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MEASUREMENTS OF CIRCUIT FUNCTIONS OF ANALOG PARTS OF MIXED-SIGNAL SYSTEMS BY MICROCONTROLLERS

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Abstract: In the paper, two approaches to measurements of circuit functions of analog parts of mixed-signal systems controlled by microcontrollers are presented. They base on the utilization of internal resources of the microcontrollers. The first approach uses an analog to digital converter (ADC), an analog comparator and a timer. The second one uses only the ADC and the timer. The measurement procedures are realized also by the microcontroller. As an example, the transfer voltage function of a circuit function was chosen.

Keywords: fault diagnosis, mixed-signal systems, microcontrollers.

1. INTRODUCTION

The fast development of the telecommunications, multimedia and automobile markets which base on mixed-signal embedded systems causes increased interest in the diagnosis of analog parts of these systems. Often they have hard-tested analog parts. It was reported [1] that in mixed-signal circuits, 95% of the test cost is expended on testing the analog parts, while the digital counterparts account for only 5% of the overall test cost. Hence, new methods enabling measurement and testing of analog parts of these systems are needed, especially using of BISTs, which minimalize test cost and guarantee high quality of products.

Testing of analog parts is very difficult and not standardized, because analog circuits are very varied and they are applied in various applications. In addition, the offered BISTs are dedicated, only for selected few classes of circuits, e.g.: adc-BISTs for analog to digital converters [2], BISTs for fully differential circuits [3], BISTs based on the oscillation-test methodology for active analog filters [4], BISTs for opamps [5]. An application of these BISTs introduces additional elements to the system, so it increases production costs. Hence, development of new measurement and testing methods simplifying the structure and design of BISTs, which allows to decrease costs, is needed.

In the paper two new measurement methods satisfying the above requirements and an analysis of accuracy are presented. Thanks to these methods we can use the microcontroller mounted in the system (its hardware resources and computing power) to realize the BIST. In this way we obtain a reconfigurable BIST, which is created only during testing time. Hence, we considerably decrease the number of elements of the BIST which have to be added to the system.

2. THE MEASUREMENT METHODS

In the papers [6,7] real and imaginary parts of the circuits functions were measured in a standard way using a transmittance analyzer. Next, the measurement result (the measurement point) was placed on a map of identification curves (Fig. 1) and fault localisation and identification were carried out.

A particular identification curve l_i was drawn based on the transformation:

$$T(p_i) = \mathrm{Re}(F(p_i))\mathbf{i}_1 + \mathrm{Im}\,F(p_i))\mathbf{i}_2, \qquad (1)$$

where: $\mathbf{i}_1$, $\mathbf{i}_2$ - are versors, $F(p_i)$ – a circuit function in relation to the value of the element p_i.

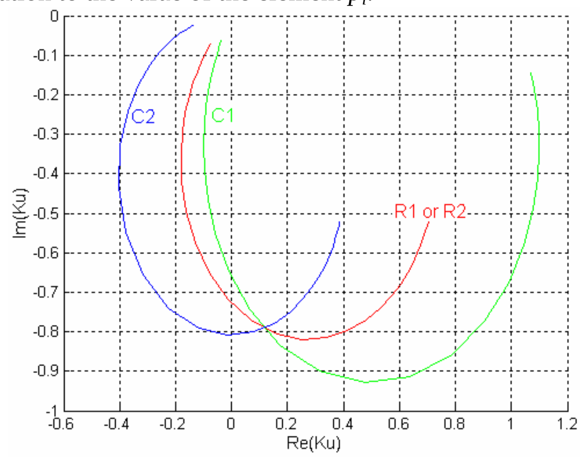

Fig. 1. A map of identification curves of the analog circuit from Fig. 2 for the voltage transfer function K_u

The curves represent changes of values of particular elements from $0.1p_{i\ nom}$ to $10p_{i\ nom}$, where $p_{i\ nom}$ is nominal value of the *i*-th element.

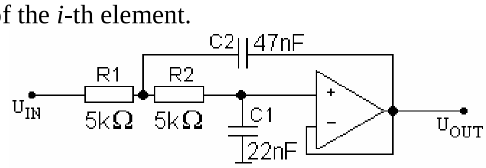

Fig. 2. An example of the analog part (where R1=R2=5kΩ, C1=22nF, C2=47nF)

2.1. *The method bases on the ADC, the analog comparator and the timer*

In the paper [8] a new way of measurement of the circuit functions using internal resources of the microcontroller was proposed. It was illustrated on the example of a transfer function. It is represented by values easily-measured and simply computed by the microcontroller: the voltage amplitude measured by the ADC (representing the magnitude) and the time delay measured by the timer (the phase shift) of an output signal of the tested analog circuit. The voltage amplitude, the voltage offset and the frequency of a stimulating signal are known and determined.

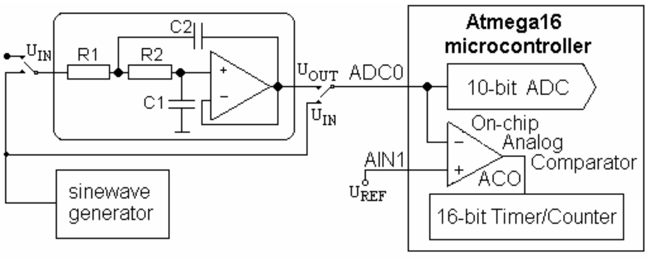

Fig. 3. An example of the mixed-signal system (where R1=R2=5kΩ, C1=22nF, C2=47nF) for the first method

In this case the identification curve l_i is described in the following way [8] (1):

$$T(p_i) = U_{OUTi}(p_i)\mathbf{i}_1 + \tau(p_i)\mathbf{i}_2\,, \tag{2}$$

where: $U_{OUT\ i}$ - the output voltage amplitude, τ_i - time delay.

For all p_i elements of the tested circuit we obtain the family of identification curves shown in Fig. 4.

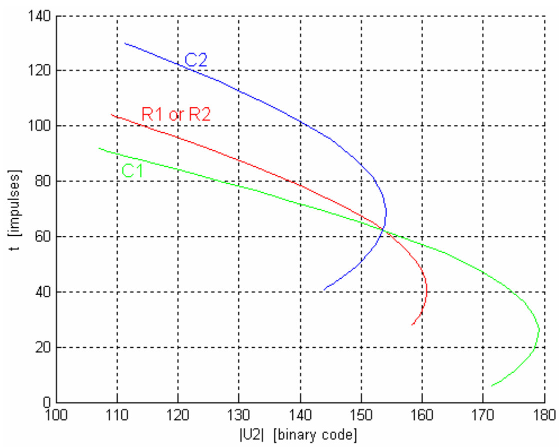

Fig. 4. A map of identification curves of the analog circuit from Fig. 2 for the transformation (2)

The measurement procedure consists of three parts [8] as shown in Fig. 5:

- measurement of the period T of the signal,
- measurement of maximum voltage U_{OUT} of the signal,
- measurement of the time delay τ.

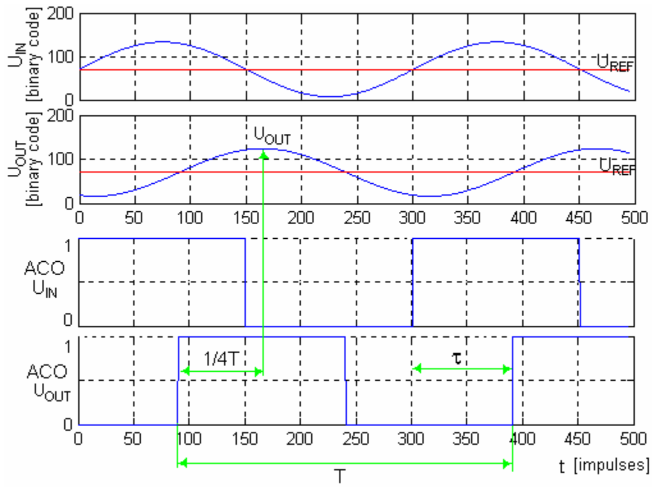

Fig. 5. The timing of the measurement procedure

Details of this procedure are described in [8]. It is realized by the microcontroller according to the timing shown in Fig. 5. A sine wave u_{IN} is applied to the input of the analog part. Its output is connected to the input of the internal analog comparator and the input of the ADC. If the analog comparator detects a voltage greater than the threshold voltage U_{REF}, it turns on the Timer 0, which counts 1/4 of the period T of the stimulus signal. The end of this time determines the moment of the measurement of voltage U_{OUT} of the circuit response signal by the ADC. Next the stimulating signal is applied to the input of the analog comparator. Start of the analog comparator activates the measurement of time delay τ_m.

Measurement results of the voltage u_m and time delay τ_m are stored in the form of single bytes.

2.2. *The method bases on the ADC and the timer*

The novelty of the paper is the new measurement method described in this paragraph. The method needs for the measurement of the circuit function only the ADC and the timer.

At present almost each modern microcontroller has an ADC and at least one timer. The analog comparator is contained in not numerous microcontrollers. Implementation of the previous method in microcontrollers without analog comparators requires to add an external analog comparator, which extends the BIST and increases its costs.

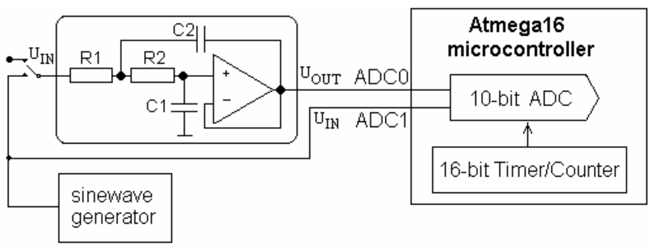

Fig. 6. An example of the mixed-signal system (where R1=R2=5kΩ, C1=22nF, C2=47nF) fir the second method

By giving up the analog comparator we simplify the BIST (Fig. 6). However it is obtained by increased complexity of the measurement algorithm, because we have to deduce the voltage amplitude of the input and output signals and the time delay between these signals based only on voltage samples (measured by the ADC) at moments determined by the timer.

Creating the measurement algorithm the following assumptions were made:

- To determine the amplitudes of stimulus u_{IN} and response u_{OUT} signals and the time delay τ_m between them only the ADC is used, synchronized by the timer.
- The algorithm should be simple as it is possible, because:
  - its code has to occupy a small size in the program memory of the microcontroller, because this memory is already occupied by the main program controlling the work of the embedded system,
  - calculations should not be complicated. They should base on an integer addition, a subtraction and a rotation (these operations are implemented as single assembler instructions), because the microcontrollers have small computing power.
- The period T and the voltage offset U_{offset} of the input stimuli signal are known.
- Measured amplitudes are stored with 8-bit resolution (one byte), and the time delay τ_m with 16-bit resolution (two bytes – the resolution of the Timer 1).

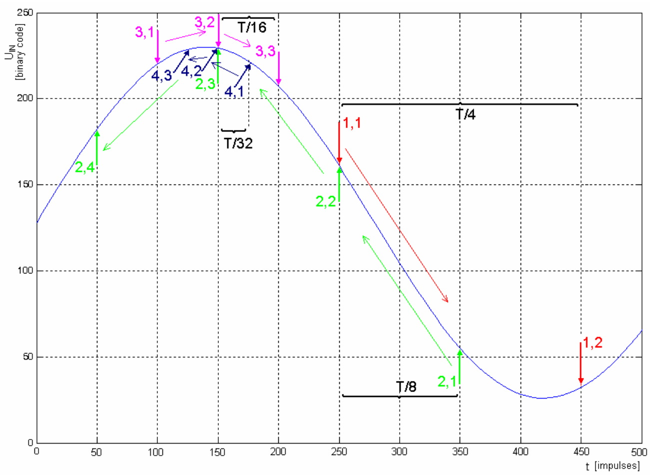

Fig. 7. The idea of searching for the amplitude of the sine wave signal

An idea of determination of the amplitude (maximum value) of the input signal and also the output signal is shown in Fig. 7. The amplitude is searched in a iterative way. Fig. 7 shows only four iterations of sampling of the signal. Moments of the samples are represented by arrows, where the first number is the iteration step, the second one is the number of the sample in the given iteration step.

At the beginning of the algorithm of determination of the amplitude the ADC measures the first sample of the input stimulating signal in the first iteration step (1,1) at the random moment which is assumed as the reference moment for all the algorithm. The value T is written also to the variable t_m which keeps relative time between moments of samples. In the next step (1,2) the ADC takes the sample at the moment $t_m = t_m + t_d$, where $t_d = T/4$ (in practice $t_m = t_m + nT + t_d$, to consider the long conversion time of the ADC, where n = 1,2, ..). If the voltage value at the moment (1,2) is smaller than the value at the moment (1,1), the $t_d = t_d/2$ (the right rotation instruction) and "direction" of sampling is changed to the opposite (in this case $t_m = t_m - t_d$). So, we start the second iteration – steps: from (2,1) to (2,4). If the last voltage sample is smaller than the previous one, the algorithm goes to the next iteration step with t_d divided by two and changed "direction" of changes of the value t_m. This procedure is repeated until, in the j-th iteration step $u_{m\,(j,k)} - u_{m\,(j,\,k-1)} < u_d$, where k – the number of the voltage sample in the j-th iteration step, u_d – assumed minimum difference between two last measured voltage samples, for which the algorithm is finished. We stored $u_{IN} = u_{m\,(j,k)}$, and $t_{IN} = t_m$.

Next, still to continue counting of the time t_m by the Timer 1, the ADC is connected to the output response signal and the algorithm of determination of the amplitude described above is again started with $t_d = T/4$. At the end of running this algorithm we obtain $u_{OUT} = u_{m\,(j,k)}$, and $t_{OUT} = t_m$.

So the measurement procedure is finished with two bytes stored, which represent amplitudes (maximal values) of the input stimulating signal u_{IN} and the output response signal u_{OUT}, and one 16-bit world (also two bytes), which holds time delay between these signals $\tau_m = t_{OUT} - t_{IN}$.

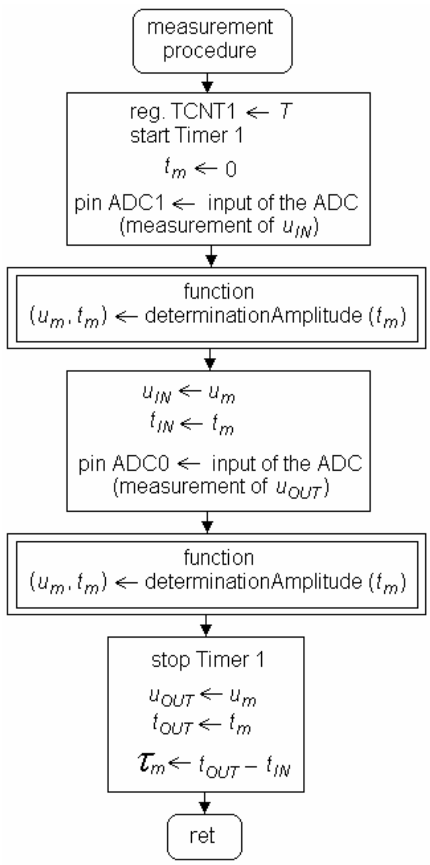

Fig. 8. Algorithm of the full measurement procedure

Fig. 8 shows the full measurement procedure. It is implemented in the form of a function. It consists of an initial stage and two time calling of the amplitude determination function.

At the initial stage the Timer 1 is started with the value T written to its data register. This solution gives time for executing instructions making the ADC ready for the first measurement of the input signal. The first calling of the amplitude determination function determines the amplitude of the input signal u_{IN} and the relative time for which this signal has a maximum value t_{IN}. The second one provides the amplitude of the output signal u_{OUT} and the time of occurrence of the maximum value t_{OUT}. At the end the Timer 1 is stopped, the time delay τ_m is calculated and variables u_{IN}, u_{OUT}, τ_m are stored.

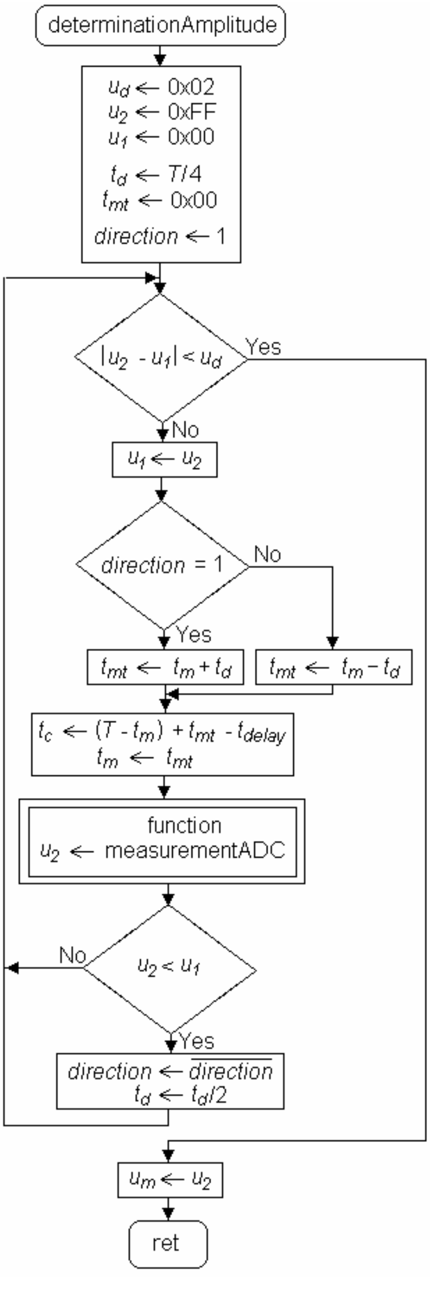

Fig. 9. Flowchart of the amplitude determination function

The algorithm of determination of the amplitude of the sinus wave (Fig. 7) was implemented in the amplitude determination function. This function gets the variable t_m keeping an initial value of time for which the algorithm starts. It returns variables which contain the amplitude of the signal u_m applied to the input of the ADC and the time t_m of the maximum value of this signal.

The variables u_1, u_2 and t_{mt} contain temporary values of the voltage sample earlier measured, the currently measured voltage sample and time to activation of the next measurement of the voltage sample by the ADC. The variable u_d keeps a value of an assumed precision of determination of the signal amplitude. If the difference between two last measured voltage samples is less then this value, the algorithm is stopped and variable u_m contains the voltage value of the last measured sample. The variable t_d represents the time distance to the next voltage sample. If the algorithm goes to the next iteration step, this value is divided by two. The bit variable *direction* appoints the "direction" of changes of the value t_m. If it is equal "1", the time to the next measurement of the voltage sample is lengthened by addition of the t_d value, else this value is subtracted from this time. The value included in the variable t_c is directly written to the Timer 1 Data Register TCNT1. The Timer 1 counts the time t_{mt} diminished by the time t_{delay} needed to activate the ADC and to write a new value to the TCNT1 register. The idea of calculation of the time t_c is shown in Fig. 11.

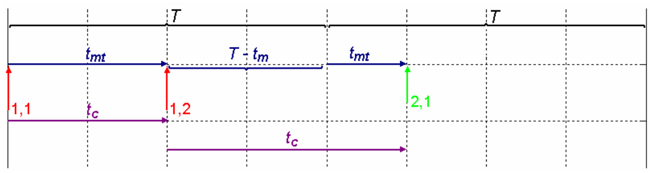

Fig. 10. Illustration of the idea of calculating the time t_c introduced to the Timer 1

This way of determination of moments of voltage samples is possible only for periodical signals. It is seen that the signal is sampled only one for the period T. The determination of the amplitude takes $k_1 + k_2 + ... + k_j$ periods T of the signal, where k_j – the number of samples in the j-th iteration step. So, this procedure occupies a long time. Because the measurement procedure is elaborated for using it for e.g. self-testing of analog parts of the mixed signal embedded systems and not for monitoring them, the duration time of the procedure is not critical. Moreover, the time distance between two samples measured by the ADC has to be greater than its long conversion time t_{ADC} (minimum 65μs). It is attended when $t_c > nT > t_{ADC}$, where $n = 1, 2, ..$. Our approach satisfies this criterion because the time t_c is always greater then period $T = 1.12$ ms.

After calculation of the time t_c the measurementADC function is called. This function returns the voltage sample of the signal measured by the ADC in the form of a single byte u_2. Its flowchart is shown in Fig. 11.

This flowchart consists of three parts. First part of the measurementADC function is realized in the main program. Its task is to synchronize the execution of the program with the moments of the sampling by the ADC (to wait for the end of conversion of the ADC). The bit variable *wait* is used for this aim. It is set by the main part of the function and reset after the measurement by the ADC in its interrupt service.

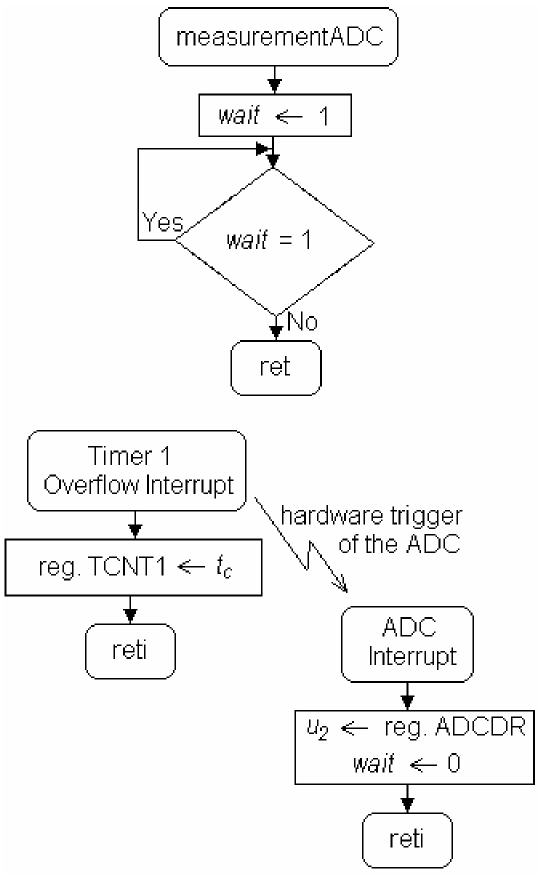

Fig. 11. Flowcharts of the measurementADC function and united interrupt services

Two remaining parts are realized in the interrupt services of the Timer 1 Overflow Interrupt and the ADC Conversion Complete Interrupt.

The interrupt service of the Timer 1 is trivial – it only actualizes the data register of the new value of the time t_c. The overflow of the Timer 1 auto triggers the ADC conversion (in a hardware way).

In the interrupt service of the ADC the conversion result is written to the variable u_2 and the variable *wait* is reset.

From Fig. 11 it is seen that the measurement algorithm is very simple. It is possible, because the ATmega16 microcontroller has a rich set of multifunctional, flexible end extended peripheral devices (e.g. used by the method: flexible Timer/Counter 1 and especially an 8-channel, 10-bit ADC with start conversion by auto triggering on interrupt sources). It enables to elaborate a relatively simple algorithm of the measurement procedure.

Using the interrupt system, for which each interrupt has a separate program vector in the program memory space, and using the ADC with source triggers: Timer/Counter1 Overflow, it is possible to count exactly times t_c between successive voltage samples with the precision of a crystal oscillator connected to the microcontroller.

The presented flowcharts (Fig. 8, 9 and 11) of respective functions, where the measurement function calls two time the determinationAmplitude functions, which in turn calls the measurement function, show the hierarchic structure of the full measurement algorithm. Each of its levels (the algorithm of the particular function) is simple. Hence, the code of the complete measurement procedure is short and satisfies the accepted condition of minimization of space occupied in the program memory.

3. AN ANALYSIS OF THE ACCURACY OF THE MEASUREMENT METHODS

For the first measurement method, moments of beginning and end of the period T and the time delay τ are determined by the analog comparator (see Fig. 5). Its inaccuracy depends on the delay of a comparison and the threshold voltage which has to be equal to the offset voltage. Because we use only triggering of the Timer/Counter 1 Input Capture function on the comparator output rising edge, the synchronization introducing a delay of 1 – 2 clock cycles [9] for all measurements is invariable and it compensates itself.

So the measurement error $\Delta\tau$ of determination of time delay τ mainly depends on the deviation of the threshold (reference) voltage U_{ref} of the analog comparator in relation to the offset voltage U_{offset} of the signal. It is described by the following relation:

$$\frac{\Delta\tau}{T} = \frac{1}{2\pi}\arcsin\left(\frac{U_{offset} \pm U_{ref}}{U_{amp}}\right) \qquad (2)$$

where U_{amp} is the amplitude of the sine wave signal.

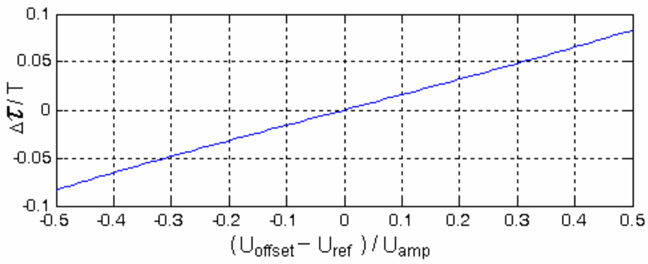

Fig. 12. Graph of delay comparison of the analog comparator as a function of the difference between offset and threshold voltages

In spite of the fact, that error $\Delta\tau/T$ is about one grade smaller than its source (difference between the threshold and offset voltage), what is shown in Fig. 12 with the graph of the relation (2), it is worth to reduce this error. We can do it in a simple way by the ADC measurement of the DC voltage U_{offset} before proper measurements and by setting up U_{ref} to this value.

For both measurement approaches the accuracy of the measurement result of the ADC is equal to 1 LSB. It follows from the fact that the resolution of the ADC is 10-bits [9], the absolute accuracy (including INL, DNL, quantization error, gain and offset error) by the ADC_{CLOCK} = 200 kHz is equal maximum 2.5 LSB, and we take into account only 8 high bits of the ADC conversion result.

The 16-bit Timer 1 works with the precision of a crystal oscillator and it introduces only a quantization error.

For the second measurement approach an error Δt of the time delay between the input and the output signal particularly depends on the assumed minimum difference u_d between two last-measured voltage samples, for which the algorithm of the amplitude determination is finished. The relation (3) presents the relation between these magnitudes:

$$\frac{\Delta t}{T} = \pm \frac{1}{2} \arcsin\left(\sqrt{\frac{u_d}{2U_{amp}}} \right) \quad (3)$$

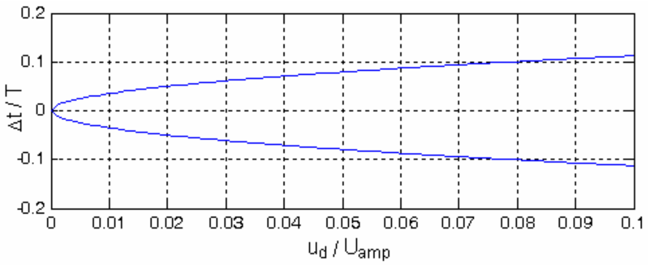

Fig. 13. Graph of the error of the determination of the moment for which the sine wave signal has its maximum value, as a function of the **assumed precision of determination of the signal amplitude u_d**

The graph of the relation (3) was drawn on Fig. 13. In this case it is seen that small changes of u_d significantly influence the value of the error Δt. It results from the shape of the sine wave. Around the maximum value of the sinus function (for the angle equal to $\pi/2$) the characteristic is flat, so variations of the angle around $\pi/2$ effect small changes of values of the sinus, as shown in Fig. 14.

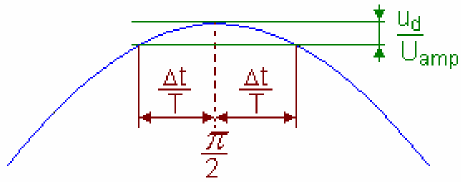

Fig. 14. Graph of the sinus wave around $\pi/2$ illustrating dependences between the error Δt of determination of the moment of maximum value of the sinus function and the **assumed precision of its determination u_d**

The influence of the error Δt can be reduced in a few ways. For instance, when this measurement approach is used to self-testing of the analog part by the embedded system, we can determine the delay time with an 16-bit accuracy (the resolution of the Timer 1) and next we reduce this result to 8 high bits. In this way we adapt it to the detection and localization procedure, which bases on the fault dictionary consisting of only 8-bit constants, e.g. [8].

3. CONCLUSIONS

The originality of the work presented in this paper is a new measurement procedure enabling the measurement of the circuit function of the analog part of the embedded system controlled by the microcontroller. This approach needs only internal resources currently implemented in each microcontroller: the ADC, whose measurements are synchronized by the timer. Hence, this approach does not exact excess hardware. Additionally, it should be fully realized by embedded electronic systems in which it is implemented.

Based on the internal devices of the microcontroller and its computing power we obtain a reconfigurable BIST. It is created only during the self-testing time. Apart from this time, the microcontroller and its internal devices perform normal functions. Hence, we considerably decrease the number of elements of the BIST which have to be added to the system, which allows to decrease production costs.

This approach can be used everywhere measurements of circuit functions of analog circuits are needed. So, it can be not only used for fault detection and localization of single faults in the analog part of the mixed-signal embedded electronic systems, as presented in [8], but also e.g.: for parametric identification of technical or biomedical objects modelled by electrical circuits.

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