

## Digital filters for Band-pass Sigma-Delta converter for complex sensor systems

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**Abstract**—Sigma delta modulation is useful for high performance analog-to-digital conversion of narrow band signals. Band-pass sigma delta modulation (BP  $\Sigma\Delta$  ADC) is suitable for communication systems such as AM/FM receivers and mobile phones. Application of BP  $\Sigma\Delta$  ADC in sensor systems is presented in the paper. BP  $\Sigma\Delta$  ADC performs I/Q conversion of the complex impedance from two dimensional sensor into two digital values representing real and imaginary part of sensor output. The BP  $\Sigma\Delta$  ADC is useful for outputs processing from the modulating sensors too. Implemented digital filters have important impact on the metrological properties of whole BP  $\Sigma\Delta$  ADC. The various types of FIR and IIR filters are studied in the paper and their phase sensitivity and transmission of modulated signal are studied.

### I. Introduction

The main of structure bandpass BP  $\Sigma\Delta$  AD converter (BP  $\Sigma\Delta$  ADC) consist of LP  $\Sigma\Delta$  modulator, which has structural element is differential amplifier processing different between input signal and comparator adjoin on output lowpass filter realized through the use of integrator. Internal structure of both types modulators and discrete model can see on Fig. 1. Substitution lowpass filter for resonator will cause, that lowpass modulator is change on bandpass. Resonator is realized time discrete structure of resonator in the surrounding of resonance frequency, which is determined by sampling frequency. It imagines transformation transfer function of LP modulator in  $z$  – area. Transformation is profitable, because properties LP model, like stability and dynamics remain equal. Disadvantage is, that noise transfer function (NTF) achieving minimum on fixed determined frequency  $f_s/4$  toward sampling frequency. Output from BP  $\Sigma\Delta$  modulator is connected to the digital demodulator and digital LP filter. [1], [2]

The structure of BP  $\Sigma\Delta$  ADC is shown on Fig. 1. Resolution of each component at the digital output is affected by the length LP FIR filtration.

### II. Filters at the output of digital down converter

Application of LP digital filter in signal processing in sigma delta converter sequence is not a trivial task for designer. Observing in filters study devotes to FIR and IIR filters that were utilised in signal processing according to Fig.1. Only the filter on upper leg was modified. Signal spectra in the processing sections are shown on Fig. 1. Those spectra are: spectrum behind BP SDM block, spectrum behind digital demodulator at each leg and spectra behind upper leg filter. There were used only the LP filters.

The following digital filters were studied:

FIR with window functions - Rectangular, Hanning, Hamming, Kaiser and Gaussian

IIR this types - Bessel, Chebyshev and Butterworth

FIR filters with various window function and decimation.

Attention was given also to the filtration effect (FIR), while solving FIR filters with decimation of noisy signal. Decimation in sigma delta transfers can be realized by the several forms. Usually, the decimation is a combination with the filtration process. Realisation of that is comb filter described with equation:

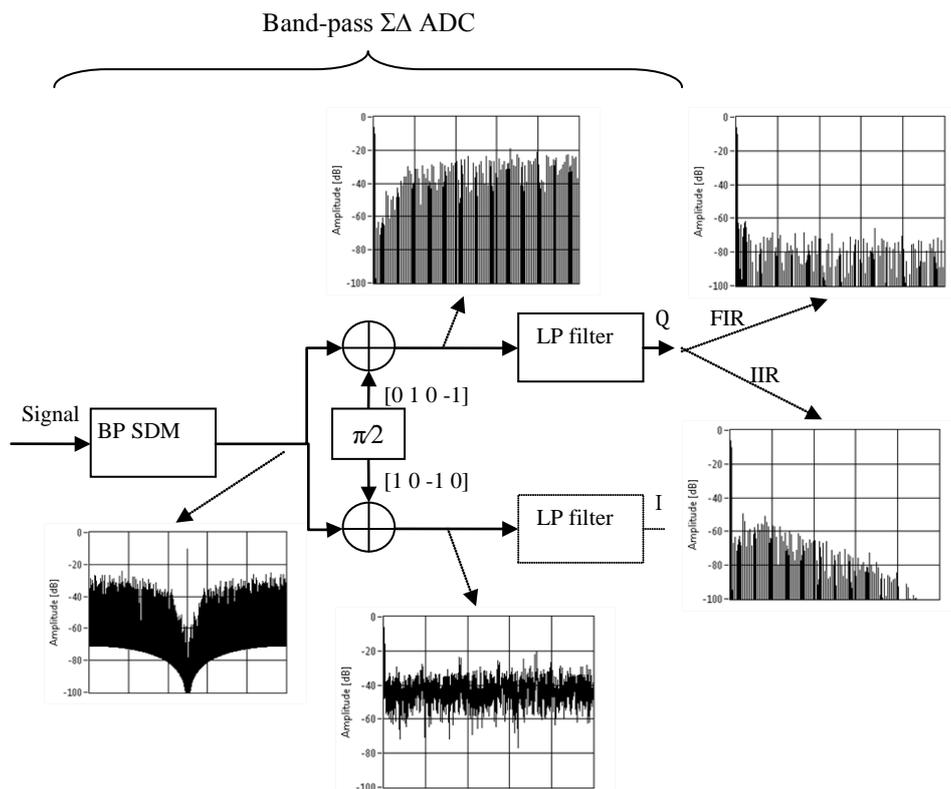


Figure 1. Consequential AD converter for decoding I/Q component of harmonics signal.

CIC FILTER (moving average)

$$y(i) = \frac{1}{M} \sum_{j=0}^{M-1} x(i-j) \quad (1)$$

where M represent number of filter coefficients and even decimation coefficient.

Other filters which were implemented are:

*FIR with constant coefficient and floating window*

$$y(i) = \sum_{j=0}^{N_b-1} b(j)x(i-j) \quad (2)$$

Where y is a filtrated input x,  $N_b$  is number of FIR coefficients

*FIR with window function and decimation*

$$y(k) = \sum_{j=0}^{N_b-1} b(j)x(L.k-j) \quad (3)$$

$$k = 0,1,2,\dots$$

$b(j)$  is j-th FIR coefficient

If  $L=1$  is the moving window FIR filter without decimation. If the  $L=N_b$  the output signal is being decimated  $N_b$  times.

The structure FIR filter with individually implemented decimation is done according formula (3) and the decimation is cancelation of samples according parameter  $N_b$ . While  $\Delta t$  between samples is increasing, the sample frequency is decreasing.

The simulation of BP  $\Sigma\Delta$  modulator with digital filter was performed with the aim to evaluate the suppression of superimposed Gaussian noise by the filtration and decimation. Filter with decimation was the same as previous one, but the implemented algorithm (1) performed the decimation of samples on output. Selected decimation

value was equal to number of coefficients of FIR filter. The result of application of FIR filter coefficients on selected size of window of input samples was one value. It causes that from one window only one value is extracted. The coefficients of the implemented rectangular window in both FIR filters where  $b(j) = \frac{1}{N_b}$ .

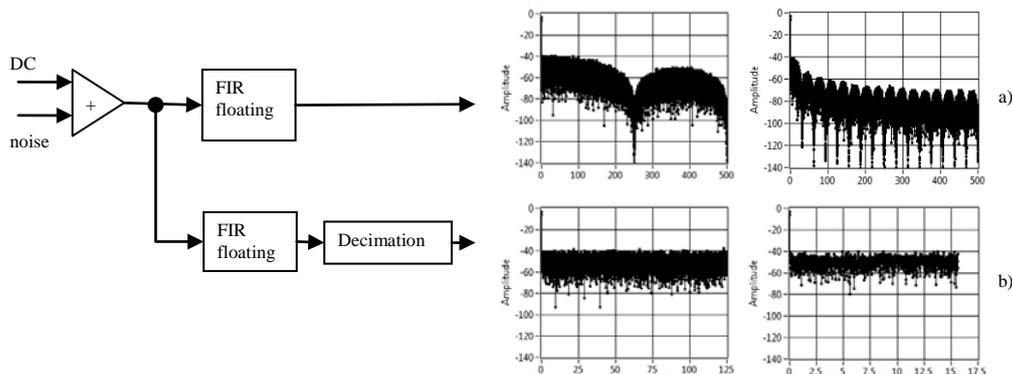


Figure 2. Realization of examined filtration by FIR filter ( $N_b=4$  and 32)

The effect of coefficients and decimation factor are shown on Fig. 2. , The figure shows the power spectrums. The spectrum is compressed along the X axis as shown on Figure 2.b). The compression is caused by the decimation.

The notch frequencies at the filter output are spaced with smaller frequency step. It is caused by the longer time window where full averaging on zero value is being achieved for lower frequencies.

### Bessel, Chebyshev and Butterworth IIR filters

Design of digital IIR filters is based on the transformation of their analog counterparts from analog to digital domain. The required frequency thresholds and attenuations are designed for the analog filter. The general formula for IIR filter is:

$$y(n) = \sum_{i=0}^{N-1} b_i \cdot x(n-i) - \sum_{i=1}^{N-1} a_i \cdot y(n-i) \quad (4)$$

Number of IIR coefficients is lower than FIR coefficients of similar transfer characteristic. Polynomial coefficients  $a_i$ ,  $b_i$  are estimated using formulas published in the monograph [3].

### III. Simulation results for studied filters

The stimulus signal at the input of sigma delta ADC was considered monoharmonic signal, where the carrier frequency was coherent with internal clock of the BPΣΔ ADC. The input frequency was 4 times higher than internal clock in around. Amplitude and phase of input signal was adjustable. It allows simulating the sensors where output electrical quantity is represented by complex impedance. Real and imaginary component is being impacted by two different physical quantities from the sensor's input. Capacitive sensor of air pressure is an example of two parametric sensor. Here real part of output impedance is proportional to humidity of measured air and imaginary part is proportional to the air pressure. Such sensor system, where the processing block consists of BP ΣΔ ADC perform direct I/Q conversion of both measured physical quantities air pressure and its humidity into two digital values.

The AM signal is another application useful for modulating sensors. Here measured parameter influence the amplitude of harmonic source signal. The transfer function of digital LP filter influences the whole transfer function of the modulating physical quantity to output digit. AM modulated signal in the contrary to monoharmonic signal allowed to study the impact of side lobes of studied low-pass filters at the output of BP ΣΔ modulator and digital demodulate

Let consider the carrier frequency of the modulated signal  $f_{car} = f_s/3$ . The modulation frequency represented by the frequency of modulating physical quantity is  $f_{mod} = f_s/12,5$ . The simulated modulation index for such stimulus

is 0,5. The modulation signal is incoherent with the carrier harmonic signal. The simulation studied situation of the processing AM signal by BP  $\Sigma\Delta$  modulator, digital demodulation with  $f_s/4$  and final digital LP filtering for this case. The measured modulation signal from one side lobe at the output has the frequency

$$f_{out} = \left( \frac{f_s}{3} - \frac{f_s}{12,5} \right) - \frac{f_s}{4} = 0,003 \cdot f_s \quad (5)$$

The signal to noise expressed by SINAD was taken as a criteria parameter evaluating filter efficiency. The power of the demodulated signal  $S(f_{out})$  with the superimposed power of noise and distorted components was in the numerator. Denominator in the formula for SINAD was represented by the mean square of the noise power of all components in the frequency band  $\Delta B=f_s$ , except frequency  $f_{out}$ .

$$SINAD[dB] = 10 \cdot \log \frac{P_{SIGNAL} + P_{NOISE} + P_{DISTORTION}}{P_{NOISE} + P_{DISTORTION}} \quad (6)$$

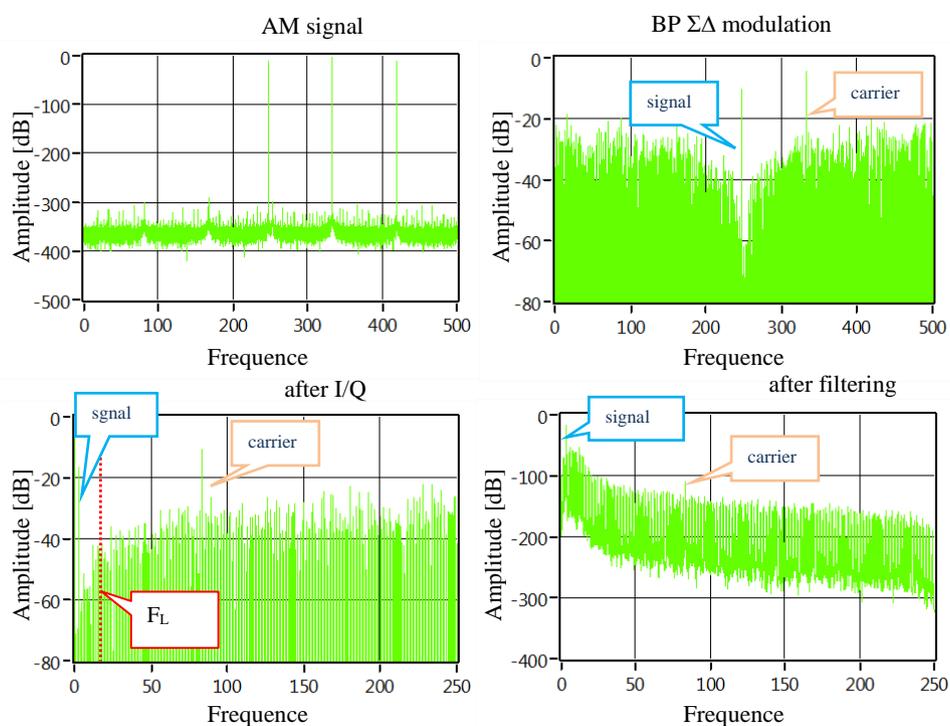


Figure 3. Signal in front of BP SDM, signal after BP SDM, signal after digital demodulation and after filtering

The optimal selection digital LP filter is a complex task. Type of filter depends on the boundary frequency selection. The simulation is useful tool for solving this trade-off. Every filter has different shape of the transfer function and therefore the boundary frequency is different for FIR and IIR filters. Figure 4 shows that FIR filters with the Rectangular and Keiser windows of order 32 are adequate to the IIR filters with order 4. Starting with order 16 the Hanning and Hamming windows FIR filter are better then similar filters with rectangular window. IIR filter are achieving high efficiencies from low order filters and for most of the cases the best solution is Butterworth filter.

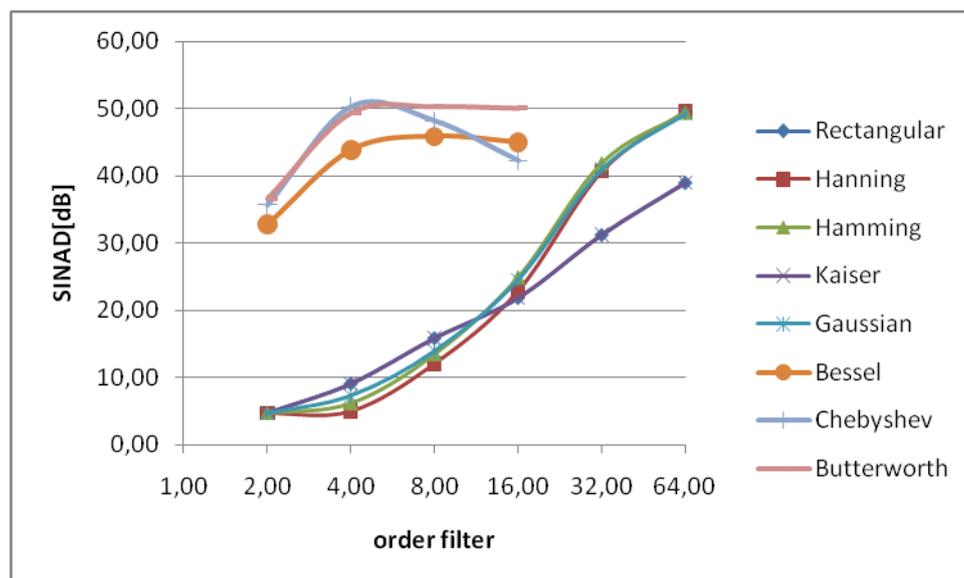


Figure 4. Graph effectiveness of filters used in the AM signal.

#### IV. Conclusions

The parameters of LP filter were studied in the paper. The suitable signals for simulation are harmonic signals with and without amplitude modulation. The simulation results show application of BP  $\Sigma \Delta$  ADC for two-dimensional sensors. Result of these studies allows to design digital filters for practical application. Proposed simulation tool allows selection of the compromise between the boundary frequency and the filtering algorithm together with assessment of rounding errors. While the FIR filter is represented by the simple algorithm and high number of processed samples, the stability hazard with lower number of samples is characteristic feature of the IIR filters. Simulation of signal processing in sensor systems could be implemented for communication systems too.

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