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Quick Method for Parameter Research of Higher Order Sigma-Delta Modulators Using Dynamically Reprogrammable FPAA

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Abstract—**Development of mixed signal circuits is expensive and time-consuming. Lack of flexible CAD tools makes new methods of prototyping very attractive for designers. The ORG_SecOrd software controlling a prototype Sigma-Delta modulator, using the capabilities for dynamic reprogramming of FPAA AN221E04 device from the Anadigm®, is proposed in the paper. It is an innovative tool providing an effective method for the analysis and tests of experimental structures of modulators. It allows the experimental selection or adjustment of the structure of the modulator to achieve its specific properties. To confirm the validity of the design assumptions of the proposed system the measurement results of three different structures for Sigma-Delta second order modulator are shown.**

Keywords—**Sigma-Delta modulator; FPAA; analog circuits design; dynamic programmable circuits**

I. INTRODUCTION

In recent years, ADC using Sigma-Delta modulators [1, 2] are very popular among designers of integrated circuits, because they offer a high accuracy of conversion at high resolution, while demonstrating a high tolerance to dispersion and accuracy of the elements included in the converter. The structure of the modulator can be formed in many ways. The general scheme of the *m*-th order modulator of negative feedback is shown in Fig. 1. By properly adjusting the gains coefficients A_i, B_i, G_i, and C_1, any structure of a one-stage *m*-th order modulator can be implemented. In most applications, the coefficient B_1 is 1, and the coefficients B_2, ..., B_{m+1} are equal to zero, which allows optimizing the signal to noise ratio (SNR). The coefficients A_1, ..., A_m are the coefficients of a negative feedback loop therefore determine the transfer function for the quantization noise of the modulator and determine the stability of the system. The C_1 coefficient may be placed in addition, in order to shape the transfer function of the input in modulator baseband, which allows increasing the dynamic range.

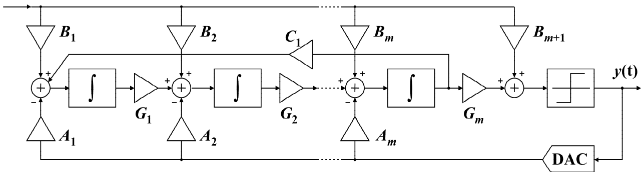


Fig. 1. The general block diagram of a Sigma-Delta modulator of *m*-th order.

II. RAPID PROTOTYPING OF MIXED SYSTEMS

The rapid development of VLSI technology allows performing mixed systems (analog and digital) in one system on chip (SoC) [3]. The increasing levels of integration and packing causes the process of designing and manufacturing them to become more laborious and expensive. Most CAD tools are intended for the design of digital systems and include modules for simulation and testing of digital circuits, which can most often be used inefficiently or not at all, to simulate the operation of the analog portion of the chip. Simultaneously, the functioning of analog systems prior to their implementation is usually simulated and verified using programs such as SPICE, which are not effective in the design of digital circuits. For these reasons, the design and prototypes of mixed systems is difficult and involves the possibility of errors [4]. The dynamic development of reprogrammable systems meets these challenges by allowing faster and more efficient design of mixed systems [5]. One solution to this problem could be the use of reprogrammable circuits designed to build prototypes of mixed systems and their initial verification. Complex programmable logic devices (CPLDs and FPGAs) are currently widely used to implement prototype applications of digital systems [6] and creation of short-run production of digital systems, where it is uneconomic to bear the cost of an individual project or it is important to shorten the project cycle. Reprogrammable systems are still the domain of digital circuits, but there are also solutions of reprogrammable analog matrices with diverse functionality [7]. They can be successfully used for the rapid and effective implementation of analog circuit's prototypes [8–10] and certain types of mixed systems [11]. This work uses field programmable analog array (FPAA) Anadigm®'s AN221E04 device. It is dynamically reconfigurable, which allows on-the-fly and real-time control of analog functions by the microprocessor in an embedded system. We can design prototype of circuit which can be reconfigured in-system [12, 13] to implement multiple analog functions whose parameters can be changed in accordance with the new requirements of the system. All these changes can be done without interrupting the operation of the system, and all under the control of prepared system software. Using dynamic reconfiguration, we can manipulate the loop response of the designed prototype: change its characteristics in response to changing environmental conditions, or simply adjust coefficients.

This paper presents the construction and use of the test system and the software for the hardware implementation and testing of second order Sigma-Delta modulators. The Anadigmvortex evaluation board with three AN221E04 FPAA devices and GEN_SecOrd – especially designed dedicated software were used to control and dynamically modify the most important parameters of the prototype. By modifying the gain values for the input signal B_1, feedforward B_2 and B_3, signal amplification in the main loop G_1 and G_2, positive feedback C_1 and negative feedback A_1 and A_2, any structure of a single-stage second order Sigma-Delta modulator can be created and analyzed.

III. FPAA IMPLEMENTATION OF MODULATOR

An implementation of second order Sigma-Delta modulator is shown in Fig. 2. The circuit consists of two integrators and a comparator connected in main loop. The output from the comparator is fed back to a summing switch on both integrators to allow the reference voltage to be either added or subtracted during each clock cycle. If the comparator is high, the reference voltage is subtracted (and vice-versa), thus creating a negative feedback loop.

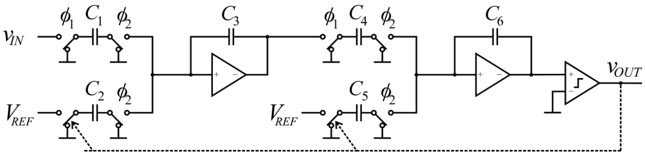


Fig. 2. A simplified diagram of second order Sigma-Delta modulator implemented in a FPAA evaluation board.

Implementation of the general structure of the second order Sigma-Delta modulator of Fig. 2 in a FPAA AN221E04 device is shown in Fig. 3. It is realized as a fully differential switched capacitor circuit. The system consists of two integrators, the S/H system (Sample and Hold), the adder and comparator in the main loop and connections serving positive feedforward (B_2 and B_3), feedback (C_1) and a negative feedback to the inputs of the integrators (A_1 and A_2). Systems are switched with a two-phase clock of frequency of 4 MHz.

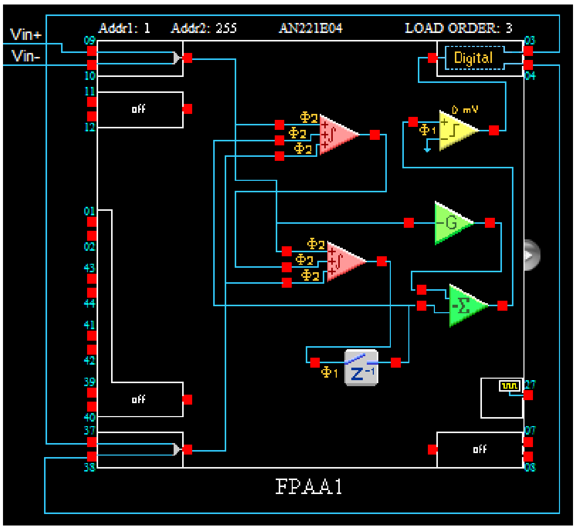
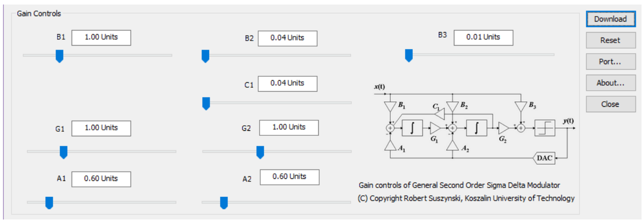


Fig. 3. An implementation of second order Sigma-Delta modulator.

The modulator prototype used triple input integrators with a dynamically adjustable gain on the inputs in range of 0.04 – 4.20 units, allowing unrestricted shaping of modulator feedback and feedforward. The processed signal in the main loop is delayed by half the processing period in the arrangement z-1. The comparator at the output converts the analog signal processed by the integrators into a digital output stream. Conversion of the digital signal to analog negative feedback signal is implemented external to the FPAA, on the resistive voltage dividers. This simplifies the construction of the prototype and obtains the voltage level adjustment of the output digital signal to the range of analog input voltage of the modulator.

IV. DEDICATED GEN_SECORD SOFTWARE

The author's program ORG_SecOrd is shown in Fig. 4, it controls the Anadigmvortex evaluation board with three AN221E04 FPAA devices. It allows the programming of the overall structure of the second order Sigma-Delta modulator with initial parameters. After starting the modulator, GEN_SecOrd software allows the modification of the selected or all parameters of its structure. Properties of dynamic reconfiguration of the AN221E04 device are used. In the process of changing any of the parameters B_1, B_2, B_3, C_1, G_1, G_2, A_1 or A_2, corrected data is sent to the test system, and the prototype is modified in real time. Update time of the new system structure is less than one clock cycle, or one cycle of signal processing. This allows modifying the properties of the modulator in real time. Observation and measurement of parameters on the output of the modulator allows immediate testing of certain parameters of the structure or their effective optimization.



B1 1.00 Units
B2 0.04 Units
B3 0.01 Units
C1 0.04 Units
G1 1.00 Units
G2 1.00 Units
A1 0.60 Units
A2 0.60 Units

Gain controls of General Second Order Sigma Delta Modulator
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Fig. 4. A screenshot of the author's program ORG_SecOrd.

V. PROTOTYPE MEASUREMENTS

The developed ORG_SecOrd software cooperating with a general structure of the second order Sigma-Delta modulator, implemented in a FPAA device, is an efficient tool to study the dynamic properties of any type of single-stage modulator. In order to verify the solutions and the prototyping system, measurements were taken for the three characteristic structures of the modulators of different build and properties. Modulators with feedback, feedforward and mixed feedback were optimized due to the characteristics of noise shaping.

The first examined structure is a standard solution Sigma-Delta modulator with two branches of negative feedback, obtained by minimizing the gain factors in the branches of a positive feedforward B_2=0.04, B_3=0.01 and the feedback signal C_1=0.04 while gain factors of the input signal B_1=1, and the main branch G_1=1 and G_2=1. Negative feedback coefficients

A_1=0.3 and A_2=0.3 were chosen by optimizing the parameters of the modulator output. The basic parameters measured for an optimized structure of a Sigma-Delta modulator with two negative feedback loops are shown in Table I. Selection of gain in feedback loops allows for shaping frequency response in the modulator bandpass BW = 20 kHz and optimize its output parameters. The resulting parameter SNDR = 62.3 dB is typical for the tested modulator structure, implemented in the technology of switching capacities and oversampling values OSR = 4000. The obtained parameters allow the modulator to work in ADC with 10-bit resolution. Figure 5b shows a frequency spectrum at the output of a modulator with an input signal at a frequency of 1 kHz. The waveform is obtained from the built-in FFT analysis of the measuring instrument Tektronix MSO 4054 for the digital output signal of the modulator. The analysis was performed for 10^8 samples using Hamming window. Spectral characteristics allows to determine the SFDR parameter = 68.4 dB and the amplitude of the first harmonic illustrate the shaping of frequency response of the modulator and the shift of quantization noise towards higher frequencies, beyond the useful modulator band, and allows to evaluate the SNDR value determining the resulting resolution.

TABLE I.
COMPARISON OF PERFORMANCES OF THREE PROPOSED STRUCTURES OF SIGMA-DELTA MODULATOR

	Modulator with two negative feedback loops	Modulator with feed-forward loops	Modulator with mixed feed-forward and feedback loops
Resolution (bit)	10	12	11
Sampling (MHz)	4	4	4
OSR	4 000	4 000	4 000
Power (mW)	148	164	196
SNDR (dB)	62.3	71.8	70.4
SFDR (dB)	68.4	76.2	75.8

Another analyzed structure is a modulator with a feed-forward. The configuration of such a modulator was achieved through the establishment of gains factors B_1=1, B_2=1, B_3=0.28. Feedback coefficient C_1=0.04 is at a minimum value, and the gain factors in the main branch G_1=1 and G_2=1. The gain coefficients of the negative feedback branches A_1=0.96 and A_2=1 were chosen by obtaining the optimum output of the modulator. The values of each parameters of the structure of the modulator prototype are summarized in Table I. During the selection of the optimum parameters, modulator with a feed-forward shows favorable characteristics of quantization noise shaping, but unfortunately it is less stable. For this reason, it is necessary to carefully select the gains B_1, B_2 and B_3, or the introduction of negative feedback, which is implemented in a third example discussed below. The obtained parameters presented in Table I (SNDR = 71.8 dB) have improved properties of this type of modulator compared with a conventional configuration using negative feedback. Modulator configured in such a way can operate with a resolution of 12 bits. Figure 5d shows the frequency spectrum of the output of the modulator with an input signal at a frequency of 1 kHz. Spectral analysis allows to determine the SFDR parameter = 76.2 dB, SNDR = 71.8 dB.

The third analyzed structure is not guided by the selection of coefficients to obtain a specific configuration of a modulator in exchange to obtain specific properties of the modulator. The premise for this structure was to achieve such shaping of quantization noise to get the maximum shift towards higher frequencies. This is achieved by iteratively changing the group parameters of the structure so as to obtain the minimum values of the first five harmonics of the input signal, at the expense of an increase of amplitude of higher harmonics (B_1=1, B_2=0.54, B_3=0.01, C_1=0.04, G_1=1, G_2=1, A_1=0.64, A_2=0.48). The measurement results of such structures are shown in Table I and Fig. 5f. The measurement results of such configured structures are slightly worse than the feed-forward modulator (SNDR = 70.4, dB SFDR = 75.8 dB), but the harmonic values indicate a better shaping of the quantization noise. This is important when using modulator as an ADC, because it simplifies the construction of the decimator and output filters. The obtained parameters show improved properties of this type of modulator compared with a conventional configuration using negative feedback. Modulator configured in such a way can operate with a resolution of 11 bits.

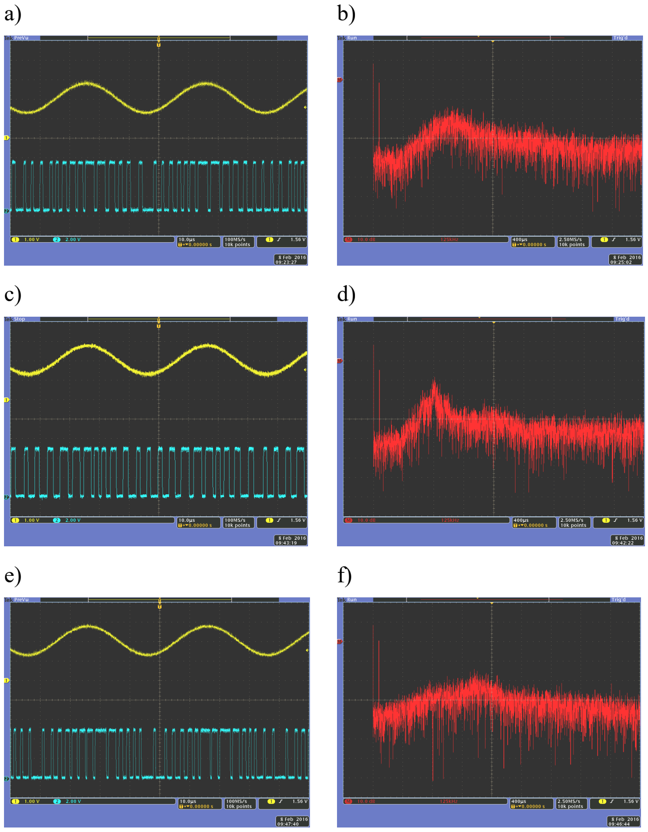

Fig. 5. Sinusoidal input signal with output data stream waveforms and spectral analysis of Sigma-Delta modulator with a),b) two negative feedback loops c),d) feed-forward loops e),f) mixed feed-forward and feedback loops.

The presented prototyping system makes it possible to influence the dynamic properties of a working modulator and shaping its characteristics in real time. Time of obtaining output parameters is limited only by the accepted method of measurement. Using an efficient measuring device with a built-in FFT analysis can obtain the spectral analysis of the output signal of the modulator in real time. Modifying any one of these structure parameters is immediately reflected in the spectrum observed on an FTT oscilloscope, which allows for intuitive shaping of the characteristics and achieving the desired levels of harmonics. Analytical experience of the designer in conjunction with an immediate measurement of the parameters of any prototyped modulator structure enables fast, efficient and optimal designing of Sigma-Delta modulator.

VI. CONCLUSIONS

Sigma-Delta modulators are still important and interesting to research for new solutions for modulators of specific properties. Because Sigma-Delta modulators are non-linear systems, their analysis, design and simulation tests cause numerous problems [14–16]. The developed ORG_SecOrd software controlling a prototype Sigma-Delta second order modulator, using the capabilities for dynamic reprogramming of FPAA, is an innovative tool providing an effective method for the analysis and tests of experimental structures of modulators. It presents a reliable tool for analyzing the properties of structures developed analytically, but also allows the experimental selection or adjustment of the structure of the modulator to achieve its specific properties.

The advantage of the developed system is that the prototype structures of the modulators are tested in real c-switched systems (switched capacitor circuit). Selection of new parameters of the structure, and hence new properties of the modulator, is no longer an iterative process, but we have the ability to dynamically influence the properties of the proposed system by a smooth change of a particular parameter or even a group of parameters. Determination of the characteristics and properties of a modulator does not occur based on the mathematical analysis of more or less accurate model of the system, but based on the measurement of the real electronic circuit, made using the c-switched technology. The implementation of a specific prototype, in a real c-switched structure, allows for a reliable estimate of the parameters of power consumption, frequency and noise.

The value of this work is the innovative method of prototyping Sigma-Delta modulator using the capabilities for dynamic “in-system” reprogramming of AN221E04 device. The proposed original software ORG_SecOrd, which uses the properties of dynamic AN221E04 reconfiguration, allows for efficient use of developed prototype to study the properties of Sigma-Delta modulators. Particularly notable is the availability and simplicity of modifying the structure of the modulator, previously inaccessible to standard methods of prototyping new solutions. That approach allows examination of any structure of a second order modulator and optimizing its parameters. It may also become a research tool to look for systemic solutions that meet specific requirements. The ability to interfere in any parameter of the structure and the correlation with an immediate result specifying the parameters of the system is an effective tool to support the design process, because reliable results for real c-switched systems are obtained. The presented results of three structures for Sigma-Delta second order modulator confirmed the validity of the design assumptions of the system presented. The proposed software, the prototype developed, the test procedure and the results obtained provide a basis for further design work. There are plans to develop the driver software ORG_SecOrd towards the implementation of more complex structures of Sigma-Delta modulators and to develop more effective methods of measurement that automate the research process such as testing the susceptibility of modulator resolution to a change in a certain parameter of the modulator’s structure.

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