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Harmonic Analysis Using the ADE9000

by Aaron Heredia

INTRODUCTION

Traditionally, harmonic analysis requires complex computations and processing. Harmonic analysis goes to an order of processing data in which a fixed analog-to-digital converter (ADC) sampling rate is used, then a window is applied into the data to account for the fact that the data is not sampled coherently. Lastly, a Fourier transform is performed, which can be difficult, because the number of samples of the data is not an exact amount of 2^n integral numbers.

The ADE9000 metering IC is capable of performing the desired Fourier transform coherently or noncoherently using the waveform buffer application. Typically, this waveform buffer samples an amount of data and gives a set of values for a Fourier transform process. The output generated contains the fundamental signal plus all harmonics.

Another concern in harmonic analysis is that the signal being measured in the ADE9000 passes digital filtering, and the gain varies over frequency, thus attenuating the measurements at higher frequencies more noticeable beyond 500 Hz. Proper gain compensation factors must be introduced in measuring those frequencies affected by this process.

This application note discusses the ways of performing harmonic analysis and the gain compensation analysis using the EVAL-ADE9000EBZ evaluation board.

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REVISION HISTORY

11/2017—Revision 0: Initial Version

COHERENT VS. NONCOHERENT SAMPLING

To obtain the fundamental and harmonic contents of the signal after the transformation process, it is essential to sample the signal in a way that it gives a perfectly generated output in root mean squared (rms) of the energy contents of each frequency.

Noncoherent sampling in the ADE9000 uses the waveform buffer to read enough samples for a fast Fourier transform (FFT). The timing clock and the size of the sample set is the main concern for noncoherent sampling. The energy content is concentrated at a single frequency if proper amounts of samples are generated for an FFT. It can be obtained by using an external clock, probably operating at the same timing with the generated signal and the input clock of the ADE9000. The requirement is also to generate a sample set that ends with the same exact point in the waveform where sampling starts. By doing this, each content of the signal is concentrated only to one specific point, thus measuring the rms values accurately.

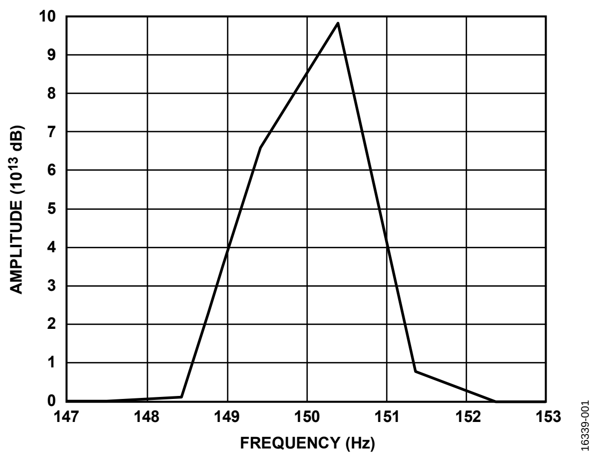

Figure 1. Response of a Third Harmonic of a Noncoherent Sampling Without Integral Number of Periods Using the ADE9000, NI PXI 4461 Signal Generator, and EVAL-ADE9000EBZ

Figure 1 shows an FFT response if noncoherent sampling is performed without taking into consideration the timing and the integral number of line periods. However, Figure 2 shows that when sampling starts and ends at the exact line period together with the clock sync, the content of the signal is concentrated on its specific frequency.

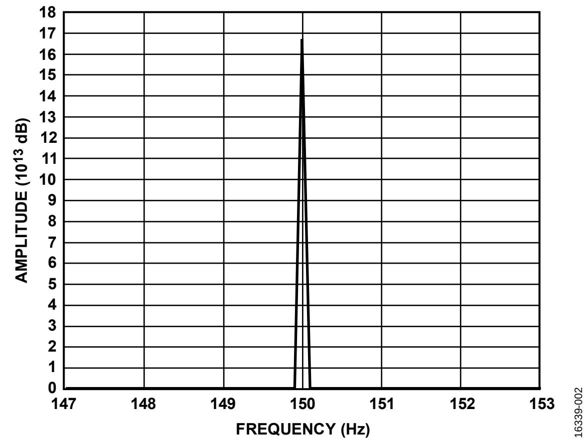

Figure 2. Third Harmonic of a 50 Hz Signal Noncoherent Sampling with Integral Number of Periods Using ADE9000, NI PXI 4461 Signal Generator, and EVAL-ADE9000EBZ

The ADE9000 simplifies noncoherent signal processing by constantly tracking the power line frequency and using this information to resample the data to provide 128 points of data per power line, thus making the sampling coherent.

Coherent sampling also uses the waveform buffer and performs resampling of the original set of values. Each set contains 128 (128 × 4 maximum) interpolated samples providing one complete line cycle, which makes the number of samples an integral number of 2^n power, thus making Fourier transform easy to compute. Interpolation introduces small errors that increase with the range of the harmonic (see Figure 3).

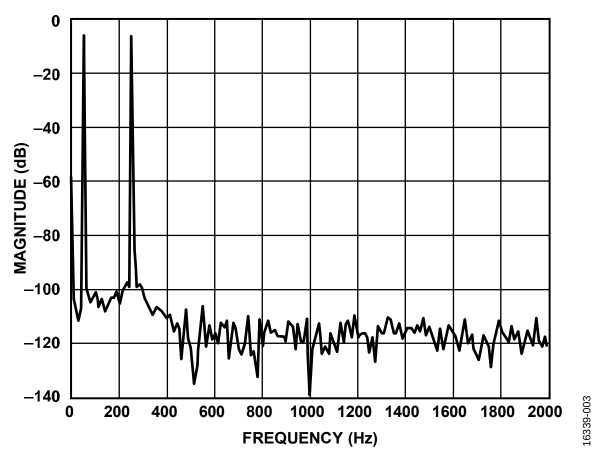

Figure 3. Response (in dB) of a Fundamental and Fifth Harmonic on Current Channel B Using 128 Samples/Line Cycle

This application note discusses harmonic analysis using both noncoherent and coherent sampling modes.

MEASURING FUNDAMENTAL AND HARMONIC CONTENTS

In performing harmonic analysis in the ADE9000, an FFT can be performed using a microcontroller or any software capable of performing signal processing (like LabVIEW®). Before measurement, a precalibration must be done using the ADE9000 Calibration Tool.

HARMONIC ANALYSIS USING NONCOHERENT SAMPLING

The main register for measuring the harmonic content of the signal is the waveform buffer register.

Configure the register WFB_CFG with the following operations to control it in the desired waveform buffer setting to perform a noncoherent sampling mode. Make sure that the chip is precalibrated and working with the digital signal processor (DSP) on. See the ADE9000 Technical Reference Manual.

To set the waveform buffer, perform the following procedure:

1. Write 0x03F8 to WFB_CFB (Address 0x4A0) to configure the waveform.
2. Write 0'0b0 to WF_IN_EN (Bit 12) to disable waveform in neutral channel to be read through the serial peripheral interface (SPI).
3. Write 0'b11 to WF_SRC (Bits[9:8]) to enable current and voltage channel waveform samples processed at 8 kSPS by the DSP.
4. Write 0'b11 to WF_MODE (Bits[7:6]) to enable continuous fill on the buffer. See the ADE9000 Technical Reference Manual for more information on continuous filling mode.
5. Write 0'b1 to WF_CAP_SEL (Bit 5) to enable the fixed data rate sampling (noncoherent).
6. Write 0'b1 to WF_CAP_EN (Bit 4) to start waveform capturer.
7. Write 0'b0000 for all channels to BURST_CHAN (Bits[3.0]) to select channels. See the ADE9000 data sheet for other channels.

Figure 4 shows the different sources of the waveform buffer. Waveform samples presented in this application note are captured from the output of the DSP core at a rate of 8 kSPS. It is recommended that the BURST_CHAN bits be 0′b0000 to access all channels.

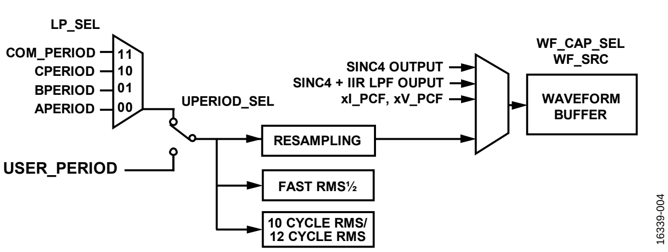

Figure 4. Resampling Mode and Waveform Buffer Source

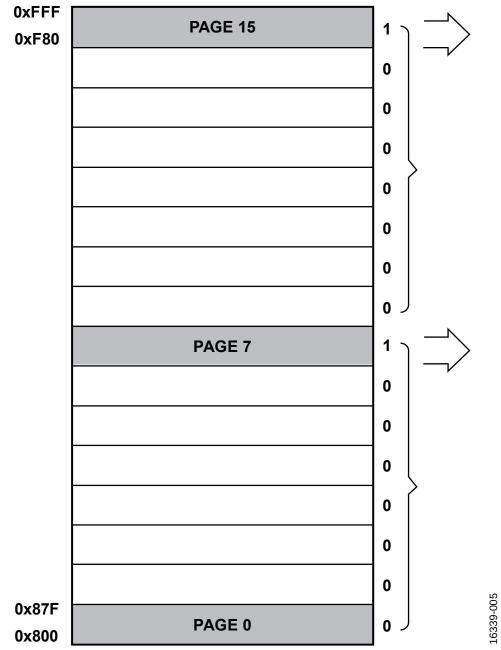

Figure 5. Continuous Mode and Ping Pong Routine for Waveform Buffer

By setting WFB_PG_IRQEN in continuous sampling, an interrupt sets at Page 7 and Page 15, dividing the waveform buffer into two major buffers and creating a ping pong buffer. After Page 0 to Page 7 are full, an interrupt enables, and a microcontroller and a PC can read the values on those pages, while the signal is continuously sampled on the remaining Page 8 to Page 15. After Page 8 to Page 15 are full, an interrupt enables again, reading the values stored on the pages while signal is sampled again on Page 0 to Page 7. Through this ping pong routine, no part of the wave is lost in continuous sampling. The WFB_LAST_PAGE bits on the WFB_ TRIG_STAT register help determine which part of the buffer is filled to start the read routine on that part of the buffer.

To execute this process, take the following steps:

1. Write 0x20000 to MASK0 (Address 0x405) to enable the page full interrupt.
2. Write 0x8080 to WFB_PG_IRQWN (Address 0x4A1) to set the interrupt at Page 7 and Page 15.

Figure 6 summarizes the procedure on how to operate the noncoherent sampling mode using the waveform buffer.

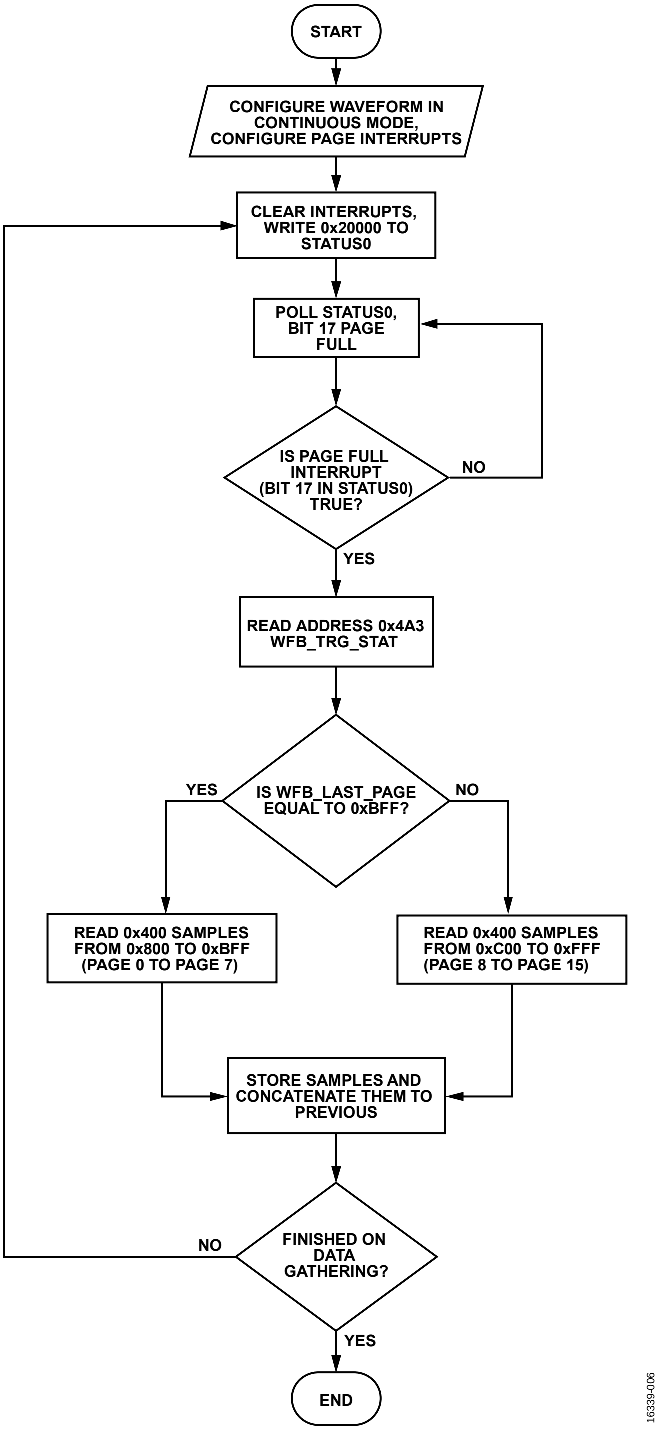

Figure 6. Implementing the Noncoherent Mode Resampling

The complete list of registers for the waveform buffer is available in the ADE9000 data sheet.

The expected values to be measured after an FFT process can be computed using the following equations:

$$Expected\ xI\ rms_{nth} = \%\ Full\ Scale_{nth} \times 52{,}702{,}092 \quad (1)$$

$$Expected\ xV\ rms_{nth} = \%\ Full\ Scale_{nth} \times 52{,}702{,}092 \quad (2)$$

where $\%\ Full\ Scale_{nth}$ is the percentage of the full-scale content of the signal.

Input defined in this application note are expressed in terms of percentages of the full-scale ADC output in codes.

To compute for the expected total rms values, use the following equation:

$$Expected\ xI\ rms_{Total} = \sqrt{\sum_{i=1}^{N} Expected\ xI\ rms\_nth^2}$$

This application note provides an actual measurement of the rms of a fundamental 50 Hz with a harmonic content following the IEC62053-21 with the test conditions found in Table 1.

Table 1. IEC62053-21 Test Conditions

Test Condition	Value
Fundamental Current	0.5 I_{MAX}
Fundamental Voltage	U_N
Fundamental Power Factor	1
Content of the Fifth Harmonic Voltage	10% of U_N
Content of the Fifth Harmonic Current	40% (0.5 I_{MAX})

I_{MAX} was selected to be used as the full-scale 1 V.

$$Expected\ xI\ rms_{1st} = 50\% \times 52{,}702{,}092$$

$$Expected\ xI\ rms_{1st} = 26{,}351{,}046$$

$$Expected\ xI\ rms_{5th} = 40\% \times (0.5 \times 52{,}702{,}092)$$

$$Expected\ xI\ rms_{5th} = 10{,}540{,}418$$

U_N was selected to be 20% of the full-scale code.

$$Expected\ xV\ rms_{1st} = 20\% \times 52{,}702{,}092$$

$$Expected\ xV\ rms_{1st} = 10{,}540{,}418$$

$$Expected\ xV\ rms_{5th}\ 10\% \times (20\% \times 52{,}702{,}092)$$

$$Expected\ xV\ rms_{5th} = 1{,}054{,}042$$

To compute for the expected total I rms and V rms, take the rms of the individual values:

$$Expected\ xI\ rms_{Total} = \sqrt{26{,}351{,}046^2 + 10{,}540{,}418^2}$$

$$Expected\ xI\ rms_{Total} = 28{,}380{,}945$$

$$Expected\ xV\ rms_{Total} = \sqrt{10{,}540{,}418^2 + 1{,}054{,}042^2}$$

$$Expected\ xV\ rms_{Total} = 10{,}592{,}989$$

An actual test for noncoherent mode is performed using the EVAL-ADE9000EBZ evaluation board. After the waveform sampling, the microcontroller performs an FFT in which each harmonic content is extracted. For this case, the input is a fundamental signal with a fifth harmonic same as above. For this experiment, LabVIEW has been used as a tool to calculate the FFT and output the harmonic contents of the signal. The rms values of each (fundamental and harmonics) is measured after an FFT for further analysis. The results are shown in Table 2 and Table 3.

Table 2. Phase A Current Channel RMS

Input	Expected Value	Measured FFT	Percent Error
Fundamental	26,351,046	26,347,599	0.0131%
Fifth Harmonic	10,540,418	10,532,242	0.0776%

Table 3. Phase A Voltage Channel RMS

Input	Expected Value	Measured FFT	Percent Error
Fundamental	10,540,418	10,547,428	0.0665%
Fifth Harmonic	1,054,042	1,054,775	0.0695%

The reading from the AIFRMS register during this experiment is 26347436, which is 0.014% off of the expected value, and the reading from the AVFRMS register is 10,548,545, which is 0.0771% off of the expected value.

Using the rms values after the FFT, the total rms for voltage and current were calculated.

$$Measured\,(FFT)\; xI\; rms_{Total} = \sqrt{26{,}347{,}599^2 + 10{,}532{,}242^2}$$

$$Measured\ (FFT)\ xI\ rms_{Total} = 28{,}374{,}709$$

The same calculation is used for the voltage.

$$Measured\,(FFT)\; xV\; rms_{Total} = \sqrt{10{,}547{,}428^2 + 1{,}054{,}775^2}$$

$$Measured\ (FFT)\ xV\ rms_{Total} = 10{,}600{,}037$$

Table 4 and Table 5 describe the comparison between the expected values of the total rms, the FFT measured total rms, and the reading on the register.

Table 4. Measured Values after FFT

Input	Expected Value	Measured FFT	Percent Error
$xI\ rms_{Total}$	28,380,945	28,374,709	0.0220%
$xV\ rms_{Total}$	10,592,989	10,600,037	0.0665%

Table 5. Expected vs. Register Values

Input	Expected Value	Register Reading AI rms/AV rms	Percent Error
$xI\ rms_{Total}$	28,380,945	28,374,967	0.0211%
$xV\ rms_{Total}$	10,592,989	10,599,835	0.0646%

The current total harmonic distortion can also be calculated using the following equation:

$$ITHD = \frac{\sqrt{\sum_{i=2}^{k} I_h^{\,2}}}{I_f}$$

Calculate the expected ITHD using the following equation:

$$ITHD_{Expected} = \frac{\sqrt{I_{5th}^{\,2}}}{I_{1st}}$$

$$ITHD_{Expected} = \frac{\sqrt{10{,}540{,}418^2}}{26{,}351{,}046} = 40\%$$

ITHD using the measured values from FFT can be figured by the following equation:

$$ITHD_{Measured\ FFT} = \frac{\sqrt{10{,}532{,}242}}{26{,}347{,}599} = 40.0318\%$$

The AITHD register can also be read for comparison. The total harmonic distortion (THD) discussion is further elaborated on in the ADE9000 data sheet.

$$\%THD = AITHD \times 2^{-27} \times 100\%$$

With the same input, the measured value on AITHD is 0x33327DC and using the formula, the %THD is 39.9978%.

Table 6. ITHD Comparison Table

Expected ITHD	Computed ITHD Based on Measured (FFT)	THD Based on AITHD Register
40%	40.0318%	39.9978%

The same procedure is repeated in the voltage channel, and the data in Table 7 was obtained.

Table 7. ITHD Comparison Table

Expected VTHD	Computed VTHD Based on Measured (FFT)	THD Based on AVTHD Register
10%	10.0147%	10.0012%

HARMONIC ANALYSIS USING COHERENT SAMPLING

There are initial configurations to be considered before performing harmonic analysis using coherent sampling. The same register, WFB_CFG, is to be configured with the same settings as with the noncoherent sampling except for the WF_CAP_SEL bit. This bit must be set to 0 to configure the waveform buffer in resampled data mode. The resampled data mode has a full scale of 18,196. The following equation can be used to obtain the expected values converted in rms:

$$Expected\ Resampled\ Data_{Nth} = \%\ Full\ Scale_{nth} \times \frac{18196}{\sqrt{2}}$$

Using the same input as the noncoherent mode and the equations for computing current and voltage resampled data and THD, a new set of expected values were obtained and compared to the measured value upon performing an FFT.

The ITHD and VTHD are also computed based on expected resampled values, measured values after the FFT, and on the AITHD and AVTHD registers.

Table 8. Current Channel A Result (Resampled)

Content	Percentage Full Scale	Full Scale	Expected Value	Measured (FFT)	Percentage Error
Fundamental	50%	18,196	6433	6417	0.2493%
Fifth Harmonic	20%	18,196	2573	2565	0.3319%

Table 9. Voltage Channel A Result (Resampled)

Content	Percentage Full Scale	Full Scale	Expected Value	Measured (FFT)	Percentage Error
Fundamental	20%	18,196	2573	2570	0.1167%
Fifth Harmonic	2%	18,196	257	258	0.3876%

Table 10. THD Comparison Table (Resampled)

Parameter	Expected THD (Based on Resampled Values)	Computed THD Based on Measured (FFT)	Reading on AxTHD Register
AITHD	39.9969%	40.0499%	39.9978%
AVTHD	9.9883%	10.0585%	10.0012%

HARMONIC GAIN RESPONSE OF THE ADE9000 DIGITAL FILTER

The signal that passes through the DSP of the ADE9000 is processed through digital filtering, which has a sinc4 filter with 32 KSPS output data rate followed by a low-pass filter (LPF). Due to the digital filtering, the gain of the samples in the waveform buffer varies over frequency, thus attenuating the measurements at higher frequencies. Figure 7 shows the gain performance of the digital filter.

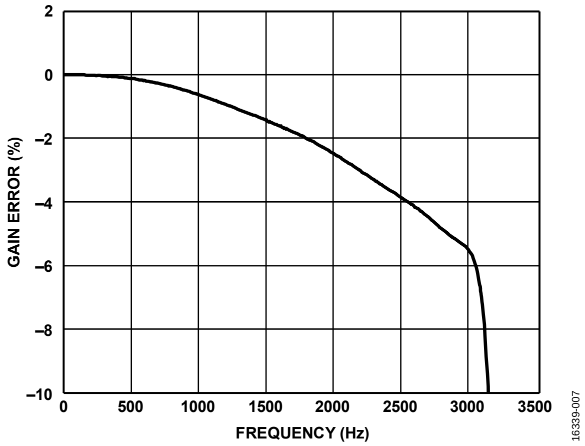

Figure 7. % Gain Error of ADE9000 Sinc4 + LPF Response

Table 11 and Table 12 summarize the whole performance of the digital filter in percent gain error and the gain compensation factor of each harmonic at 50 Hz and 60 Hz.

Table 11. Sinc4 + LPF Performance Summary at 50 Hz

Harmonic No.	Frequency	Attenuation Factor	Gain Compensation Factor
1	50	1.00000	1.00000
2	100	0.99997	1.00003
3	150	0.99992	1.00008
4	200	0.99985	1.00015
5	250	0.99976	1.00024
6	300	0.99964	1.00036
7	350	0.99948	1.00052
8	400	0.99930	1.00070
9	450	0.99908	1.00092
10	500	0.99882	1.00118
11	550	0.99851	1.00149
12	600	0.99816	1.00184
13	650	0.99777	1.00223
14	700	0.99732	1.00269
15	750	0.99683	1.00318
16	800	0.99629	1.00372
17	850	0.99571	1.00431
18	900	0.99508	1.00494
19	950	0.99441	1.00562
20	1000	0.99370	1.00634
21	1050	0.99297	1.00708
22	1100	0.99220	1.00786
23	1150	0.99141	1.00866
24	1200	0.99060	1.00949
25	1250	0.98977	1.01034
26	1300	0.98893	1.01119
27	1350	0.98808	1.01206
28	1400	0.98723	1.01294

Harmonic No.	Frequency	Attenuation Factor	Gain Compensation Factor
29	1450	0.98636	1.01383
30	1500	0.98547	1.01474
31	1550	0.98457	1.01567
32	1600	0.98365	1.01662
33	1650	0.98270	1.01760
34	1700	0.98172	1.01862
35	1750	0.98069	1.01969
36	1800	0.97962	1.02080
37	1850	0.97849	1.02198
38	1900	0.97730	1.02323
39	1950	0.97605	1.02454
40	2000	0.97475	1.02590
41	2050	0.97340	1.02733
42	2100	0.97200	1.02881
43	2150	0.97058	1.03031
44	2200	0.96914	1.03184
45	2250	0.96770	1.03338
46	2300	0.96627	1.03491
47	2350	0.96486	1.03642
48	2400	0.96347	1.03792
49	2450	0.96209	1.03940
50	2500	0.96069	1.04092
51	2550	0.95925	1.04248
52	2600	0.95772	1.04415
53	2650	0.95608	1.04594
54	2700	0.95431	1.04788
55	2750	0.95244	1.04993
56	2800	0.95056	1.05201
57	2850	0.94878	1.05399
58	2900	0.94722	1.05572
59	2950	0.94572	1.05740
60	3000	0.94335	1.06005
61	3050	0.93736	1.06683
62	3100	0.92128	1.08545
63	3150	0.88338	1.13202

Table 12. Sinc4 + LPF Performance Summary at 60 Hz

Harmonic No.	Frequency	Attenuation Factor	Gain Compensation Factor
1	60	1.00000	1.00000
2	120	0.99996	1.00004
3	180	0.99989	1.00011
4	240	0.99978	1.00022
5	300	0.99964	1.00036
6	360	0.99945	1.00055
7	420	0.99922	1.00078
8	480	0.99893	1.00107
9	540	0.99858	1.00142
10	600	0.99817	1.00183
11	660	0.99769	1.00232
12	720	0.99714	1.00287
13	780	0.99652	1.00349
14	840	0.99583	1.00419
15	900	0.99508	1.00494

Harmonic No.	Frequency	Attenuation Factor	Gain Compensation Factor
16	960	0.99428	1.00575
17	1020	0.99342	1.00662
18	1080	0.99251	1.00755
19	1140	0.99157	1.00850
20	1200	0.99060	1.00949
21	1260	0.98961	1.01050
22	1320	0.98860	1.01153
23	1380	0.98757	1.01259
24	1440	0.98653	1.01365
25	1500	0.98548	1.01473
26	1560	0.98439	1.01586
27	1620	0.98328	1.01700
28	1680	0.98212	1.01821
29	1740	0.98090	1.01947
30	1800	0.97962	1.02080
31	1860	0.97826	1.02222
32	1920	0.97681	1.02374
33	1980	0.97528	1.02535
34	2040	0.97368	1.02703
35	2100	0.97201	1.02880
36	2160	0.97029	1.03062
37	2220	0.96857	1.03245
38	2280	0.96684	1.03430
39	2340	0.96514	1.03612
40	2400	0.96347	1.03792
41	2460	0.96181	1.03971
42	2520	0.96013	1.04153
43	2580	0.95835	1.04346
44	2640	0.95643	1.04555
45	2700	0.95432	1.04787
46	2760	0.95207	1.05034
47	2820	0.94983	1.05282
48	2880	0.94782	1.05505
49	2940	0.94604	1.05704
50	3000	0.94336	1.06004
51	3060	0.93525	1.06923
52	3120	0.90957	1.09942
53	3180	0.84404	1.18478
54	3240	0.72078	1.38739
55	3300	0.55810	1.79179

GAIN RESPONSE OF ANTIALIAS FILTER

The external resistor capacitor (RC) that prevents aliasing has a response that affects the signals at frequencies higher than 2000 Hz.

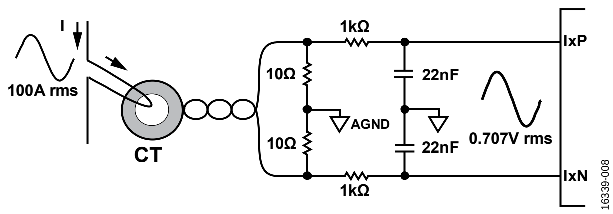

Figure 8. ADE9000 Antialias Filter

The recommended values of 1 kΩ and 22 nF theoretically follow the transfer function that provide the gain response expressed in Figure 9.

$$G(s) = \frac{1}{1 + \frac{s}{w_b}}$$

where $w_b = \frac{1}{RC}$

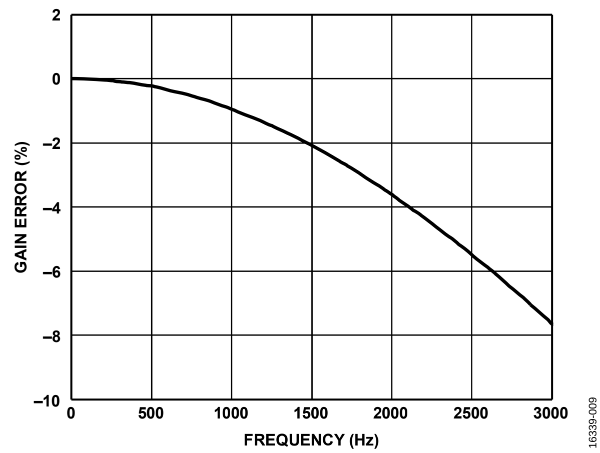

Figure 9. ADE9000 Antialias Filter Response (1 kΩ, 22 nF)

The combined effect of the sinc4 and LPF digital filter and the external antialias filter create a significant gain error to high frequencies. Table 13 and Table 14 the whole performance of the digital filters including the recommended antialias filter with proper gain compensation factors for each harmonic at 50 Hz and 60 Hz.

Table 13. Effect of Antialias (1 kΩ, 22 nF) Performance Summary at 50 Hz

Harmonic No.	Frequency	Attenuation Factor	Gain Compensation Factor
1	50	1.00000	1.00000
2	100	0.99993	1.00007
3	150	0.99981	1.00019
4	200	0.99964	1.00036
5	250	0.99943	1.00057
6	300	0.99917	1.00083
7	350	0.99886	1.00114
8	400	0.99850	1.00150
9	450	0.99809	1.00191
10	500	0.99764	1.00237
11	550	0.99715	1.00286
12	600	0.99660	1.00341
13	650	0.99601	1.00401
14	700	0.99538	1.00464
15	750	0.99469	1.00534
16	800	0.99396	1.00608
17	850	0.99319	1.00686
18	900	0.99237	1.00769
19	950	0.99151	1.00856
20	1000	0.99060	1.00949
21	1050	0.98965	1.01046
22	1100	0.98866	1.01147
23	1150	0.98762	1.01254
24	1200	0.98654	1.01364
25	1250	0.98542	1.01480
26	1300	0.98426	1.01599
27	1350	0.98305	1.01724
28	1400	0.98181	1.01853
29	1450	0.98052	1.01987
30	1500	0.97920	1.02124
31	1550	0.97783	1.02267

Harmonic No.	Frequency	Attenuation Factor	Gain Compensation Factor
32	1600	0.97643	1.02414
33	1650	0.97499	1.02565
34	1700	0.97351	1.02721
35	1750	0.97199	1.02882
36	1800	0.97044	1.03046
37	1850	0.96885	1.03215
38	1900	0.96722	1.03389
39	1950	0.96556	1.03567
40	2000	0.96387	1.03748
41	2050	0.96214	1.03935
42	2100	0.96038	1.04125
43	2150	0.95859	1.04320
44	2200	0.95676	1.04519
45	2250	0.95490	1.04723
46	2300	0.95302	1.04930
47	2350	0.95110	1.05141
48	2400	0.94916	1.05356
49	2450	0.94718	1.05577
50	2500	0.94518	1.05800
51	2550	0.94315	1.06028
52	2600	0.94109	1.06260
53	2650	0.93901	1.06495
54	2700	0.93690	1.06735
55	2750	0.93476	1.06979
56	2800	0.93261	1.07226
57	2850	0.93043	1.07477
58	2900	0.92822	1.07733
59	2950	0.92599	1.07993
60	3000	0.92375	1.08254
61	3050	0.92148	1.08521
62	3100	0.91919	1.08791
63	3150	0.91688	1.09066

Table 14. Effect of Antialias (1 kΩ, 22 nF) Performance Summary at 60 Hz

Harmonic No.	Frequency	Attenuation Factor	Gain Compensation Factor
1	60	1.00000	1.00000
2	120	0.99990	1.00010
3	180	0.99972	1.00028
4	240	0.99948	1.00052
5	300	0.99918	1.00082
6	360	0.99880	1.00120
7	420	0.99835	1.00165
8	480	0.99784	1.00216
9	540	0.99726	1.00275
10	600	0.99661	1.00340
11	660	0.99590	1.00412
12	720	0.99512	1.00490
13	780	0.99427	1.00576
14	840	0.99336	1.00668
15	900	0.99238	1.00768
16	960	0.99134	1.00874
17	1020	0.99024	1.00986
18	1080	0.98907	1.01105

Harmonic No.	Frequency	Attenuation Factor	Gain Compensation Factor
19	1140	0.98784	1.01231
20	1200	0.98655	1.01363
21	1260	0.98520	1.01502
22	1320	0.98379	1.01648
23	1380	0.98232	1.01800
24	1440	0.98079	1.01959
25	1500	0.97921	1.02123
26	1560	0.97756	1.02296
27	1620	0.97587	1.02473
28	1680	0.97411	1.02658
29	1740	0.97231	1.02848
30	1800	0.97045	1.03045
31	1860	0.96853	1.03249
32	1920	0.96657	1.03459
33	1980	0.96456	1.03674
34	2040	0.96250	1.03896
35	2100	0.96039	1.04124
36	2160	0.95823	1.04359
37	2220	0.95603	1.04599
38	2280	0.95379	1.04845
39	2340	0.95150	1.05097
40	2400	0.94917	1.05355
41	2460	0.94679	1.05620
42	2520	0.94438	1.05890
43	2580	0.94193	1.06165
44	2640	0.93944	1.06446
45	2700	0.93691	1.06734
46	2760	0.93434	1.07027
47	2820	0.93175	1.07325
48	2880	0.92912	1.07629
49	2940	0.92645	1.07939
50	3000	0.92376	1.08253
51	3060	0.92103	1.08574
52	3120	0.91827	1.08900
53	3180	0.91549	1.09231
54	3240	0.91268	1.09567
55	3300	0.90984	1.09909

A full harmonic analysis is performed on Current Channel A at 50 Hz to verify the combined effect of the antialias filter of the EVAL-ADE9000EBZ and the sinc4 + LPF. The correction factors are introduced to the measurements to compensate the attenuation introduced by the sinc4 + LPF plus antialias filter. The results are shown in Table 15 and Table 16.

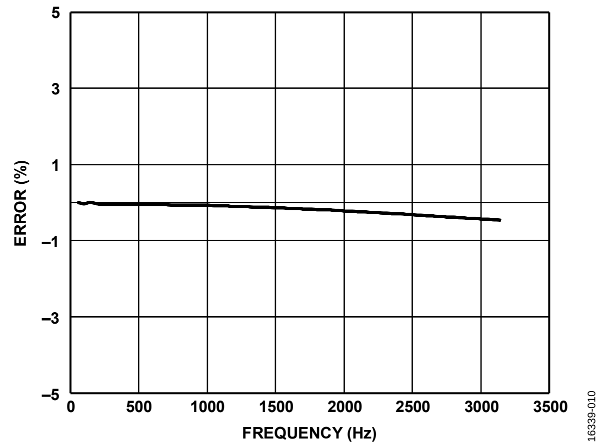

Figure 10. EVAL-ADE9000EBZ Current Channel A RMS Error vs. Frequency after correction (50% Full Scale, 50 Hz)

Table 15. Combined Performance of Sinc4 + LPF and Antialias Filter (1 kΩ, 22 nF) at 50 Hz

Harmonic No.	Frequency (50 Hz)	Combined Attenuation	Combined Gain Compensation Factor
1	50	1	1.00000
2	100	0.9999	1.00010
3	150	0.999732	1.00027
4	200	0.999494	1.00051
5	250	0.999184	1.00082
6	300	0.998801	1.00120
7	350	0.99834	1.00166
8	400	0.997798	1.00221
9	450	0.997173	1.00284
10	500	0.996462	1.00355
11	550	0.995662	1.00436
12	600	0.994771	1.00526
13	650	0.993788	1.00625
14	700	0.992712	1.00734
15	750	0.991542	1.00853
16	800	0.990281	1.00981
17	850	0.98893	1.01119
18	900	0.987491	1.01267
19	950	0.985969	1.01423
20	1000	0.984368	1.01588
21	1050	0.982692	1.01761
22	1100	0.980947	1.01942
23	1150	0.979137	1.02131
24	1200	0.977267	1.02326
25	1250	0.975343	1.02528
26	1300	0.973366	1.02736
27	1350	0.97134	1.02951
28	1400	0.969266	1.03171
29	1450	0.967143	1.03397
30	1500	0.964971	1.03630
31	1550	0.962747	1.03869
32	1600	0.960465	1.04116
33	1650	0.958121	1.04371
34	1700	0.955708	1.04634
35	1750	0.953221	1.04907
36	1800	0.950655	1.05191

Harmonic No.	Frequency (50 Hz)	Combined Attenuation	Combined Gain Compensation Factor
37	1850	0.948003	1.05485
38	1900	0.945265	1.05790
39	1950	0.94244	1.06108
40	2000	0.939531	1.06436
41	2050	0.936545	1.06775
42	2100	0.933491	1.07125
43	2150	0.930383	1.07483
44	2200	0.927234	1.07848
45	2250	0.92406	1.08218
46	2300	0.920872	1.08593
47	2350	0.917679	1.08971
48	2400	0.914482	1.09352
49	2450	0.91127	1.09737
50	2500	0.908024	1.10129
51	2550	0.904714	1.10532
52	2600	0.901305	1.10950
53	2650	0.897768	1.11387
54	2700	0.894094	1.11845
55	2750	0.890311	1.12320
56	2800	0.886497	1.12804
57	2850	0.882771	1.13280
58	2900	0.879228	1.13736
59	2950	0.875728	1.14191
60	3000	0.87142	1.14755
61	3050	0.863753	1.15774
62	3100	0.84683	1.18087
63	3150	0.809953	1.23464

Table 16. Combined Performance of Sinc4 + LPF and Antialias Filter (1 kΩ, 22 nF) at 60 Hz[1]

Harmonic No.	Frequency (60 Hz)	Combined Attenuation	Combined Gain Compensation Factor
1	60	1	1.00000
2	120	0.999855	1.00015
3	180	0.999612	1.00039
4	240	0.999267	1.00073
5	300	0.998815	1.00119
6	360	0.998252	1.00175
7	420	0.997573	1.00243
8	480	0.996772	1.00324
9	540	0.995844	1.00417
10	600	0.994786	1.00524
11	660	0.993595	1.00645
12	720	0.99227	1.00779
13	780	0.990811	1.00927
14	840	0.989222	1.01090
15	900	0.987506	1.01265
16	960	0.98567	1.01454
17	1020	0.983721	1.01655
18	1080	0.981667	1.01868
19	1140	0.979518	1.02091
20	1200	0.977282	1.02325
21	1260	0.974966	1.02568
22	1320	0.972575	1.02820
23	1380	0.970115	1.03081
24	1440	0.967586	1.03350

Harmonic No.	Frequency (60 Hz)	Combined Attenuation	Combined Gain Compensation Factor
25	1500	0.964985	1.03629
26	1560	0.962309	1.03917
27	1620	0.959549	1.04216
28	1680	0.956696	1.04526
29	1740	0.953739	1.04850
30	1800	0.950669	1.05189
31	1860	0.947477	1.05543
32	1920	0.944159	1.05914
33	1980	0.940718	1.06302
34	2040	0.937162	1.06705
35	2100	0.933505	1.07123
36	2160	0.929769	1.07554
37	2220	0.92598	1.07994
38	2280	0.922162	1.08441
39	2340	0.918332	1.08893
40	2400	0.914495	1.09350
41	2460	0.910638	1.09813
42	2520	0.906723	1.10287
43	2580	0.902696	1.10779
44	2640	0.8985	1.11297
45	2700	0.894107	1.11843
46	2760	0.88956	1.12415
47	2820	0.885002	1.12994
48	2880	0.880636	1.13554
49	2940	0.876462	1.14095
50	3000	0.871433	1.14754
51	3060	0.861391	1.16091
52	3120	0.835236	1.19727
53	3180	0.772715	1.29414
54	3240	0.65784	1.52013
55	N/A	N/A	N/A
56	N/A	N/A	N/A
57	N/A	N/A	N/A
58	N/A	N/A	N/A
59	N/A	N/A	N/A
60	N/A	N/A	N/A
61	N/A	N/A	N/A
62	N/A	N/A	N/A
63	N/A	N/A	N/A

[1] N/A means not applicable.

MEASURED TEST RESULTS USING EVAL-ADE9000EBZ

A full harmonic analysis using the EVAL-ADE9000EBZ was performed on Channel IA using the noncoherent analysis with 50% full scale for both fundamental and harmonics. After the FFT, the gain errors listed in Table 17 were obtained and compared to the gain errors of the combined sinc4 + LPF + antialias listed in Table 15. The rms contents with the errors are corrected using the compensation factors listed in Table 13. The results are shown in Table 18.

Table 17. Comparison of Typical Combined Gain Error (ADE9000 Digital Filter + Antialias) vs. Actual Measured Value Using Current Channel A at 50 Hz

Harmonic No.	Frequency	Actual Measured Gain Error	Typical Combined Gain Error
1	50	0%	0%
2	100	0.0085%	−0.010%
3	150	−0.0209%	−0.027%
4	200	−0.0482%	−0.051%
5	250	−0.0814%	−0.082%
6	300	−0.1234%	−0.120%
7	350	−0.1703%	−0.166%
8	400	−0.2278%	−0.220%
9	450	−0.2911%	−0.283%
10	500	−0.3654%	−0.354%
11	550	−0.4487%	−0.434%
12	600	−0.5392%	−0.523%
13	650	−0.6396%	−0.621%
14	700	−0.7508%	−0.729%
15	750	−0.8686%	−0.846%
16	800	−0.9991%	−0.972%
17	850	−1.1358%	−1.107%
18	900	−1.2837%	−1.251%
19	950	−1.4379%	−1.403%
20	1000	−1.6026%	−1.563%
21	1050	−1.7728%	−1.731%
22	1100	−1.9529%	−1.905%
23	1150	−2.1355%	−2.086%
24	1200	−2.3255%	−2.273%
25	1250	−2.5249%	−2.466%
26	1300	−2.7260%	−2.663%
27	1350	−2.9330%	−2.866%
28	1400	−3.1420%	−3.073%
29	1450	−3.3594%	−3.286%
30	1500	−3.5799%	−3.503%
31	1550	−3.8069%	−3.725%
32	1600	−4.0397%	−3.954%
33	1650	−4.2800%	−4.188%
34	1700	−4.5263%	−4.429%
35	1750	−4.7801%	−4.678%
36	1800	−5.0414%	−4.935%
37	1850	−5.3127%	−5.200%
38	1900	−5.5913%	−5.473%
39	1950	−5.8785%	−5.756%
40	2000	−6.1742%	−6.047%
41	2050	−6.4778%	−6.346%
42	2100	−6.7909%	−6.651%
43	2150	−7.1056%	−6.962%
44	2200	−7.4254%	−7.277%
45	2250	−7.7491%	−7.594%

Harmonic No.	Frequency	Actual Measured Gain Error	Typical Combined Gain Error
46	2300	−8.0723%	−7.913%
47	2350	−8.3985%	−8.232%
48	2400	−8.7237%	−8.552%
49	2450	−9.0526%	−8.873%
50	2500	−9.3832%	−9.198%
51	2550	−9.7194%	−9.529%
52	2600	−10.0646%	−9.870%
53	2650	−10.4263%	−10.223%
54	2700	−10.7984%	−10.591%
55	2750	−11.1817%	−10.969%
56	2800	−11.5689%	−11.350%
57	2850	−11.9442%	−11.723%
58	2900	−12.3064%	−12.077%
59	2950	−12.6606%	−12.427%
60	3000	−13.0965%	−12.858%
61	3050	−13.8693%	−13.625%
62	3100	−15.5630%	−15.317%
63	3150	−19.2473%	−19.005%

Table 18. Corrected Harmonic Contents Using Current Channel A at 50 Hz (50% Full Scale)

Harmonic No.	Frequency	Harmonic Content in RMS	Gain Compensation Factor	Corrected Value	% Error
1	50	26348904	1	26348903.6	0.00495%
2	100	26337468	1.0001	26340102	−0.02845%
3	150	26343066	1.00027	26350178.2	0.00979%
4	200	26323856	1.00051	26337280.9	−0.03916%
5	250	26313297	1.00082	26334873.5	−0.04830%
6	300	26304634	1.0012	26336200	−0.04326%
7	350	26292245	1.00166	26335890.2	−0.04444%
8	400	26277729	1.00221	26335802.3	−0.04477%
9	450	26260805	1.00284	26335386	−0.04635%
10	500	26241411	1.00355	26334567.7	−0.04946%
11	550	26220309	1.00436	26334629.8	−0.04922%
12	600	26196100	1.00526	26333891.6	−0.05203%
13	650	26169823	1.00625	26333384.1	−0.05395%
14	700	26140410	1.00734	26332280.6	−0.05814%
15	750	26109163	1.00853	26331874.1	−0.05968%
16	800	26075242	1.00981	26331040.1	−0.06285%
17	850	26038681	1.01119	26330053.6	−0.06659%
18	900	25999739	1.01267	26329156.1	−0.07000%
19	950	25959225	1.01423	26328624.5	−0.07202%
20	1000	25916479	1.01588	26328032.6	−0.07426%
21	1050	25870936	1.01761	26326523.6	−0.07999%
22	1100	25823584	1.01942	26325077.6	−0.08548%
23	1150	25774163	1.02131	26323410.5	−0.09181%
24	1200	25723526	1.02326	26321855.2	−0.09771%
25	1250	25671636	1.02528	26320614.7	−0.10242%
26	1300	25617889	1.02736	26318794.7	−0.10932%
27	1350	25563016	1.02951	26317380.4	−0.11469%
28	1400	25506991	1.03171	26315817.3	−0.12062%
29	1450	25449687	1.03397	26314212.8	−0.12671%
30	1500	25390639	1.0363	26312319.5	−0.13390%
31	1550	25330763	1.03869	26310810.7	−0.13963%
32	1600	25268285	1.04116	26308327.5	−0.14905%

Harmonic No.	Frequency	Harmonic Content in RMS	Gain Compensation Factor	Corrected Value	% Error
33	1650	25204549	1.04371	26306240	−0.15697%
34	1700	25139013	1.04634	26303954.7	−0.16565%
35	1750	25071823	1.04907	26302097.1	−0.17270%
36	1800	25001965	1.05191	26299817	−0.18135%
37	1850	24930558	1.05485	26297999.4	−0.18825%
38	1900	24856230	1.0579	26295405.5	−0.19810%
39	1950	24779510	1.06108	26293042.4	−0.20706%
40	2000	24700898	1.06436	26290647.4	−0.21615%
41	2050	24619876	1.06775	26287872.1	−0.22669%
42	2100	24537541	1.07125	26285841	−0.23440%
43	2150	24452885	1.07483	26282694.2	−0.24634%
44	2200	24368062	1.07848	26280467	−0.25479%
45	2250	24282321	1.08218	26277841.9	−0.26476%
46	2300	24195538	1.08593	26274661	−0.27683%
47	2350	24109229	1.08971	26272068.2	−0.28667%
48	2400	24022755	1.09352	26269362.5	−0.29694%
49	2450	23936309	1.09737	26266987.8	−0.30595%
50	2500	23848192	1.10129	26263774.9	−0.31815%
51	2550	23759036	1.10532	26261338.2	−0.32740%
52	2600	23666544	1.1095	26258030.1	−0.33995%
53	2650	23570712	1.11387	26254709.2	−0.35256%
54	2700	23471248	1.11845	26251417.5	−0.36505%
55	2750	23369748	1.1232	26248900.8	−0.37460%
56	2800	23267349	1.12804	26246500.1	−0.38371%
57	2850	23166448	1.1328	26242952.3	−0.39718%
58	2900	23070843	1.13736	26239853.9	−0.40894%
59	2950	22976865	1.14191	26237512	−0.41783%
60	3000	22861848	1.14755	26235113.5	−0.42693%
61	3050	22657995	1.15774	26232066.6	−0.43849%
62	3100	22211497	1.18087	26228890.6	−0.45055%
63	3150	21242010	1.23464	26226235.5	−0.46062%

CONCLUSION

The following sections describe the advantages and disadvantages of both coherent and noncoherent sampling method prior to FFT.

NONCOHERENT SAMPLING

Advantages

Accurate harmonic contents can be obtained by following a proper FFT.

Noncoherent mode can perform sampling continuously using the ping pong buffer routine.

A continuous FFT process is possible.

Disadvantages

An FFT is difficult to perform and needs a more complex routine.

If signals are generated using a function generator to perform the analysis, proper timing, and sync must be considered between the CLK_IN of the ADE9000 and the frequency of the generators.

COHERENT SAMPLING

Advantages

An FFT is easier to perform, because 128 samples are constantly tracked during the resampling per line cycle.

Disadvantages

Coherent sampling is less accurate than the noncoherent sampling, because the maximum codes for resampled data is 18,196 codes.

Resampling is limited to 512 samples per waveform buffer.

Performing a continuous FFT is difficult, because portions of the signal are lost when the waveform buffer calculates resampled data.

The ADE9000 simplifies harmonic analysis by using the waveform buffer register. It is possible to calculate up to the 63rd harmonic and introduce the gain compensation factors to correct the attenuation caused by the digital filtering plus effects of the antialias filter.

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