

## A toolbox for the $\Sigma\Delta$ modulator design

**Abstract.** The paper presents a toolbox to support  $\Sigma\Delta$  modulators design. The Matlab based tools have been prepared to use at structural level. At this level different structures, with different noise shaping filters can be simulated. Important parameters of the modulators (SNDR, ENOB, FoM) are calculated and can be used as a goal function during the optimization process. The optimization procedure can be easily connected to these tools. The elaborated tools were practically applied in the second order, current mode sigma-delta modulator design.

**Streszczenie.** Artykuł przedstawia toolbox wspomagający projektowanie modulatorów  $\Sigma\Delta$ . Proces projektowania obejmuje poziom opisu strukturalnego. Możliwe jest zasymulowanie wybranych struktur modulatorów z różnymi filtrami kształtującymi szum. Opracowane skrypty wyliczają podstawowe parametry charakteryzujące testowane struktury (SNDR, ENOB, FoM). Obliczane funkcje mogą zostać użyte jak funkcje celu w procesie optymalizacji projektowanych modulatorów. Procedura optymalizacyjna w łatwy sposób może zostać dołączona do opracowanego środowiska. W celu ułatwienia obsługi system, opracowano interfejs w środowisku Simlink. Wykorzystanie opracowanych narzędzi, zostało w praktyce zweryfikowane w projekcie prądowego modulatora sigma-delta pracującego w trybie prądowym. (Toolbox wspomagający projektowanie modulatorów  $\Sigma\Delta$ ).

**Keywords:** Sigma-Delta, Matlab toolbox.

**Słowa kluczowe:** modulator Sigma-Delta, Matlab Toolbox.

### Introduction

The transistors' sizes have already achieved nanometers' level, which allows continuing the trend predicted by Gordon Moore. However, according to the International Technology Roadmap for Semiconductors (ITRS), the second trend, besides the minimization, is a functional diversification of semiconductor-based devices. This trend may be designated "More-than-Moore" (MtM). The MtM approach typically allows for the non-digital functionalities (e.g. RF communication, power control, sensors, actuators) to migrate from the system board level into a particular package level (System-in-Package) or chip level (System-on-Chip) solution. Nowadays, we measure just about everything imaginable via sensors and convert the analog data into digital signals utilizing analog-to-digital converters (ADC). Among possible architectures of the ADCs, the converters basing on  $\Sigma\Delta$  modulators are very popular in mentioned above applications. This class of converters can offer reasonable speed and resolution parameters without necessity of using high accuracy components [1,2].  $\Sigma\Delta$  modulators are based on two signal processing techniques, namely oversampling and noise-shaping. A designer, in order to find the optimal for given requirements solution, can choose among different structures of the modulator. They can differ in a noise shaping filter structure (feed-forward, feed-back or combine), order of the filter, a quantizer's number of bits and finally oversampling ratio. Hence, to find an optimal solution a designer has to validate different circuits. There are many possible approaches presented in publications. MATLAB toolbox dedicated to  $\Sigma\Delta$  modulator circuits was presented in [3] and is continuously upgraded. Another approach, presented in [4], applied VHDL-AMS language for modeling and simulating  $\Sigma\Delta$  structures. Modeling of continuous-time functions for fast simulation using MATLAB-Simulink and VHDL-AMS is presented in [5]. This paper presents computer tools prepared as MATLAB toolbox, which can be useful to accelerate the  $\Sigma\Delta$  modulators design process. The tool was prepared to support current mode modulators design. The second section of the paper introduces some basic information of the  $\Sigma\Delta$  modulators structures and characteristics. The blocks used for current mode  $\Sigma\Delta$  modulators are briefly described. Next, their models elaborated as MATLAB classes are presented. The third section presents an example design case.

### Modulator structure

An example modulator structure with depicted a noise shaping filter is presented in Fig. 1.

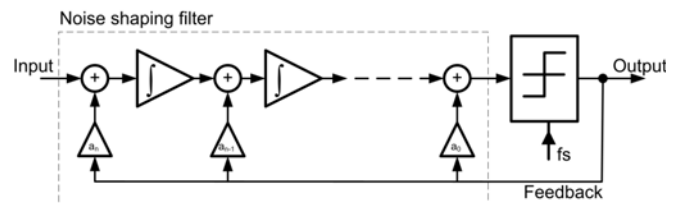


Fig. 1.  $\Sigma\Delta$  modulator structure with a feed-back noise shaping filter

There are many qualitative parameters to characterize a  $\Sigma\Delta$  modulator based converters. The first group of parameters is related to the transfer function and the second group expresses the deformation induced on the converted signal [6]. As an example of the abovementioned relation the expression used to dynamic range calculation is presented:

$$DR|_{dB} = 10 \log \left[ \frac{3(2^B - 1)^2(2L + 1)OSR^{(2L+1)}}{2\pi^{2L}} \right] \approx$$

$$(1) \quad \approx 6.02B + 1.76 + 10 \log_{10} \left( \frac{2L+1}{\pi^{2L}} \right) + (2L + 1)10 \log_{10}(OSR)$$

where B - is the quantizer's number of bits, L - is the noise shaping filter order, and OSR is the oversampling ratio. Expression (1) for an ideal N-bit Nyquist rate converter (B=N, L=0, OSR=1), is simplified to the well-known expression:

$$(1) \quad DR|_{dB} \approx 6.02N + 1.76$$

In practice only the first, the second and the third order structures are used because of the stability problems. If necessary, MASH structure can be applied to achieve better accuracy. More information about the  $\Sigma\Delta$  modulators structures can be found in [4].

The main component of the modulator is a noise shaping filter. In the continuous time current mode modulators, we proposed to use an integrator built based on a current mirror [7,8]. Two structures can be applied. The basic one is presented in Fig. 2.

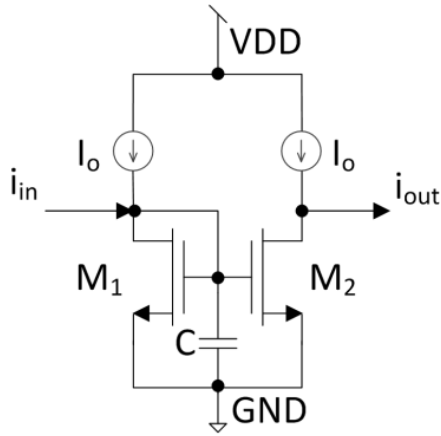


Fig. 2. CT integrator based on current mirror structure

Its transfer function is represented by expression:

$$(3) \quad H_M(s) = \frac{I_{out}(s)}{I_{in}(s)} = \frac{-g_{m2}}{s + \frac{g_{m1}}{C}}$$

where  $g_{m1}$  and  $g_{m2}$  are transconductances of transistors  $M_1$  and  $M_2$  respectively. Assuming the same transistors' sizes and neglecting mismatches the transfer function can be simplified to expression:

$$(4) \quad H_M(s) = \frac{I_{out}(s)}{I(s)} = \frac{-g_m}{sC + g_m}$$

Another possible structure, which can be applied in CT current mode  $\Sigma\Delta$  modulators, is a fully differential circuit presented in Fig. 3.

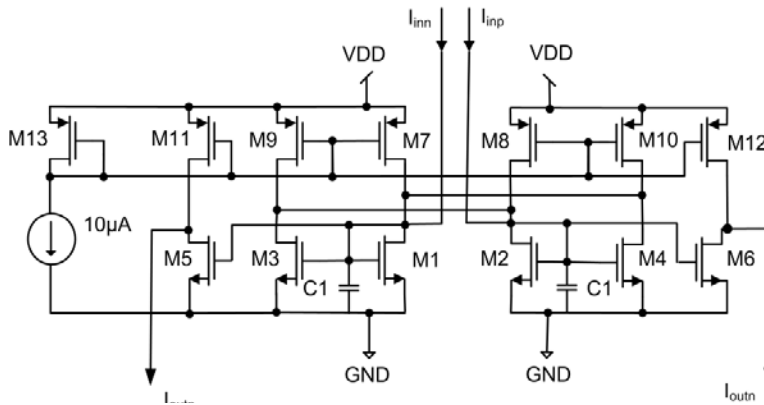


Fig. 3. CT fully differential current mode integrator

The transfer function for the fully differential integrator presented in Fig. 3 is given by expression:

$$(4) \quad H_M(s) = \frac{I_{out}(s)}{I(s)} = \frac{g_m}{sC}$$

Having the transfer function of the noise shaping filter, it is possible to simulate the modulator and choose its optimal configuration and parameters.

#### MATLAB/SIMULINK tools

To simulate and find an optimal structure of the  $\Sigma\Delta$  modulators the MATLAB class was elaborated. Object oriented approach was chosen to prepare the project for further development. Additionally, the SIMULINK interface was designed to offer a user friendly interface. The optimization procedure is not at the scope of this paper, but some possible approach, using Hooke-Jeeves algorithm, was presented in previous publication [9]. The *sigmadelta* class has properties, which can be set using a dialog box presented in Fig. 5. Besides these visible properties, there are additional, which are used by the script internally like: number of points for FFT, number of periods required for coherent sampling, simulation time, structure to save FFT results, signal to noise and distortion ratio. Methods, which are elaborated for this class, are presented in Table 1 together with their functionality.

Table 1. Methods, which are elaborated for this class

| Methods            | Functionality  |
|--------------------|--|
| set_property       | Used to set value to the class's properties.   |
| coherent_sampling  | Calculate the input signal frequency and simulation time required for proper FFT calculation (coherent sampling).          |
| simulation_mask    | Set object's properties, run simulation and save results. This method is required to simulate in the Simulink environment. |
| simulation_command | Methods allows to setup and run simulation in the command line.  |
| calc_sndr          | Calculate SNDR parameter.  |
| calc_fft           | Calculate FFT of the modulator's output signal.  |
| one_cycle          | Methods run all necessary functions in proper order.   |
| Swap               | Allows swapping a chosen parameter and multiply run the simulation.  |
| plot_bode          | Plots a bode diagram of the noise shaping filter.  |
| plot_signals       | Plots input and output signals of the modulator.   |

The whole structure of the modulator was prepared in the Simulink environment. The diagram to simulate any first or second order modulator is presented in Fig. 4

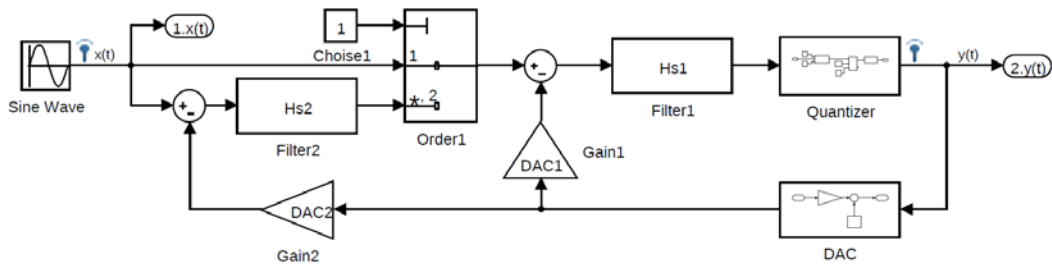


Fig. 4. Simulink environment to simulate  $\Sigma\Delta$  modulators

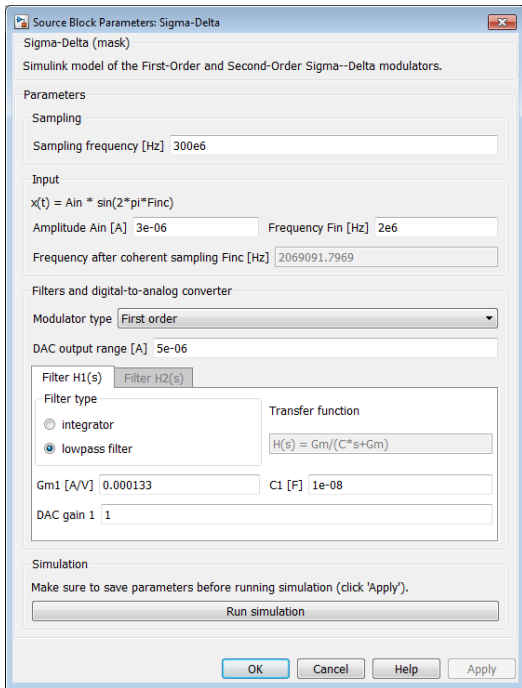


Fig. 5. Dialog box for Sigmadelta class

The elaborated tools were used to different structures with different parameters of the noise shaping filters.

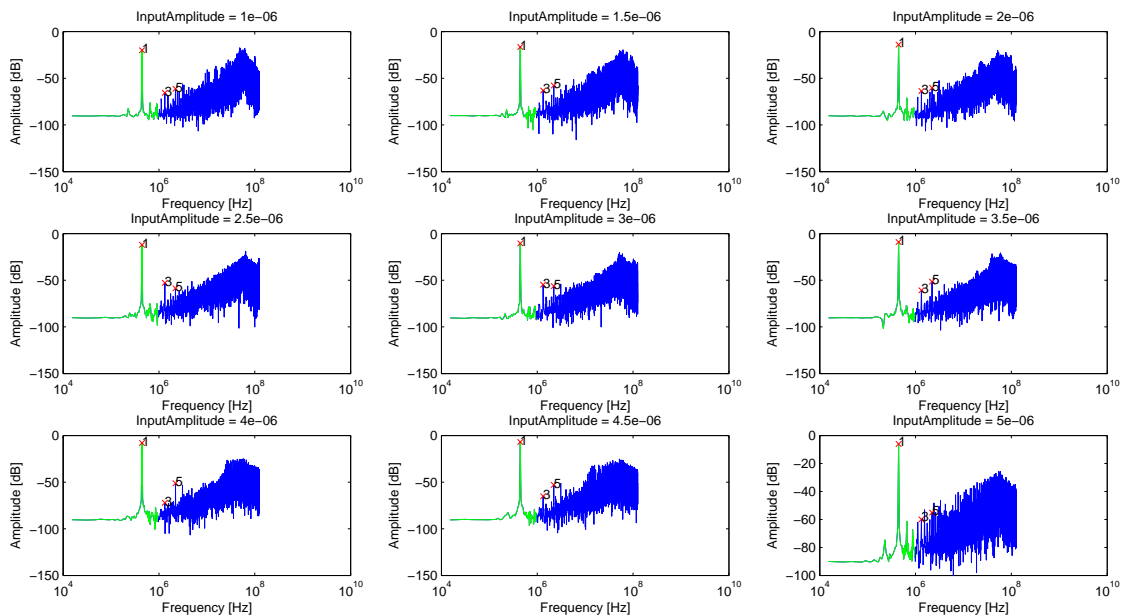


Fig. 6. FFT results of the modulators for different input signal amplitude

### Modulator simulation results

The final version of the modulator designed with the help of the presented tool was optimized for TSMC 65nm CMOS Process Technology. The elaborated tools allow performance comparison of the modulator for different combinations of  $g_m$  and  $C$  of the noise shaping filter and automatically calculate parameters of the whole modulator for different input signals. Figure 6 presents the simulation results of FFT for different input signal's amplitude.

Simulation results were aggregate into the Walden's Figure of Merit (FoM), which is also automatically calculated by the tools. The modulator designed with the help of the tools was in detailed described in [9]. For 250 MHz sampling clock frequency, we achieved 53.6 dB SNDR with power consumption equal to 93  $\mu$ W. The FoM coefficient is equal to 59.7 fJ/step.

### Conclusion

This work presented the MATLAB based tools to support sigma delta modulators design. User friendly interface prepared to use in SIMULINK environment allows validate different structures of modulators with different parameters of their components. To measure the quality of the designed circuit the main modulator's characteristics and parameters are calculated. The proposed tools were practically verified during the current mode sigma delta modulator design, prepared for fabrication in TSMC 65 nm technology.

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