International Journal of Computer Engineering Science (IJCES)
Volume 2 Issue 11 (November 2012) ISSN : 2250:3439
https://sites.google.com/site/ijcesjournal http://www.ijces.com/

Concurrent Adaptive Cancellation of Quantization Noise and Harmonic Distortion in Sigma–Delta Converter

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Abstract. Adaptive noise cancellation (ANC) technique can removes thermal and shaped wideband quantization noise from the output of sigma-delta modulator and improves SNR and SFDR ratios. ANC filter more than desired signal passes harmonics of input signal caused by analog element such as operational amplifier of the integrator without any suppression and this issue causes less increment in SNR and SFDR of analog to digital converter. This paper presents a technique by adding an adaptive harmonic canceller filter in the front of ANC filter addresses this issue and improves considerably performance of the ADC. The simulation results demonstrate effectiveness of this combination technique in first order sigma-delta converter.

Keywords: Adaptive noise cancellation, harmonic distortion, sigma-delta modulator, digital calibration.

1 Introduction

Sigma-delta ADCs were identified in the mid-1980s for their robustness when implemented in digital CMOS technology. They traditionally use large over-sampling ratios of 32x-128x to digitize low bandwidth signals with 16to 20 bits resolution. More recently, sigma-delta ADCs have been realized with low over-sampling ratios of 4x-16x.A rule of thumb says to reduce the errors introduced by finite DC gain, DC gain has to be larger than OSR[l],[2].

In CMOS processes one possibility of mitigation of effects of errors caused by analog imperfections is applying digital calibration [3]-[10]. For adaptive calibration usually Least-Mean-Squared algorithm is used [3-5]. Calibration works in sigma-delta ADCs are focused more on the DAC linearity by using dynamic element matching techniques [6], [7]. A few other works address the problems of noise transfer function mismatch between the analog and digital domain [8]. Recently, a new approach has calibrated nonlinear memory error in digital domain [9]. A fully digital technique based on Adaptive Noise Cancellation (ANC) was reported in [10] that removes wideband noise from the output of sigma-delta modulator and improves performance of conversion. .The most important advantage of this method is fully implementation capability in digital domain and its limitation is passing harmonic distortion caused by analog imperfections such as operational amplifier of discrete time integrator without any suppression. In this new approach by adding an adaptive harmonic distortion canceller in the front of ANC filter this issue will be addressed and SNR and SFDR of modulator will be increased considerably.

This paper is organized as follows. In Section 2 analysis of harmonic distortion in sigma-delta modulator is discussed. Section 3 reviews employed Adaptive Digital Filters (ADF) in sigma- delta modulator. Section 4 presents basic principles of proposed technique. Section 5 presents the simulation results to apply this technique to first order sigma–delta modulators. This paper concludes in Section 6.

2 Analysis of harmonic distortion

Main sources of harmonic distortion in sigma-delta modulators are signal-dependent clock feed through, voltage coefficient of capacitors, and nonlinear dc-gain characteristic of operational amplifier [11]. In this section first the nonlinearity of operational amplifier will be discussed and then the error caused by this nonlinearity modeled in first order sigma-delta modulator.

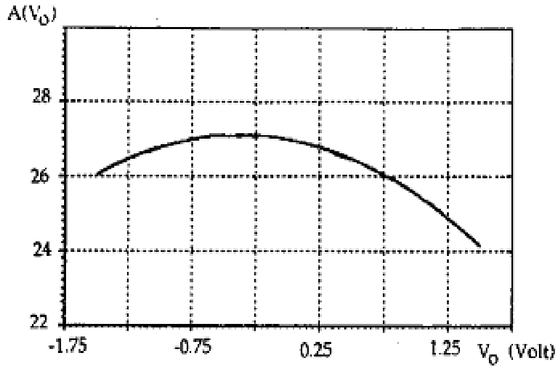


Fig. 1. Amplifier dc-gain characteristic as a function of the output voltage [11].

2.1 Amplifier dc-gain characteristic

Fig. 1 shows the gain of amplifier as function of output voltage. This characteristic can be approximated by the following N-terms interpolating polynomial:

$$A(v_o) = \alpha_0 + \alpha_1 v_o + \alpha_2 {v_o}^2 + \ldots + \alpha_{N-1} {v_o}^{N-1} \quad (1)$$

$$\frac{y(n)}{A(n)} \approx \frac{\sum_{i=1}^{N} k_i y^i(n)}{A_{max}} \quad (2)$$

Where A_{max} is the maximum gain, in this paper A_{max} =27 and k_1=1, and the higher order coefficients are determined by the amplifier nonlinearity (Fig. 1).

2.2 harmonic distortion in first order modulator

Fig. 2. (a) Shows a lossless SC integrator with variable gain $A(n)$ for operational amplifier and equal C_s and C_f. By using charge conservation law in the end of φ_2 phase the following equation will be found:

$$y_o(n) = y_i(n) + y_o(n-1) - \frac{2y_o(n)}{A(n)} + \frac{y_o(n-1)}{A(n-1)} \quad (3)$$

The above equation indicates a real integrator is composed of two parts: An ideal integrator with the two left side terms, and a perturbation that is inversely proportional to the distortion polynomial of amplifier gain. Therefore, the distortion error signal will be:

$$e_a(n) = -\sum_{i=1}^{N} a_i y_o(n)^i + \sum_{i=1}^{N} b_i y_o(n-1)^i \quad (4)$$

$$a_i = \frac{2k_i}{A_{max}}$$

$$b_i = \frac{k_i}{A_{max}} \quad (i = 1...N)$$

Now the structure of first order sigma-delta with considering distortion of amplifier is shown in Fig. 2(b).

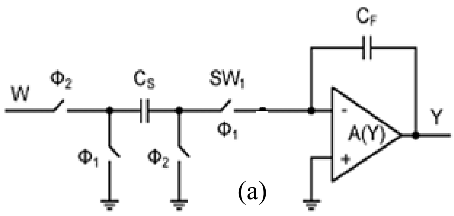
For reconstruction of distortion error signal, the require information must be extracted from the output signal (d) of modulator. The error signal cane be written as:

$$e_a(n) = -\sum_{i=1}^{N} a_i (d(n) - e_q(n))^i + \sum_{i=1}^{N} b_i (d(n-1) - e_q(n-1))^i \quad (5)$$

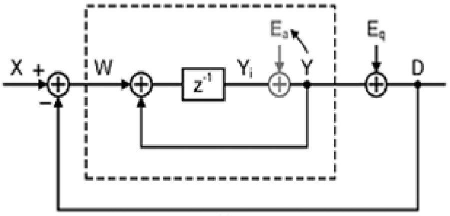
By dropping quantization noise from above equation the digital version of distortion error signal will be found:

$$e_d(n) = -\sum_{i=1}^{N} a_i (d(n))^i + \sum_{i=1}^{N} b_i (d(n-1))^i \quad (6)$$

As it is clear, the reconstructed distortion error signal ($e_d(n)$) not exactly equal with $e_a(n)$ but the difference is little and can be neglected.



(a)



(b)

Fig. 2, (a) switched-capacitor realization of the integrator, and (b) the model with considering distortion signal [9].

3 Review of ADF employed in sigma-delta ADCs

3.1 adaptive noise cancellation

Adaptive noise cancellation (ANC) is one of the interesting techniques used in voice processing for separating the periodic signal from broadband signal [13], [14]. The first time in [10] the application of ANC is discussed for sigma- delta modulator. An ANC block is shown in Fig. 3. In this application the input of ANC is output of modulator that is consist of desired signal and broadband quantization noise, defined as:

$$d(k) = s(k) + n(k) \tag{7}$$

The coefficients of the adaptive filter are tuned by Least-Mean-Squared (LMS) algorithm [3]. The delayed version of input signal is passed from adaptive filter for generation of error signal:

$$e(k) = d(k) - o(k) \tag{8}$$

If it is assumed that noise is random wideband noise and delay line is long enough, LMS for obtaining the minimum Mean-Square-Error of $e(k)$ will forces $o(k)$ to be a close estimate of $s(k)$, therefore wideband shaped noise will be attenuated and resolution of converter will be increased considerably [8].

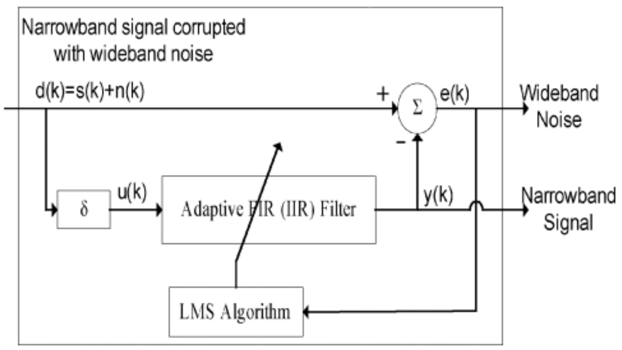


Fig. 3, Block diagram of Adaptive noise cancellation technique [10].

3.2 Adaptive harmonic distortion canceller

The harmonic error signal will be added to the output of sigma- delta modulator and for mitigating the effect of it, the signal in (6) can be reconstructed and added with negative sign to the output of modulator. For estimating of coefficients in [9] a new approach was reported. In that the first a two level pseudorandom signal will be added to the input of sigma-delta modulator and then by using Gradient-Descent Algorithm the coefficients are estimated:

$$a_{i+1} = a_i - \mu_{ai}\left[e^{i-1}(n)t(n-1)\right]e(n)$$
$$b_{i+1} = b_i - \mu_{bi}\left[e^{i-1}(n)t(n-2)\right]e(n) \quad (9)$$

The block diagram of this ADF is shown in Fig. 4.

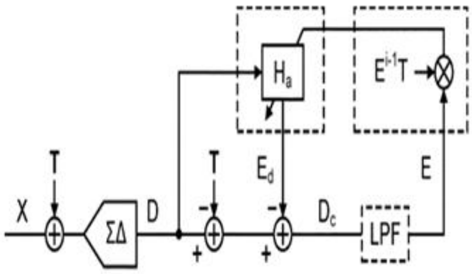


Fig. 4, Block diagram of harmonic distortion canceller [9].

4 Basic principles of proposed technique

The problem of ANC that reduces performance of it, is passing harmonics caused by analog elements described in previous section without any suppression. But if in any way the harmonics cancelled, the performance of converter will not reduced. Fig. 5 shows the block diagram of proposed technique. In this block before than ANC another ADF is used. This filter removes harmonic distortion

$$D(z) = z^{-1}X(z) + E_a(z) + (1 - z^{-1})E_q(z) - E_d(z) \quad (10)$$

after that ANC removes quantization noise:

$$O(z) \approx z^{-1}X(z) \quad (11)$$

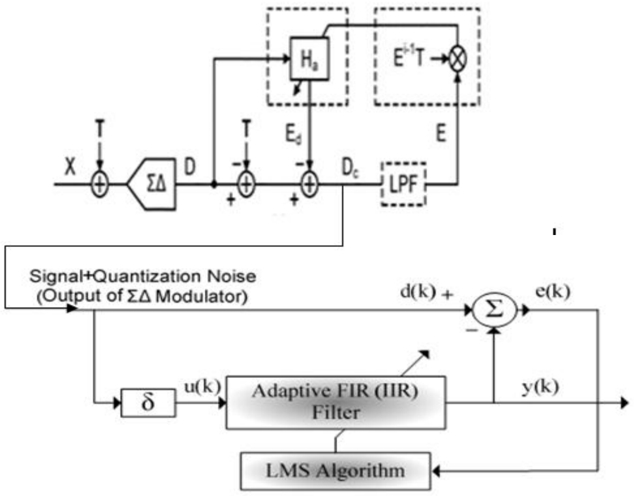


Fig. 5. Block diagram of proposed technique

5 Simulation results

The behavioral simulation for a first-order modulator with 5 bit quantizer is done. In this simulation OSR is 8 and the length of ANC filter is 64. Fig. 6(a) and (b) show output frequency spectrum with using an ANC filter in the back-end of an ideal modulator and a real modulator. In Fig. 6(b) SNDR is around 17db decreased. In Fig. 6(c) the spectrum of modulator with only calibration of harmonic distortion is shown and finally the results of using concurrently both ANC and harmonic distortion canceller are shown in Fig. 6(d). In this case the SFDR and SNDR approximately 50% and 53% in comparison with no calibration increased.

6 Conclusion

In this paper first, harmonic distortion caused by a nonlinear amplifier in the first-order sigma -delta modulator is analyzed and effect of this distortion on ANC technique is discussed. In proposed technique by using an adaptive harmonic distortion canceller before than ANC the problem of passing harmonic distortion from ANC is addressed.

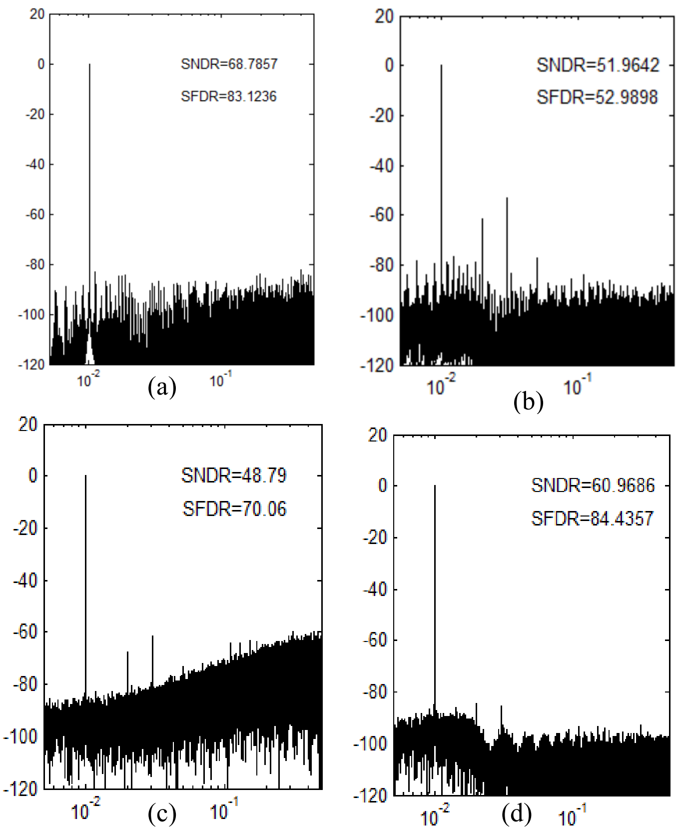


Fig. 6. Simulation results of a 5-bit first-order modulator After calibration :(a) ANC with A_{max} =1e8, (b) ANC with A_{max} =20, (c) harmonic canceller, (d) combination of both technique.

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