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AN IDEA OF AN APPROACH TO SELF-TESTING OF MIXED SIGNAL SYSTEMS BASED ON A QUADRATIC FUNCTION STIMULATION

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Abstract – A new approach to self-testing of the analog parts of mixed-signal electronic systems controlled by microcontrollers equipped with an ADC and a DAC is presented. It is based on a BIST and a new fault diagnosis method. A novelty is the use of the DAC as a component of the BIST, allowing to generate a stimulating signal with a quadratic function shape. It contributes to a better extraction of information about the state of the circuit under test.

Keywords: microcontrollers, ADCs, DACs, self-testing, BISTs

1. INTRODUCTION

Testing of analog circuits is still important in the more and more digital word of electronics. For example, the analog circuits are parts of smart sensor systems based on still used analog sensors.

There were developed a few classes of fault diagnosis methods for testing analog parts (circuits) of mixed-signal electronic systems, especially analog filters and amplifiers, for example: methods based on sigma-delta modulators [1,2], oscillation methods [3], methods using the spectral analysis [4] and methods based on BISTs (Built-in Self Testers) dynamically configured with internal hardware resources of microcontrollers controlling these systems [5-8].

The last class uses BISTs configured with such internal devices of microcontrollers as timers and ports used for generating square pulses [6,7] or square waves [8] for a stimulation of tested analog parts, and ADCs (Analog to Digital Converters) triggered by the timers for obtaining information needed to test the robustness of these parts.

We should mention that new microcontrollers are equipped with more internal measurement devices with better parameters and a better functionality than older ones. For instance, microcontrollers being part of the 8-bit AVR XMEGA A4 family of Atmel [9] have up to five 16-bit counters with four channel Output Compare functions and PWM functions, up to two pipeline 12-bit ADCs (they can simultaneously and independently measure voltages at up to four channels), two analog comparators with the window mode, an event system enabling to change the state of one peripheral to automatically trigger actions in other peripherals. But, for the fault diagnosis method proposed in the paper, the most important device is the two channel 12-bit DAC (Digital to Analog Converter).

Thus, the new fault diagnosis method has also a new architecture of the BIST being part of previously presented measurement peripheral devices used for self-testing of analog parts of electronic embedded systems controlled by microcontrollers.

2. SELF-TESTING METHOD

The main novelty of the method relating to the previous ones [5-8] is the fact that the stimulating signal is generated using the DAC. Therefore, we can generate a signal with any shape based on the DDS (Direct Digital Synthesis) method.

2.1. The BIST architecture

Thanks to this we can replace a square pulse - the only one possibly shape which can be generated at any digital output of the microcontroller- with a pulse having a shape allowing to better extract information about the state of the tested circuit.

The new architecture of the BIST based on the internal peripherals of the ATXmega32A4 [9] is shown in Fig. 1.

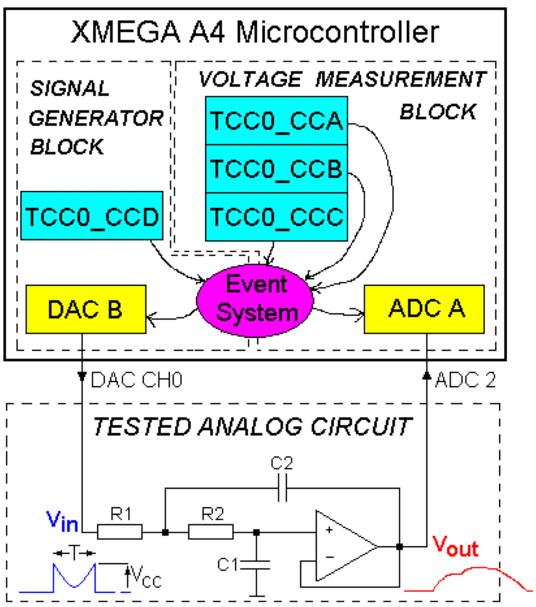

Fig. 1. An example of a BIST based on the ATXmega32A4.

Generally, the proposed BIST consists of two blocks: a signal generator block and a voltage measurement block, both connected and integrated via an event system (Fig. 1).

We use only one TCC0 (Timer/Counter version 0) for generating - and actually counting - the duration T of a stimulating pulse and determining the moments of DA conversions, and also for determining three voltage sample moments t_1, t_2 and t_3 of the time response of the tested circuit by the ADC A. It is possible, because the timer has up to four Combined Compare or Capture (CC) Channels (A, B, C, and D). They are marked in Fig. 1 as TCC0_CCA, TCC0_CCB, TCC0_CCC, TCC0_CCD, respectively. The channels A, B and C are used to determine triggering of the ADC A, and the channel D to generate events used to start next DA conversions.

Also the ADC A has an extended functionality simplifying the configuration of the BIST. It has four ADC channels (four separate MUX control registers with corresponding 16-bit result registers) numbered CH0, CH1, CH2 and CH3. In our solution we use three channels CH0, CH1, CH2 connected to one common input of the ADC 2.

However, the most important component of the BIST is the 8-channel event system. Its use simplifies the algorithm of the measurement procedure and eliminates the problem of program delays of synchronisation signals coming from the timer. These signals via the event system directly trigger the AD conversions and start the DA conversions.

To illustrate the method, a second order low-pass filter with the Sallen-Key topology was chosen as the tested analog circuit (Fig. 1), where $R_1 = R_2 = 10$ kΩ, $C_1 = 70$ nF, $C_2 = 146$ nF.

2.2. Determination of the stimulating signal shape

As was mentioned earlier, a square pulse can be generated in an easy way at any digital output of a microcontroller, what is an advantage of this approach.

But, we can note that square pulses or a square wave are the signals already "naturally filtered" by a low-pass filter as results from their Fourier series (1), because it consists of next odd harmonics with smaller and smaller amplitudes.

$$u(t) = \frac{A}{2} + \frac{2A}{\pi}\sum_{k=1}^{\infty}\frac{1}{2k-1}\sin\left(\frac{(2k-1)\pi t}{T}\right) \qquad (1)$$

where A is the amplitude, T - the period of a square wave.

Therefore, we propose a new signal still consisting of odd harmonics, but having the same amplitude. Additionally, the signal values should be included within the range between 0 V and the reference voltage of the ADC and the DAC, which is set to V_{CC} =3.3 V (i.e. the supply voltage of the microcontroller). Thus, the signal is described by the following formula (2):

$$u(t) = \xi\sum_{k=1}^{K} A\sin\left(\frac{(2k-1)\pi t}{T}\right) \qquad (2)$$

where $\xi = 0.7534$ is a coefficient determined experimentally for $K = 6$ (the number of harmonics) and $V_{CC} = 3.3$ V.

It was chosen $K = 6$ harmonics. It results from a practical reason, because frequencies of such number of the subsequent harmonics cover above one frequency decade. And we should remember that we test a second order low-pass filter for which the frequency of the first harmonic is set to the value close to the cut-off frequency of the filter [6]. Timings of the stimulating signals and the time responses of the tested circuit for $K = 6$ and also - additionally - for $K = 60$ and 600 and for $\xi = 0.7534$ are shown in Fig. 2.

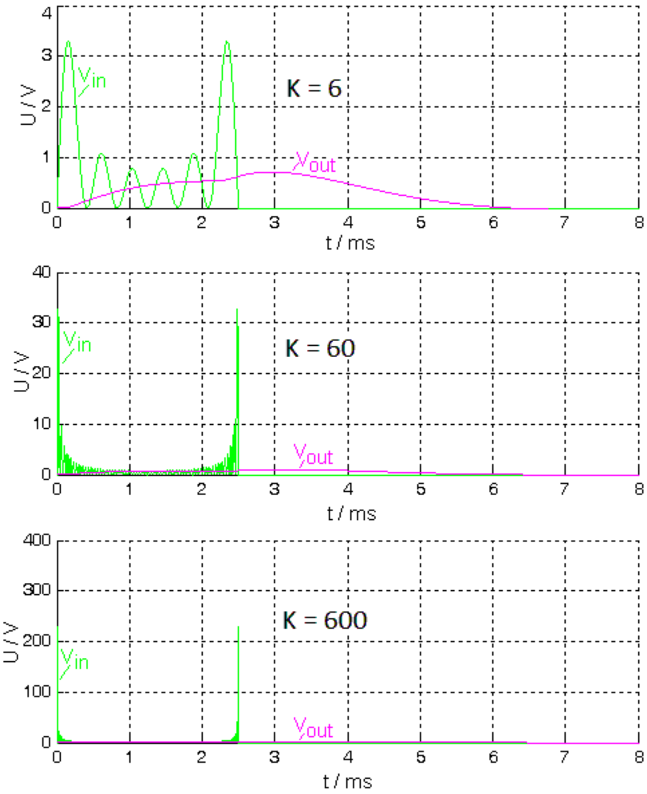

Fig. 2. Timings of the stimulating signals and the time responses of the tested circuit for $K = 6$, 60 and 600 and $\xi = 0.7534$ (simulation results).

In this case the shape of the signal for $K = 6$ (Fig. 2) is characterized by high dynamics of changes of voltage values in the time. Thus, the signal should be accurately reconstructed that needs a lot of digital values (12-bit data) and causes a high occupation of the microcontroller program memory. We should also remember about timing constraints of the DAC B [9] and particularly the volume of data transferred between the microcontroller memories and the DAC B.

We also made simulations of the shape of the signal (2) for other (bigger) values of K. The chosen results for $K = 60$ and $K = 600$ are shown on Fig. 2. We can note that the shapes of the stimulating signals are "similar" to a quadratic function. This observation allowed us to the final choice of the stimulating signal shape.

Thus, basing on these facts, we propose to replace the function (2) by a quadratic function (3) which is characterized by the simplest shape. This replacement is possible, because during the fault detection and localization we compare the measurement point and the fault dictionary, both calculated in the same way [5-8], that - in our case - is based on the same transformation (3). Hence, the quadratic function pulse is described:

$$\begin{cases} u(t) = at^2 + bt + c & \text{for } t \in \langle 0, T \rangle \\ u(t) = 0 & \text{for} \quad t > T \end{cases} \quad (3)$$

where a, b, c – coefficients of the quadratic function.

To determine coefficients of the quadratic function we need to know three points. Locations of two points depend on the voltage constraints. At the beginning (t = 0) and at the end (t = T) of the timing the signal has maximum values equal to the reference voltage V_{CC} – points (1) and (3) in Fig. 3. The voltage value U_x for t = T/2 (point (2)) should be selected in such a way that the response to this stimulation should be as close as possible to the response to the stimulating pulse (2).

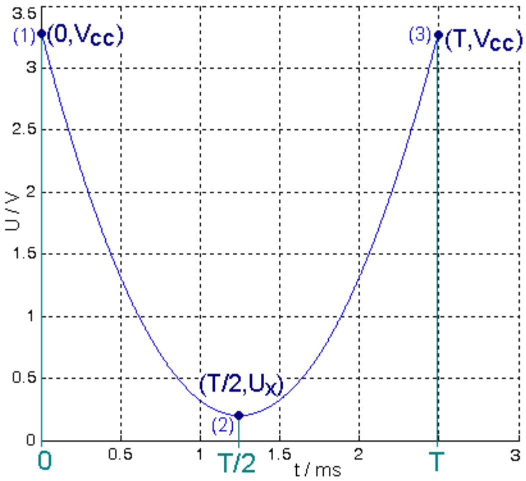

Fig. 3. The graphical illustration of determining three points of the quadratic function

So, we should derive the following three equations.

$$\begin{cases} a0 + b0 + c = V_{CC} & (1) \\ a\left(\frac{T}{2}\right)^2 + b\left(\frac{T}{2}\right) + c = V_x & (2) \\ a(T)^2 + b(T) + c = V_{CC} & (3) \end{cases} \quad (4)$$

After the derivation we obtain the formulas for the coefficients of the quadratic function

$$a = \frac{4(V_{CC} - V_x)}{T^2} \quad (5a)$$

$$b = \frac{-4(V_{CC} - V_x)}{T} \quad (5b)$$

$$c = V_{CC} \quad (5c)$$

In our case the coefficients were calculated for the value U_x = 0.2 V chosen experimentally. Thus, we obtained the quadratic function for which the response of the tested circuit had a possible similar shape as the response to the stimulation (2) for K = 6, as shown in Fig. 4. And even this response is better than one, because it is characterized by more dynamic changes of voltage values what improves the localization resolution. Additionally, the later simulation investigations showed that this response is almost the same as the response to the stimulation (2) generated for K = 33 and ξ = 0.7534 (Fig. 5).

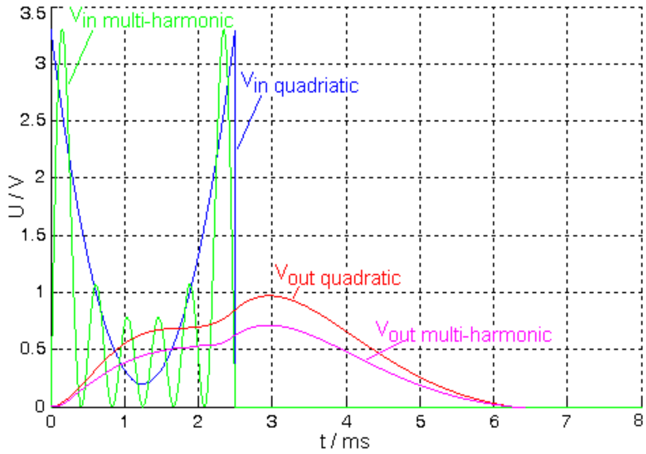

Fig. 4. Simulated timings of the stimulation signals for K = 6 and the time responses of the tested circuit.

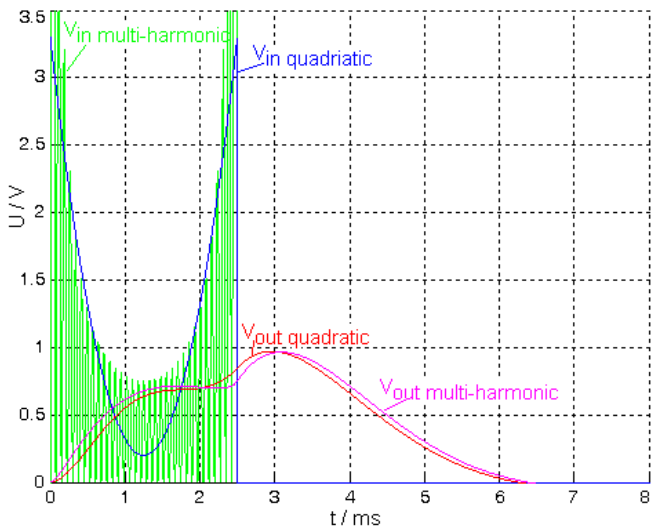

Fig. 5. Simulated timings of the stimulation signals for K = 33 and the time responses of the tested circuit.

2.3. The measurement procedure

The duration T = 2500 µs of the stimulation quadratic function pulse and the sample moments t_1 = 1108.4 µs, t_2 = 3332.5 µs and t_3 = 7221.75 µs of the time response were determined according to the rules described in [6] (the rules are based on the sensibility analysis method for determination of the duration T and statistical analysis of circuit responses for determination of the sample moments t_1, t_2 and t_3).

Thanks to the event system and an expanded functionality of measurement peripheral devices of the microcontroller, generating the stimulation by the DAC B and sampling of the response by the ADC A are realized simultaneously and independently of each other.

The subsequent data of a set of 250 unsigned integer data representing the quadratic function are sent to the DAC B each 10 µs. Thanks to this, we obtain the quadratic function pulse V_{in} at the DAC CH0 output, as shown in Fig. 6.

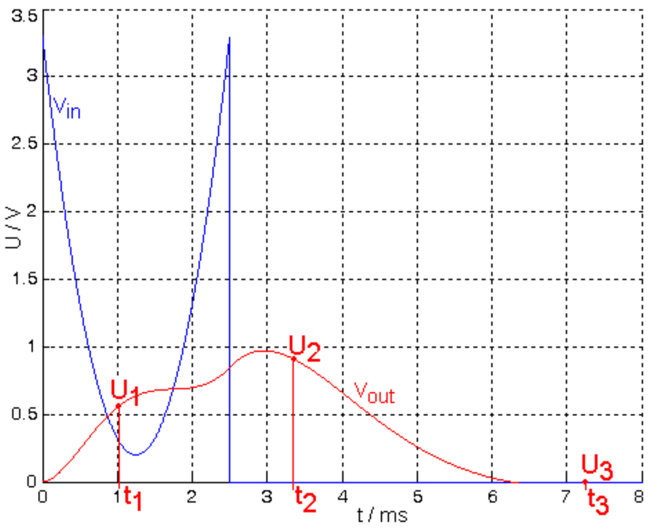

Fig. 6. Timings of the measurement procedure.

The time response at the ADC 2 input is sampled three times by the ADC (Fig. 6). These tasks are performed according to the algorithm of the measurement function with the flowchart is shown in Fig. 7 by the BIST which configuration is shown in Fig. 8.

The function is realized in the main program code (main function), where we set measurement conditions and start the TCC0. It triggers DA and AD conversions via the event system. This takes place without the involvement of software (Fig. 8).

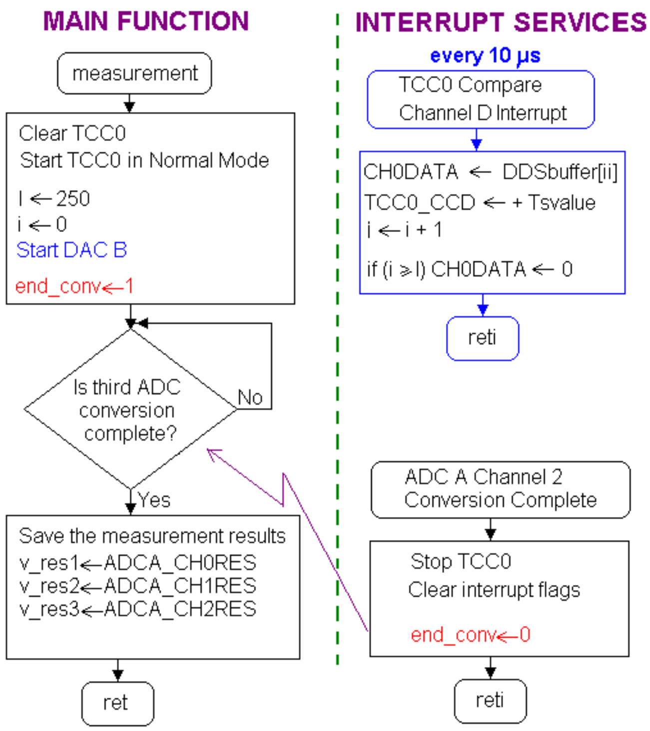

Fig. 7. The flowchart of the algorithm of the measurement procedure.

We use only two interrupt services. In theTCC0 compare channel D interrupt service we load the digital value which will be converted into a voltage value at the DAC B output by the next event signal coming from the TCC0_CCD. We also set the time interval equal to 10 µs, when this signal appears again.

The ADC A channel 2 conversion complete interrupt service stops the TCC0 and sets the flag *end_conv* informing the main function that all voltage measurements have been completed.

At the end of the main function the voltage conversion results U_1, U_2, U_3 placed in the ADC A result registers CH0RES, CH1RES, CH2RES are saved to the 16-bit variables v_res1, v_res2, v_res3, adequately.

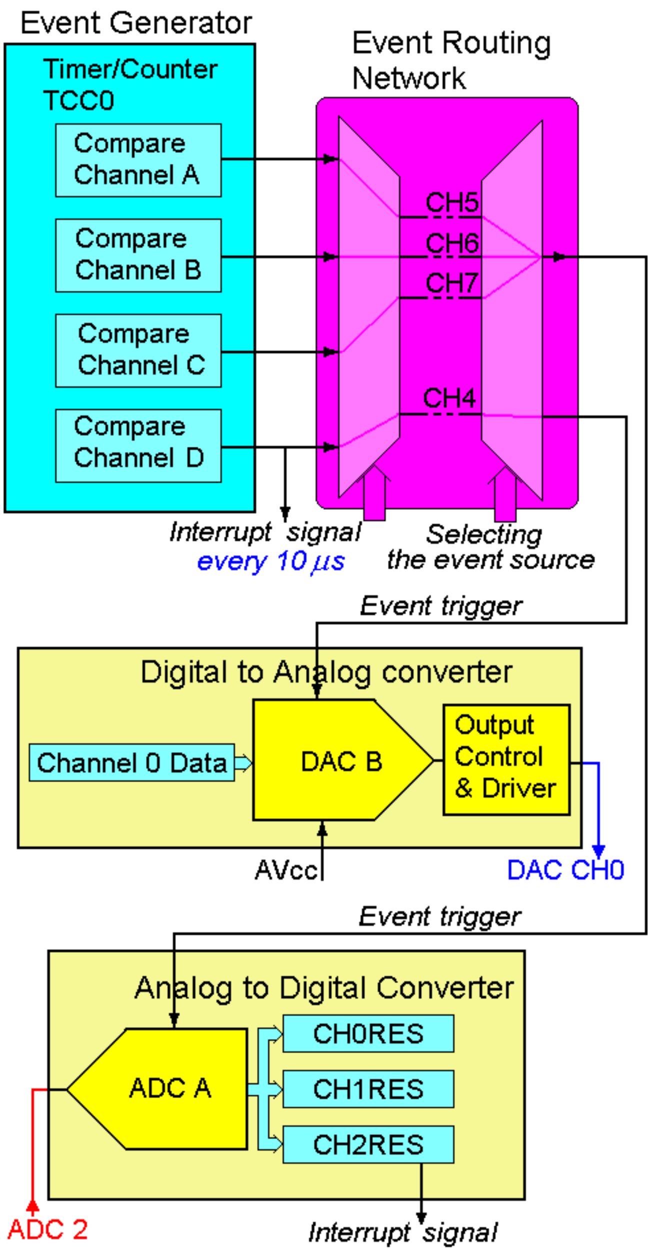

Fig. 8. Block scheme of the BIST configured from peripheral devices of the microcontroller ATXmega32A4.

As it is seen in Fig. 8, the ADC A, without the participation of software, samples three times the time response at the ADC 2 input. The match in the TCC0_CCA (counting the time t_1) triggers the first AD conversion on the CH0, the match in the TCC0_CCB (counting the time t_2) triggers the second one on the CH1 and the match in the TCC0_CCC (counting the time t_3) triggers the third one on the CH2. The match in the TCC0_CCD appearing every 10 µs generates the events which:

- trigger the DA conversion for the value written to the Channel 0 Data Register by the interrupt service for the interrupt generated by the previous event,
- generate the TCC0 compare channel D interrupt (already described).

2.4. Generation of the quadratic function pulse

As mentioned earlier the quadratic function pulse is “assembled” with 250 DA samples which each takes 10 µs, what gives the pulse with the duration T = 2500 µs (Fig. 9 and Fig. 10).

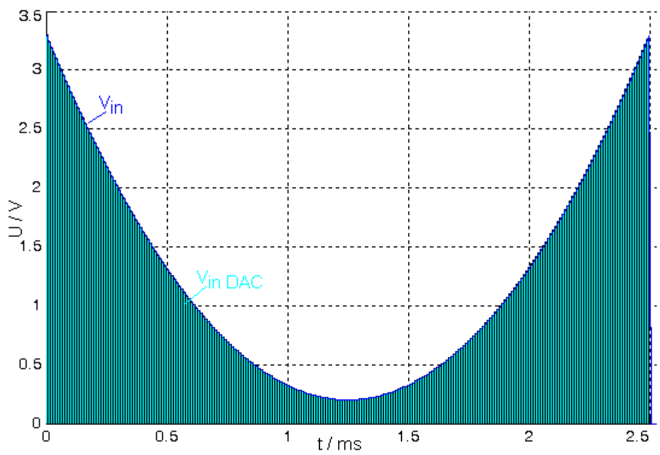

Fig. 9. Timing of the quadratic function pulse at the DAC CH0 output.

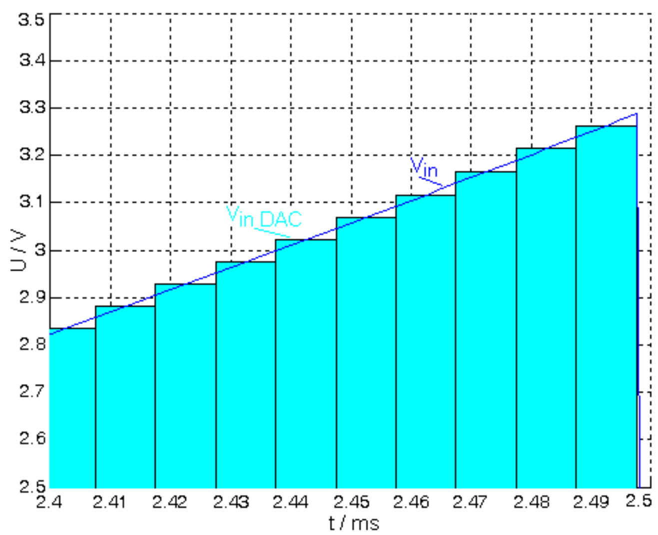

Fig. 10. Enlarged fragment of the timing of the quadratic function pulse at the DAC CH0 output.

Thanks to the event system the DA conversion is exactly triggered every 10 µs without the participation of the core processor of the microcontroller (without the use of software), what resolves problems arising from software delays and synchronization between software and hardware.

Hence, the main problem was a fact that the TCC0 compare channel D interrupt service runtime should be shorten than 10 µs. Otherwise, data needed for the DA conversion will not be updated on time.

It was solved by the appropriate notation of the program code of this interrupt service.

The program code was written in ANSI C and compiled by WinAVR 20100110. A fragment of the variable declarations used by the interrupt service and the code of the TCC0 compare channel D interrupt service are shown in Listing 1.

```
...
#define II 250
...
volatile uint16_t DDSbuffer[II];
volatile register uint8_t ii asm ("r17");
volatile register uint8_t Tsvalue asm ("r18);
...
ISR (TCC0_CCD_vect)
{
  TCC0_CCD += Tsvalue;              // line 1
  DACB_CH0DATA = DDSbuffer[ii];     // line 2

  asm ("inc r17 \n" : : );          // line 3

  if(ii > II) asm("dec r17 \n" : : );
                                   // line 4
}
```

Listing 1. Fragment of the variable declarations and the code of the TCC0 compare channel D interrupt service

The code was written in such a way that the resulting assembler code was as short as possible. From this reason two register type variables are used.

The first one *ii* is used as an index of data (placed in the buffer *DDSbuffer*[*II*]) written to the DAC Channel 0 Data Register (DACB_CH0DATA). It is an unsigned char type variable, so the quadratic function pulse can consists of only 255 pieces. However, this is not a problem, because in our case the DA conversion step duration is 250 times smaller than the quadratic function pulse duration T, and we should remember that we test a low-pass filter with the cut-off frequency approximately equal to $1/T$.

The second register variable *Tsvalue* keeps the value 0x80 corresponding to 10 µs.

Therefore, the interrupt service runtime can be divided into following steps:

- The interrupt response time – it takes 5 CPU clock cycles [9].
- The jump to the interrupt handler (the program vector *TCC0_CCD_vect*) – 3 clock cycles.
- “{“ – pushing working registers on the stack – 12 clock cycles (from a “lss” file).
- Line 1 – 10 clock cycles.
- Line 2 – 15 clock cycles.

- Line 3 – 1 clock cycle.
- Line 4 – 3 clock cycles.
- "}" – pop working registers from the stack and the reti instruction – 23 clock cycles.

Summarizing, the TCC0 compare channel D interrupt service takes 72 clock cycles. The microcontroller works with an 8 MHz external crystal oscillator. Hence, the interrupt service runtime takes 9 μs, that is this value fulfils assumptions.

Obviously, to obtain shorter durations of stimulating pulses we should use the 16 MHz external crystal oscillator or the 32 MHz run-time calibrated internal oscillator [9].

3. FAULT CLASSIFICATION

The fault classification consists of the fault detection and the single soft fault localization implemented in the microcontroller software.

These stages are based on comparing the measurement point (U_1, U_2, U_3) obtained by the measurement procedure with the fault dictionary placed in the microcontroller memory. The fault dictionary is generated once in a pre-testing stage usually in a simulation way [6-8]. It consists of a collection of coordinates of points representing respective localization curves. Thanks to this the fault dictionary can be illustrated by the family of localization curves placed in three dimensional measurement space for a three voltage sample case (Fig. 11).

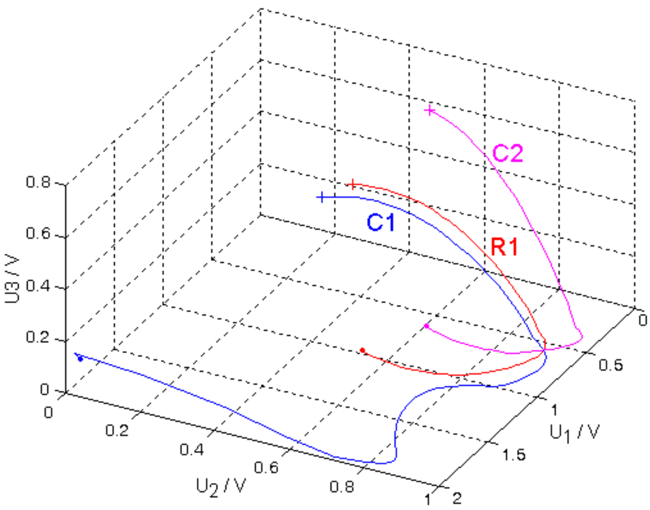

Fig. 11. The family of localization curves generated for the tested circuit (Fig. 1) stimulated by the quadratic function (3) for three voltage samples (U_1, U_2, U_3).

Hence, generally speaking [6-8], placing a measurement point at the point of intersection of all curves – which represents the nominal circuit state – indicates absence of faults in the circuit (fault detection), whereas its attribution to an appropriate curve locates a single soft fault (fault location).

4. CONCLUSIONS

In this paper, a new approach to self-testing of analog parts of mixed-signal electronic microsystems controlled by microcontrollers equipped with the ADC and the DAC is presented.

The new solution of the BIST and the self-testing method elaborated for the approach proposed in the paper required solutions of new scientific problems following the specificity of hardware and software resources of microcontrollers of the AVR XMEGA family.

The use of the DAC as a component of the BIST allowing to generate a stimulating signal with any shape made us to propose a quadratic function shape, which contributes to a better extraction of information about the state of the tested circuit.

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