequency* two-tone signal without IMD3 [3,6].

$$D_{in} = \begin{cases} X_0 = A\sin(2\pi f_1 nT_s + \varphi_0) + B\sin(2\pi f_2 nT_s - \varphi_0) & n\text{: even} \\ X_1 = A\sin(2\pi f_1 nT_s - \varphi_0) + B\sin(2\pi f_2 nT_s + \varphi_0) & n\text{: odd} \end{cases} \qquad (15)$$

$$\varphi_0 = \frac{\pi}{6} \qquad (16)$$

Fig.8 shows simulation results.

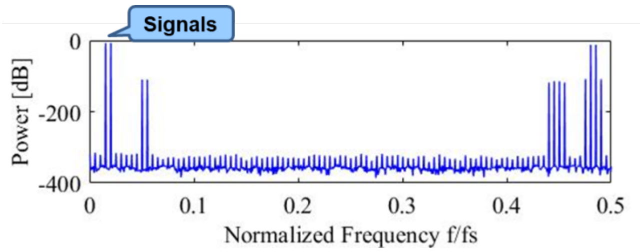


Fig.8. $Y(nT_s)$ spectrum with the phase-switching *low-frequency* two-tone signal generation method with 3rd order distortions.

3. Mid-Frequency Signal Generation

3.1 Single-Tone Signal Generation

Let us consider the *mid-frequency* signal generation case. We propose the following:

$$D_{in} = \begin{cases} X_0 = A\sin(2\pi f_{in} nT_s + \varphi_0) & n = 4k-3, \quad 4k-2 \\ X_1 = A\sin(2\pi f_{in} nT_s - \varphi_1) & n = 4k-1, \quad 4k \end{cases} \quad \textbf{(17)}$$

$$\varphi_0 - \varphi_1 = (2m-1)\pi/N$$

For the simulation conditions, we set

$$f_{in}/f_s = 49/200$$

$$A = 1, \quad a_1 = 1, \quad a_3 = -0.01$$

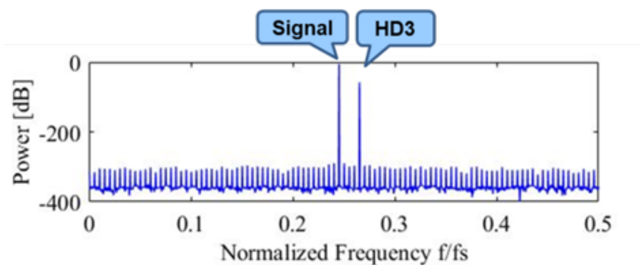


Fig.9. $Y(nT_s)$ spectrum with the direct *mid-frequency* signal generation method with AWG 3rd -order distortions. (using Eq.1).

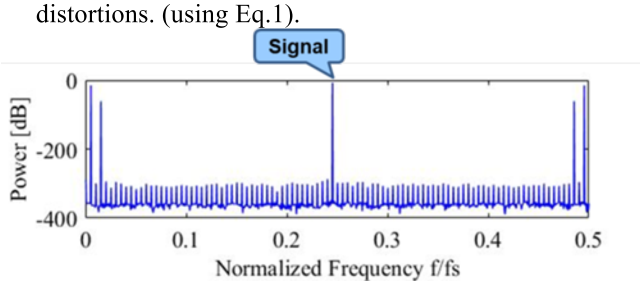


Fig.10. $Y(nT_s)$ spectrum with the phase-switching *mid-frequency* signal generation with AWG 3rd-order distortion(using Eq.17).

Figs.9, 10 show simulation results for the direct and phase switching methods respectively, and we see in Fig. 10 that HD3 component is removed by the phase switching. Although spurious appears on the low frequency side and the high frequency side, it is removed by using a band-pass filter (BPF).

In the case that the fundamental frequency is exactly $f_s/4$, fundamental and the 3rd order harmonics overlap. With the proposed algorithm, only the 3rd order harmonics can be cancelled.

$$f_{in}/f_s = 50/200$$

$$A = 1, \quad a_1 = 1, \quad a_3 = -0.01$$

The theoretical amplitude values of the fundamental frequency are as follows:

・Direct method

$$20\log_{10}\left\{\left(\frac{4a_1A + 3a_3A^3}{4} - \frac{a_3A^3}{4}\right)/2\right\} = -6.108\text{dB}$$

・Phase-switching method

$$20\log_{10}\left\{\frac{4a_1A + 3a_3A^3}{4}/2\right\} = -6.086\text{dB}$$

Output power spectrums are shown in Figs. 11 and 12.

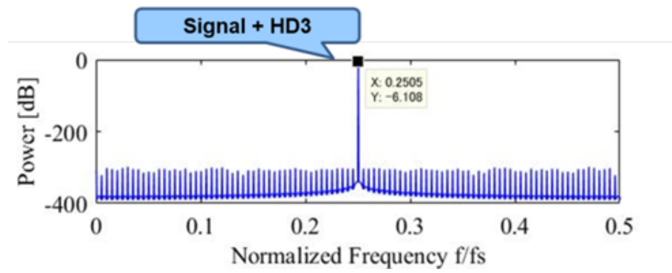


Fig.11. $Y(nT_s)$ spectrum with the direct just *mid-frequency* signal output with 3rd order harmonics (fundamental :-6.108dB)

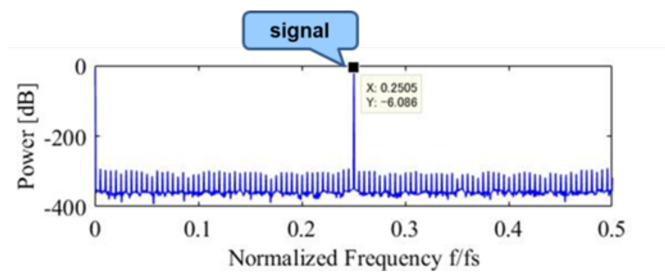


Fig.12. $Y(nT_s)$ spectrum with the phase-switching just *mid-frequency* signal output with 3rd order harmonics (fundamental : -6.086dB)

3.2 Multiple Harmonics Suppression

We propose to use Eqs.10,11 to generate a *mid-frequency* signal.

$$D_{in} = \begin{cases} X_0 = A\sin(2\pi f_{in} nT_s - \varphi_a - \varphi_b) & n = 8k-7,\ 8k-6 \\ X_1 = A\sin(2\pi f_{in} nT_s + \varphi_a - \varphi_b) & n = 8k-5,\ 8k-4 \\ X_2 = A\sin(2\pi f_{in} nT_s - \varphi_a + \varphi_b) & n = 8k-3,\ 8k-2 \\ X_3 = A\sin(2\pi f_{in} nT_s + \varphi_a + \varphi_b) & n = 8k-1,\ 8k \end{cases} \quad (18)$$

$$\varphi_a = \frac{\pi}{6}, \quad \varphi_b = \frac{\pi}{10} \quad (19)$$

Fig.13 shows the power spectrum with the direct method. Fig. 14 shows the one with the proposed method with Eqs. 18, 19; we see that there are no harmonics and spurious around the signal.

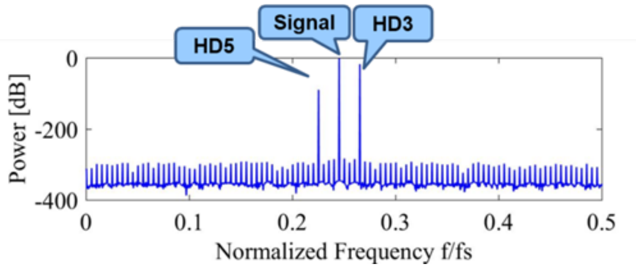


Fig.13. $Y(nT_s)$ spectrum with the direct *mid-frequency* signal with AWG 3rd and 5th-order distortion (using Eq.1).

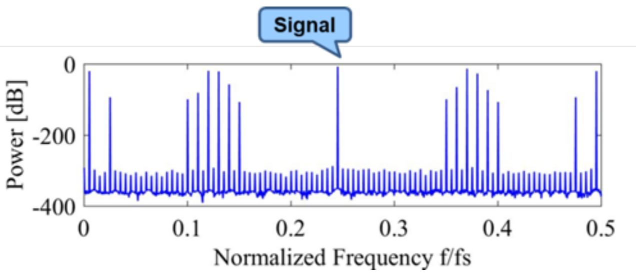


Fig.14. $Y(nT_s)$ spectrum with the phase-switching *mid-frequency* signal generation with AWG 3rd and 5th-order distortion (using Eq.18).

3.3 Two-Tone Signal Generation

For mid-frequency two-tone signal generation without IMD3, the condition for f1, f2 shown in Fig.15 should be satisfied.

$$f_1 = \frac{f_s}{4} - f_k, \quad f_2 = \frac{f_s}{4} + f_k$$

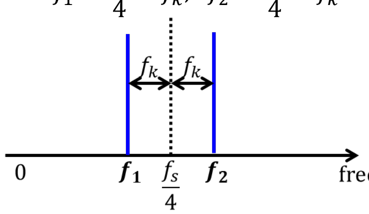


Fig.15. Condition of *mid-frequency* two-tone signal frequency configuration.

We propose to use Eqs. 17, 18:

$$D_{in} = \begin{cases} X_0 = A\sin(2\pi f_{in} nT_s + \varphi_0) + B\sin(2\pi f_{in} nT_s - \varphi_0) & n = 4k-3, 4k-2 \\ X_1 = A\sin(2\pi f_{in} nT_s - \varphi_0) + B\sin(2\pi f_{in} nT_s + \varphi_0) & n = 4k-1, 4k \end{cases} \quad (20)$$

$$\varphi_0 = \frac{\pi}{6} \quad (21)$$

Simulation condition is as follows:

$$f_1/f_s = 49/200, f_2/f_s = 51/200 \quad (f_k = 1)$$

The output power spectrum is shown in Fig. 17, and we see that the IMD3 components are cancelled. On the other hand, Fig. 16 shows the one with the direct method using Eq.14 where IMD3 components appear. Although spurious appears on the low frequency side and the high frequency side, it is removed by using BPF.

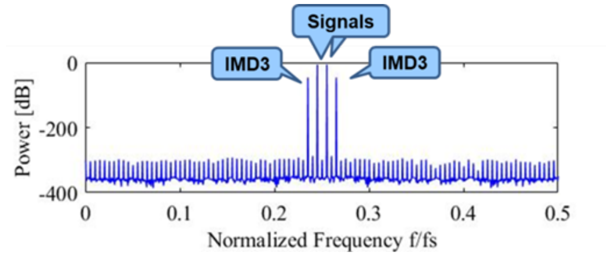


Fig.16. $Y(nT_s)$ spectrum with the direct *mid-frequency* two-tone signal generation method with AWG 3rd-order distortion (using Eq. 14)

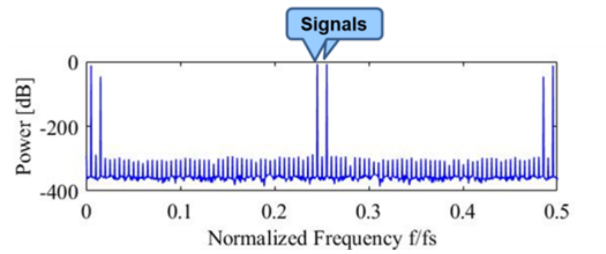


Fig.17. $Y(nT_s)$ spectrum with the phase-switching *mid-frequency* two-tone signal generation method with 3rd order distortions.

4. Experimental Verification

We have performed experiments at the laboratory level, to confirm the effectiveness of our methods. We have generated waveforms by the proposed algorithms with an AWG (Tektronix AFG3102), and measured their spectrum with a spectrum analyzer (Advantest R3267).

Fig.18 shows the AWG output spectrum measurement result of the single tone signal by the direct *mid-frequency* signal generation method, and Fig.19 shows the phase switching method. The experimental conditions are shown below.

$$f_s = 4\text{MHz}, \qquad f_{in} = 980\text{kHz}$$

In Fig.19, it is found that the 3rd harmonic is suppressed by -26 dB as compared with before application.

Fig.20 shows the measurement result of the AWG output spectrum of the two-tone signal by the direct *mid-frequency* signal generation method, and Fig. 21 shows the measurement result of the phase switching method. The experimental conditions are shown below.

$$f_s = 4\text{MHz}, \qquad f_1 = 980\text{kHz}, \qquad f_2 = 1020\text{kH}$$

Also in Fig. 21, suppression of -15 dB is seen for IMD 3 component compared with before application.

Although it was not completely suppressed up to the noise floor in either single tone or two tone methods, suppression of about 20 dB was observed. The cause of this imperfect suppression is considered to be due to the distortion of the spectrum analyzer and the finite (not-zero) rise / fall time of the AWG generation signal.

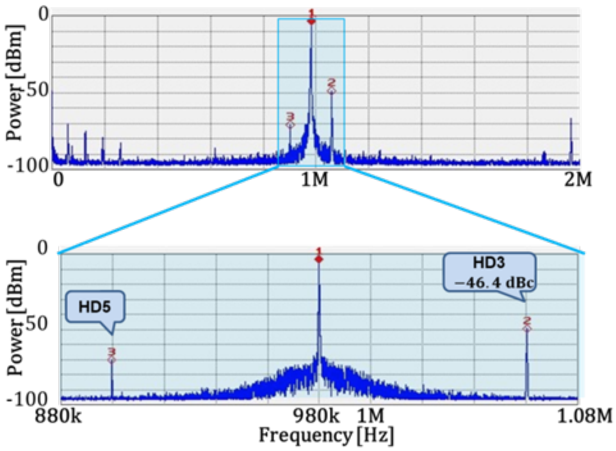


Fig.18. Spectrum with the direct *mid-frequency* signal generation method with AWG 3rd -order distortion.

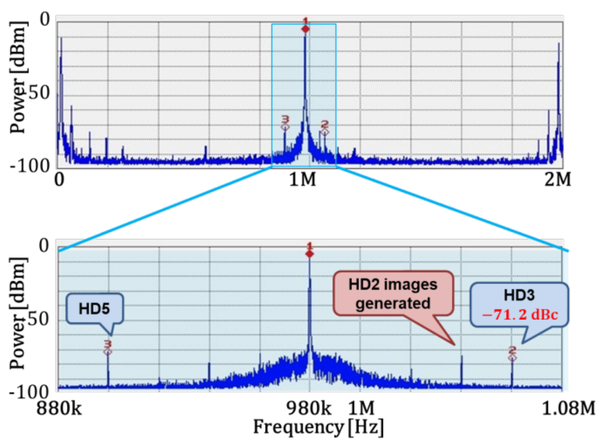


Fig.19. Spectrum with the phase-switching *mid-frequency* signal generation with AWG 3rd-order distortion

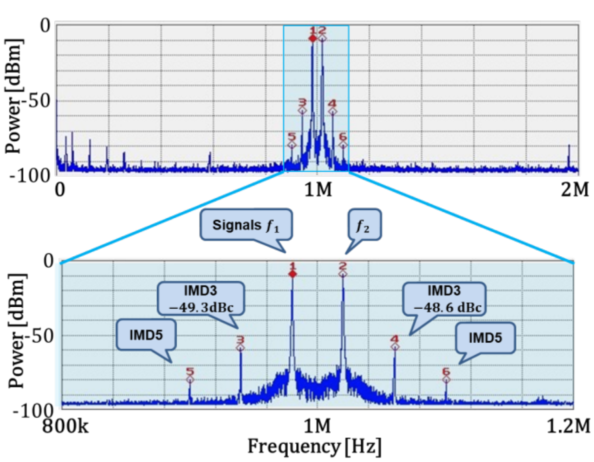


Fig.20. Spectrum with the direct *mid-frequency* two-tone signal generation method with AWG 3rd-order distortion

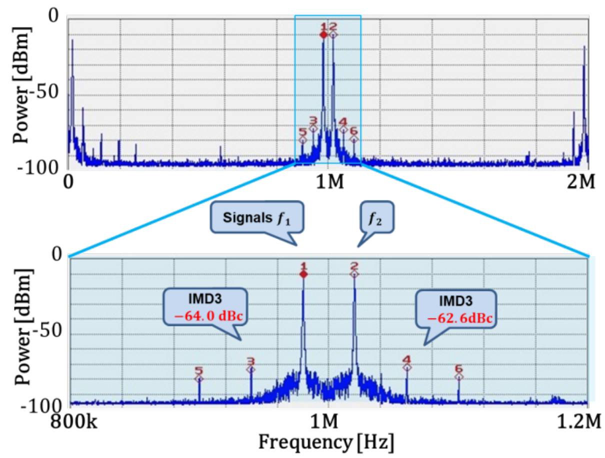


Fig.21. Spectrum with the phase-switching *mid-frequency* two-tone signal generation method with 3rd order distortions.

5. Conclusion

We have described low-distortion one-tone and two-tone generation algorithms with an AWG using the phase switching technique over full Nyquist range. Simulation and experiment results show their effectiveness.

References

[1] K.-T. Cheng, H.-M. Chang, “Recent Advances in Analog, Mixed-Signal and RF Testing”, IPSJ Trans on System LSI Design Methodology, vol. 3, pp 19-46 (2010).

[2] A. Maeda, “A Method to Generate a Very Low Distortion High Frequency Sine Waveform Using an AWG”, IEEE International Test Conference (Oct. 2008).

[3] K. Wakabayashi, K. Kato, T. Yamada, O. Kobayashi, H. Kobayashi, F. Abe, K. Niitsu, "Low-Distortion Sinewave Generation Method Using Arbitrary Waveform Generation", J. of Electronic Testing, Springer (Oct. 2012).

[4] F. Abe, Y. Kobayashi, K. Sawada, K. Kato, O. Kobayashi, H. Kobayashi, "Low-Distortion Signal Generation for ADC Testing", IEEE International Test Conference (Oct. 2014).

[5] P. Sarson, H. Kobayashi, “Using Distortion Shaping Technique to Equalize ADC THD Performance Between ATEs”, J. of Electronic Testing, Springer (June 2017)

[6] P. Sarson, T. Yanagida, S. Shibuya, K. Machida, H. Kobayashi, “A Distortion Shaping Technique to Equalize Interpolation Distortion Performance of Interpolating AWG in ATE”, J. of Electronic Testing, Springer (2018)

[7] K. Kato, F. Abe, K. Wakabayashi, C. Gao, T. Yamada, H. Kobayashi, O. Kobayashi, K. Niitsu, “Two-Tone Signal Generation for ADC Testing,” IEICE Trans. on Electronics, vol.E96-C, no.6, pp.850-858 (June 2013).

[8] S. Shibuya, Y. Kobayashi, H. Kobayashi, “High-Frequency Low-Distortion Signal Generation Algorithm with Arbitrary Waveform Generator”, IEEE International Conference on ASIC (Nov. 2015).

[9] T. Yanagida, S. Shibuya, H. Kobayashi, K. Hatayama, "High-Frequency Low-Distortion One-Tone and Two-Tone Signal Generation Using Arbitrary Waveform Generator", IEEE International Conference on Solid-State and Integrated Circuit Technology (Oct 2016).