International Journal of Applied Engineering Research ISSN 0973-4562 Volume 11, Number 2 (2016) pp 1256-1260

Analysis of SFDR Using Power Spectrum Based on Wavelet Extraction

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Abstract
The high frequency of advanced digital signal processing and data analysis in wide range of everyday data computing applications has propagated the uses of Analog to Digital Converters. However, such a converter can be very crucial and critical for some applications. Especially with the use of sensitive equipment's, errors or deviations from original signal could lead to catastrophic results. Therefore, testing output signal for dynamic parameters can always define the performance of the converters. In this research, the dynamic range parameters of Spurious-Free Dynamic Range will be tested using FFT testing application process based on Wavelet decomposition algorithms. This new proposes testing technique will utilize Wavelet special characteristic of decomposition feature, reduce compiling sample data, and expedite testing process. The new propose testing technique will be compared with conventional method of FFT application in term of accuracy, variance, and number of collect and computed samples.

Keywords: Spurious-Free Dynamic Range, Analog to Digital Converters, Wavelet Transform

Introduction
In today's curtail strive for signal processing and data transfer, Mixed Signal devices such as Analog to Digital Converters (ADC) and Digital-to-Analog Converters (DACs) are forming the joint between the real word and digital world [1]. However, Mixed Signal devices and signal generators are forming a challenging problem due to the effect of internal and external error factors. Factors such as noise, quantization error, signal to noise ratio (SNR), harmonics effect, and others, have both direct and indirect influence on regenerated signal. Therefore, numerous efforts have been devoted to improve signal processing by eliminating error causes and enhancing test process. That is, improving Mixed Signal devices and intensively testing their output signal for deviation and additive physical characteristics. Yet, at basic level, testing may seem simple procedures at low cost [2-3]. In fact, and as shown in [1-3], testing procedures and algorithms can be very complicated, extremely expensive, and it is time consuming for both static and dynamic parameter.
Several Methods of testing converters dynamic range have been developed, applied, and scrutinized to enhance testing process. Methods of such testing, based on FFT, Histogram, and discrete Wavelet transform, have been utilized to investigate the regenerated signal parameters [1-6]. However, each application (algorithm) has its own advantage and disadvantage process and testing results. FFT for instant, depend on noise summation (Average) to include quantization and very small noises [2,5]. In fact, FFT based testing is very sensitive to error caused by noise and require a large number of samples. On the other hand, in Sinusoidal Histogram data analysis, the majority of collected samples fall near the ends of the histogram producing errors near the peaks [2,7].
Meanwhile, other works have been done in Wavelet transform algorithm to improve the testing process and shorting testing time. In matter of fact and based on previous studies, Wavelet transform has shown a promising results in testing static and dynamic parameters [3, 7-9]. However, Spurious-Free Dynamic Range (SFDR), as addressed in this work, has not been investigated or tested by other algorithms than conventional based FFT testing applications.

Theoretical Background
Ideally, Analog to digital or digital to Analog converters should convert, regenerate, signals without any additive to the original signal. However, in real time operation, regenerated signal would have some error added (1)

$$X_{out}(t) = X_{in}(t) + e \qquad (1)$$

where
$X_{in}(t)$ = the original signal
e = error value

Therefore, in testing a mixed signal devices, dynamic performance is crucial factor to determine the accuracy of such an output signal. One of these dynamic elements is signal harmonics (Spurious) and their effect on the fundamental frequency. As shown in [1], noise and other distortion effect fundamental signal and can be determined through Fourier Transform frequency spectrum analyzer to measure harmonics and noise components in the signal. In IEEE Std. 1241 for Total Harmonic Distortion (THD) as in [1,8-13], is the ratio of harmonics power summation to the fundamental frequency power as in (2)

$$THD = \frac{P_2 + P_3 + P_4 + ... + P_\infty}{P_1} \qquad (2)$$

As a result, harmonics may affect the impurity of the regenerated signal based on their locations in frequency spectrum causing harmonic distortion to the original signal (tone). With the existence of harmonic distortion and undesired content (spurious) added to the spectrum, a large spurious formed and can be erroneously consider as fundamental signal tone. Such a phenomenon, may lead to degrade and miss-interpolate the desired or original converted signal, can be defined as SFDR. In IEEE Standard 1241, SFDR is define as the ratio of amplitude of converter output signal, regenerated signal averaged spectral components input frequency, to the amplitude of the largest harmonic or spurious spectral component observed over the full Nyquist band [8-10] as shown in (3)

$$SFDR = 20X\log\left(\frac{Amplitude\ of\ Fundamental\ (RMS)}{Amplitude\ of\ Largest\ Spur(RMS)}\right) \quad (3)$$

For example, a simulated sine waveform with fundamental frequency tone f=150 Hz with added noise was applied to the converter input as in figure 1.

The output digitalized signal was captured and analyzed in frequency domain power spectrum to compute harmonics effect (THD) and the ratio of fundamental frequency to the highest harmonic spurious component as shown in figure 2 and 3 respectively

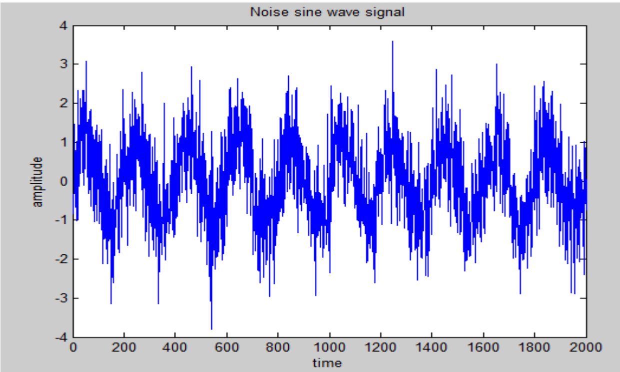

Figure 1: Simulated sinusoid waveform with noise at f=150 Hz

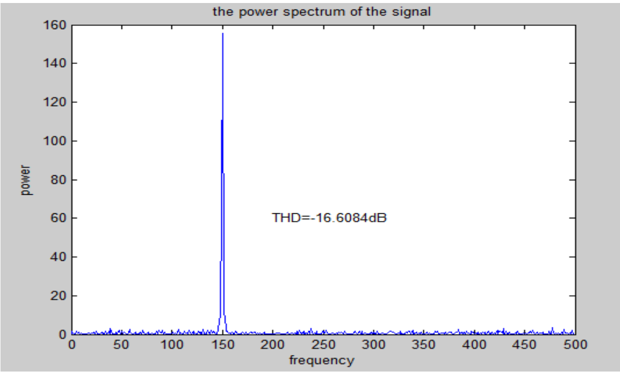

Figure 2: THD by FFT Power Spectrum

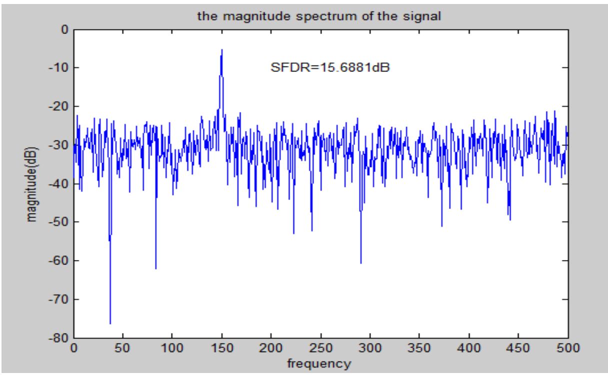

Figure 3: SFDR based on FFT Power Spectrum

As illustrated, by applying a full scale sinusoidal input signal and measure the output response, RMS of all harmonics and largest spurious components were defined by FFT spectrum to show THD and SFDR. However, such a method can be lengthy and complicated (in term of compiling process), especially with higher order ADCs.

In this study, the simulated regenerated signal was filtered and decomposed through a set of discreet Wavelet transform filters. Doing so, the processed signal was decomposed into two sub signals, of low and high frequency components with all sufficient data pertain [1-3, 14]. The low-pass, approximation coefficients, were captured and processed at first level of decomposition by FFT base algorithm to measure the ratio of new fundamental transformed signal frequency and harmonics frequency associated.

Discrete Wavelet Transform (DWT)

In conventional evaluation of SFDR, digitized analog output signal used FFT spectrum to find the ratio between the maximum content of the largest spurious and the fundamental signal tone as discussed in theoretical background. However, in most cases number of data samples collected and analyzed is very large. Therefore, and as intend of this study, the captured signal is transformed and analysed by Discreet Wavelet Transform (DWT) algorithms to obtain further information with less number of data samples [1,2,9]. With the property of DWT sub-band coding, data computation is based on successive low-pass and high-pass filtering. In [1,9,15-19], each Mother Wavelet is based on predetermined low-pass and high-pass coefficient filters. Filtering is used for down-sampling process by factor of 2 (decimation) in each energy level.

For a discrete output signal $(s_n = \{s_{nk}\})$, DWT decomposition process can be shown in 4 and 5 for both approximation and detail coefficients respectively

$$s_{n-1,j} = \sum_k \tilde{h}_{k-2j} s_{nk} \quad (4)$$

$$d_{n-1,j} = \sum_k \tilde{g}_{k-2j} s_{nk} \quad (5)$$

The decomposition process of a signal consist of of two major functions. Convoluting signal data with Wavelet coefficients as in 6 and 7.

$$(\tilde{h}(-)*s_n)_j = \sum_k \tilde{h}_{-(j-k)} s_{nk} \quad (6)$$

$$(\tilde{g}(-)*s_n)_j = \sum_k \tilde{g}_{-(j-k)} s_{nk} \quad (7)$$

And followed by down-sampling as in 8 and 9

$$s_{n-1} = (\downarrow 2)(\tilde{h}(-)*s_n) \quad (8)$$

$$d_{n-1} = (\downarrow 2)(\tilde{g}(-)*s_n) \quad (9)$$

As a result of this process, number of compiled samples will be reduced by half at each decimation level. In other word, the bandwidth of the original signal will split into multiple of halves at the high and low-pass filters [1,16,18-19] as shown in figure 4.

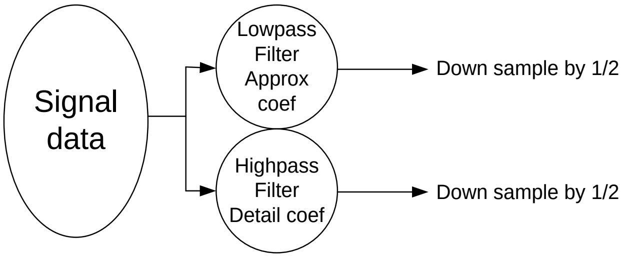

Figure 4: Wavelet Decomposition and down sampling process

In [1,16,18], many type of Wavelet can be used. However, an appropriate Mother Wavelet (orthogonal, biorthogonal) should be selected to best match and analyze the test signal in time and frequency domains.
In this work, Haar, Daubechies (orthogonal), and biorN (biorthogonal) will be used to analyze sinusoidal signal for SFDR.

Simulation and Testing Process

In this work, Matlab software was used for testing simulation and evaluation. The generated signal under test was captured and tested for SFDR. Testing algorithms was developed based on FFT power spectrum based on DWT decomposition as new algorithm process. In addition, random noise was added to the simulated output signal under test as shown in figure 5.

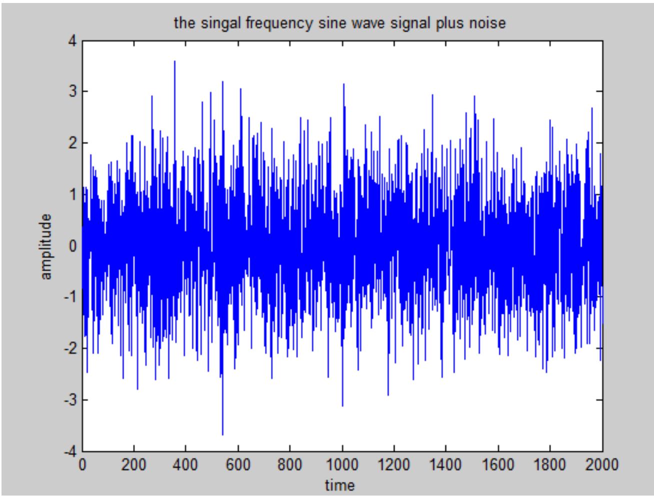

Figure 5: Raw signal under test process

Several numbers of bits ADCs (10, 12, 14 Bits) output signals were simulated at various fundamental frequencies of 100 Hz, 150 Hz, and 200 Hz with sampling rate fs (1000 Hz). By using FFT power spectrum, SFDR was determined with 2000 data samples as in figure 6.

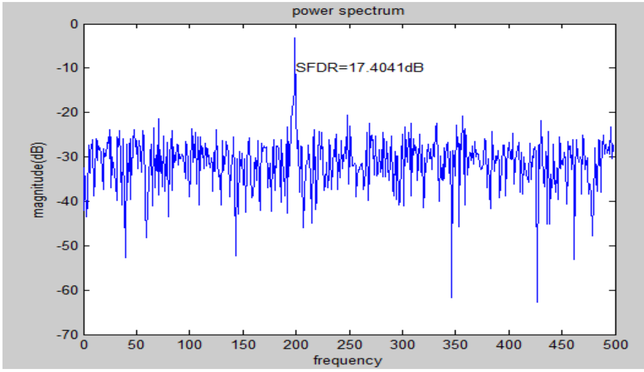

Figure 6: SFDR based on FFT power Spectrum at 200 Hz

Meanwhile, by applying the new testing algorithm, DWT were able to reduce number of compiled samples by half. Signal under test was decompose first by Wavelet high-pass and low-pass to obtain new transformed signal with half the data bandwidth as illustrated in (10) and (11) and shown in figure 7.

$$(\ldots d_{n-1,-1} d_{n-1,0}, d_{n-1,1}, d_{n-1,2}, d_{n-1,3}, d_{n-1,4}, d_{n-1,5}, d_{n-1,6}, d_{n-1,7}, \ldots) \quad (10)$$

$$(\ldots d_{n-1,-1}, d_{n-1,1}, d_{n-1,3}, d_{n-1,5}, d_{n-1,7}, \ldots) \quad (11)$$

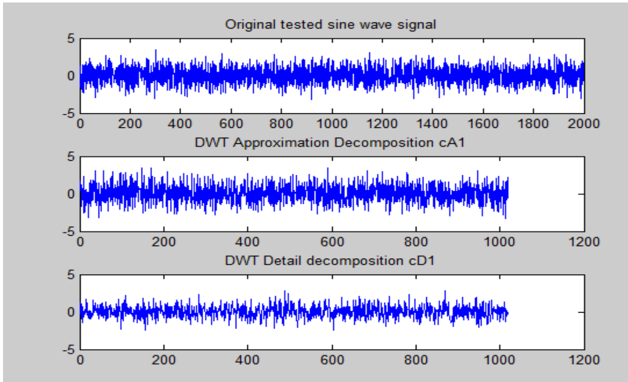

Figure 7: Illustration of original signal and Wavelet decomposition

As a result of such a process, approximation coefficients at first level of decomposition were captured to form the new tested signal as in figure 8.

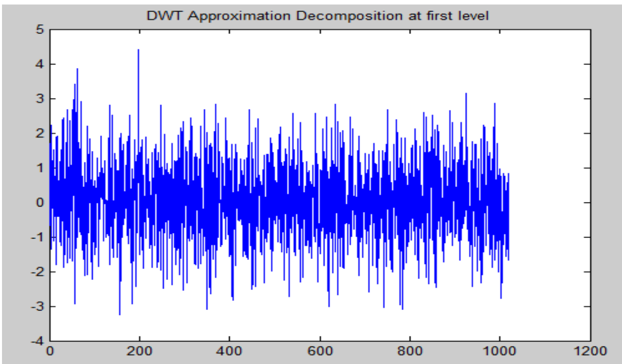

Figure 8: Illustration of original signal and Wavelet decomposition

Data from discreet Wavelet transform low-pass filter (Approximation data) where used by the FFT power spectrum based computation to estimate for SFDR as in figure 9.

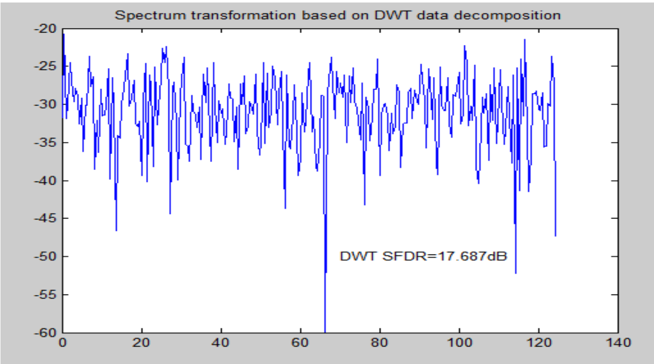

Figure 9: SFDR based on Wavelet Decomposition and FFT Analysis

Results and Discussion

To validate experiment results, testing was performed on several fundamental frequencies and types of DWT. Results were validated with classical testing algorithm of FFT spectrum as shown in Table 1, 2, 3 and figures 10, 11, and 12.

Table 1: SFDR at various fundamental frequencies and analysis techniques for 10 Bits ADC

Freq.	FFT	Db20	Db10	Coef1	Haar	Bior3.1
100Hz	16.01	16.10	15.61	19.80	19.79	18.30
150Hz	15.72	16.72	17.01	18.80	17.88	13.80
200Hz	15.45	15.77	15.92	17.14	13.32	11.98

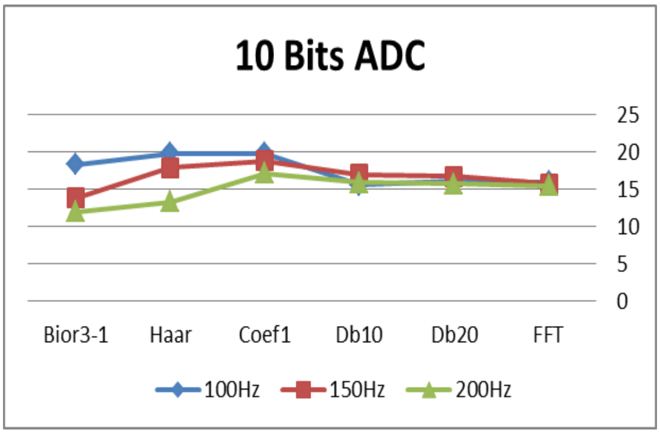

Figure 10: Illustration of SFDR values from table 1 for 10 Bits ADC

Table 2: SFDR at various fundamental frequencies and analysis techniques for 12 Bits ADC

Freq.	FFT	Db20	Db10	Coef1	Haar	Bior3.1
100Hz	14.72	12.37	12.59	13.53	13.22	12.13
150Hz	14.05	12.25	13.06	13.30	11.60	11.92
200Hz	11.88	11.98	11.90	12.11	10.44	11.31

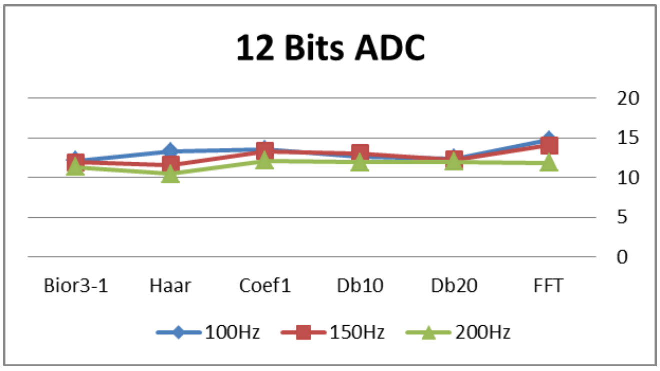

Figure 11: Illustration of SFDR values from table 2 for 12 Bits ADC

Table 3: SFDR at various fundamental frequencies and analysis techniques for 14 Bits ADC

Freq.	FFT	Db20	Db10	Coef1	Haar	Bior3.1
100Hz	12.27	11.98	12.27	12.83	12.44	10.94
150Hz	13.30	14.43	13.09	11.73	12.10	13.59
200Hz	12.90	12.36	12.61	12.89	12.01	12.31

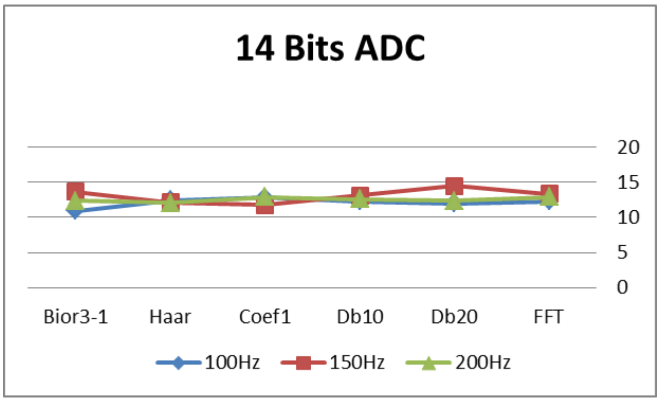

Figure 12: Illustration of SFDR values from table 3 for 14 Bits ADC

As seen from tables (1,2, and 3) and the illustrated figures (11, 12, 13), DWT algorithms of signal decomposition were able to reduce number of compiled samples. For instance, when 10 bits ADC was simulated, a total of 2000 data samples were collected to compute SFDR based on conventional method of FFT power spectrum. However, using DWT of different type, number of data sample were reduced by half prior to apply FFT computation of SFDR. With such a result closer to conventional method (FFT spectrum), DWT has shown a promising algorithm to reduce number of analyzed data and speed the computation process of SFDR.

Conclusion

In this work of testing SFDR, Wavelet transform algorithm has shown a promising technique of combining with FFT spectrum analysis. With special properties of multi-resolution and down-sampling process, SFDR was estimated with less data to allow for fast testing process, less testing cost, and enhance testing results. As a result of this simulation and other works had been done in this field, Wavelet transform can be a very helpful tools in analyzing signal to identify bit errors, distortions, noise, undesirable harmonics that can be integrated into the signal.

Acknowledgements
The author is grateful to the Applied Science Private University, Amman, Jordan, for the full financial support grated to this research project (Grant No. DRGS-2015-2016-27).

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