Testing method of analog parts for mixed signal microsystems based on microcontrollers

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Abstract **–** In the paper a new method of fault detection and location of a single soft fault in analog parts of mixed signal microsystems based on microcontrollers is presented. The idea of the method bases on the transformation which maps changes of the time response of the tested circuit on a square impulse resulting from changes of values of respective elements onto identification curves on a plane. The method consists of two stages. In the first stage a fault dictionary of an analog part in the form of a family of identification curves is generated and it is placed in the program memory of the microcontroller. In the second stage detection and a location of the fault are carried out.. This method does not require extra hardware in the microsystem. The measuring-diagnosis procedure is realised only by the microcontroller already existing in the microsystem.

I. Introduction

At present, more and more electronic microsystems consist of a digital part used for control and processing of data, and an analog part mostly used for adjustment of input signals e.g. from sensors (mixed signal circuit). Moreover, in many cases microcontrollers control the operation of these microsystems.

Hence, testing or automated testing is needed not only of digital parts of these microsystems, but also of analog parts using microcontrollers mounted in the system.

In the paper a new diagnosis method which enables the detection and the location of single parametric (soft) faults and which can be used for testing of analog parts of these microsystems, is proposed.

It was assumed that the method should not require extra hardware in the microsystem. Therefore, to exclude the hardware, the resources of microcontrollers accessible in the microsystems should be used for measuring and processing of data.

At present, the microcontrollers generally used in practice (e.g. PIC16/18, Atmega8/16/32/64/128, ST7xxx, ADuC8xx) have advanced timers/counters enabling precise measurement of time, counting of external pulses, generating programmed square impulses, and they have 8, 10, 12-bit SAR-type A/D converters with sample & hold circuits which enable the measurement of instantaneous values of voltage.

Additionally, it was also assumed that the diagnosis procedure of the method should not be numerically complicated, because the computing power of these microcontrolers is small and they have no floating-point instructions and often integer multiple and divide instructions.

II. The idea of the method

The above requirements are satisfied by the new fault diagnosis method. It consists of two stages. In the first pre-testing stage, a fault dictionary in the form of a family of identification curves is generated in a simulated way on a PC computer. Next, it is placed in the program memory of the microcontroller. The fault dictionary takes the form of a map with a family of identification curves, like it was in the methods described in [1,2].

In the second stage, two samples u_1 and u_2 of voltages of the time response of a circuit on a square impulse at two precise moments t_1 and t_2 are probed (for instance, the square impulse is generated at the output of the microcontroller, the voltages are probed by its ADC in moments established by the internal timer). The measurement result in the form of a measurement point P_m, which has co-ordinates (u_{1m},u_{2m}) is placed on the map with a family of identification curves (e.g. Fig. 4). The faulty element can be located by placing the P_m point on a particular curve. Additionally, it is possible to scale the curve, which gives the possibility of fault identification.

A. The methodology of generation of the fault dictionary

For clarity of considerations, the method is illustrated on the example of a very simple circuit – a 2-nd order low-pass Sallen-Key filter with Butterworth characteristics (Fig. 1).

In the method, a soft fault is assumed as the range of change of values of elements from 0.1 to 10 times their nominal value.

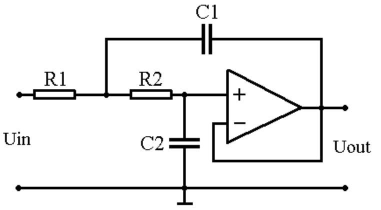

Fig. 1. TheCircuit Under Test (CUT), where R1=R2=10kΩ, C1=560pF, C2=1.1nF

Fig. 2 shows the time response of the circuit (CUT) on a square impulse for the assumed range of changes of R1 and C1 elements (Fig. 2a) and of R1 and C2 elements (Fig. 2b) (the values of remaining elements are nominal). It is seen that the responses for different elements do not fall on each other. Therefore it is possible to discern and to assign these answers to given elements and to their given values.

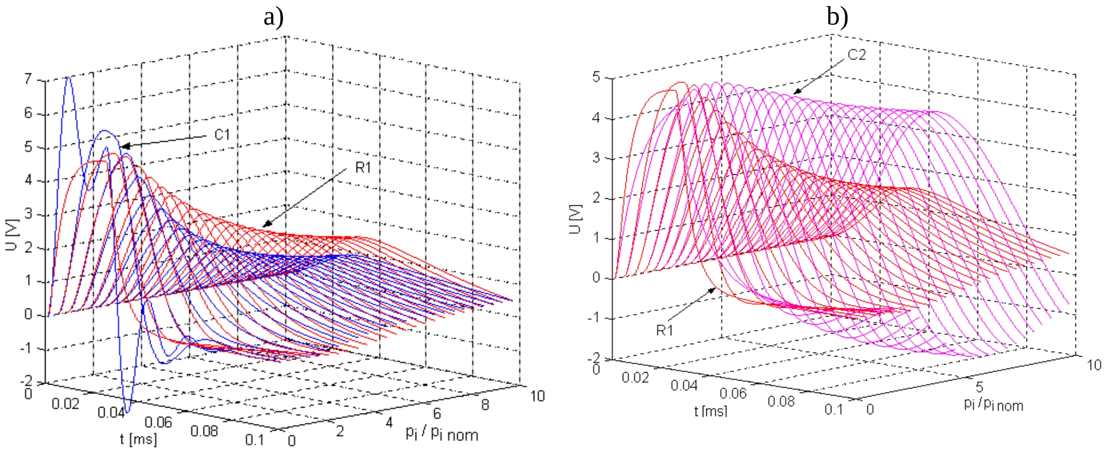

Fig. 2. The time response of the circuit for changes of: a) R1 and C1 elements, b) R1 and C2 elements

In Fig. 3 the input square impulse with duration time *T* and the response of the circuit for 0.1 of the nominal value of R1, C1 and C2 elements (from the principle of operation of the circuit the responses for R1 and R2 elements are identical) and moments of probing t_1 and t_2 are shown.

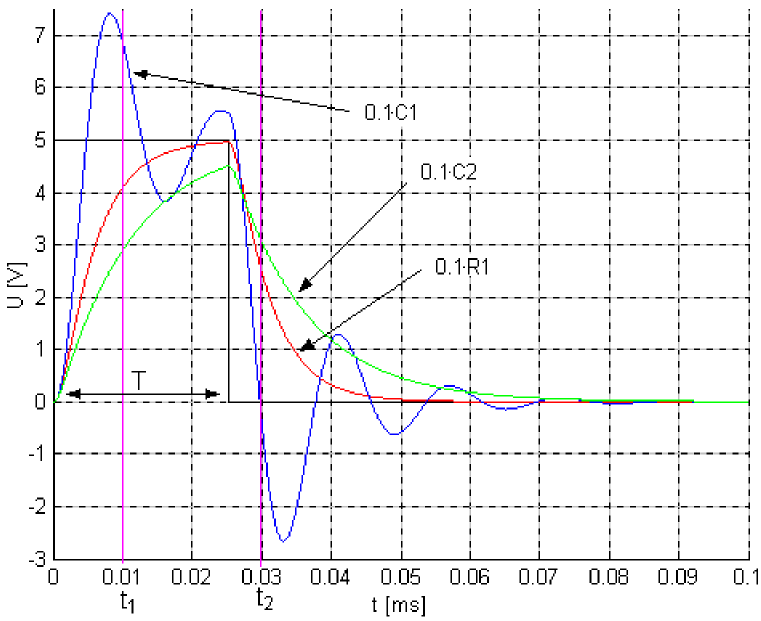

Fig. 3. The time response of the circuit for 0.1 nominal values of R1, C1 and C2 elements

Based on the above property, a new method of creation of the fault dictionary was elaborated. Its idea is described below.

We assumed that the voltage probed at moment t_1 (u_1) is the first co-ordinate and the voltage probed at moment t_2 (u_2) is the second one (Fig. 3). Successively changing the value of a particular element p_i (where i=1,..,N, N – the number of elements of the CUT) from 0.1$p_{i\ nom}$ to 10p_i nom ($p_{i\ nom}$ – the nominal value of i-th element) the particular curves are drawn on the plane U_1,U_2. In this way we obtain the family of identification curves (Fig. 4).

We can present the above operation of generation of the identification curve for the p_i element in the form of the transformation:

$$T_i(p_i) = u(p_i,t_1)\cdot\mathbf{i} + u(p_i,t_2)\cdot\mathbf{j} \tag{1}$$

where: **i**, **j** – are versors.

Hence, the transformation (1) maps changes of values of p_i elements onto identification curves on the plane. As described in [1,2] and in this case the fault location consists in putting the measurement point onto the plane. Appurtenance of the measurement point to the adequate curve locates the faulty element. In case when the curves are scaled, the location of the measurement point on the curve identifies the fault.

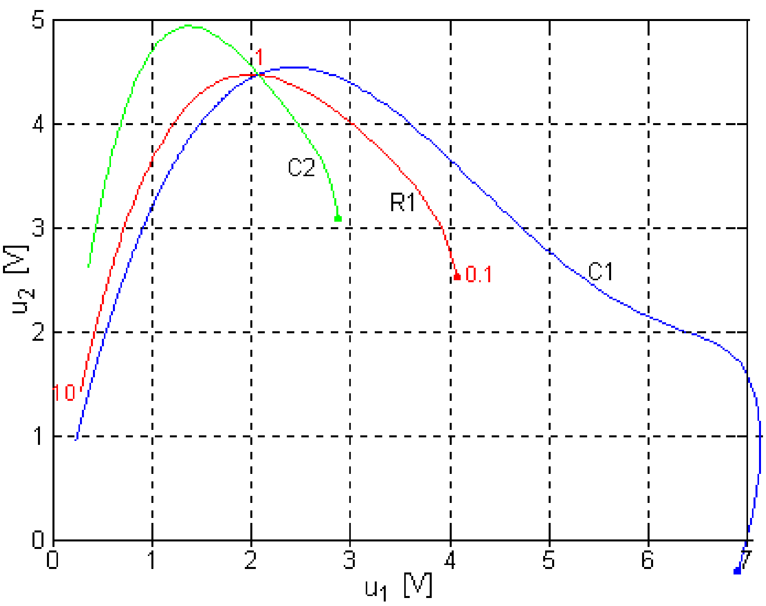

Fig. 4. The map of identification curves for the CUT from Fig. 1

B. Testing of analog parts of the microsystem

Testing of the analog part starts with the generation of a square impulse with duration time T at the input of the CUT and probing of u_1 and u_2 values of voltage at moments t_1 and t_2 of the time response at its output.

Next, the fault location or possibly fault identification of the single parametric fault is possible using the measurement point P_m (u_1,u_2) and the fault dictionary based on algorithms elaborated by the author [3,4] or based on an algorithm adapted to the computing power of the microcontrollers which will be presented below.

III. An application example of the method

The new method was illustrated on the example of a microsystem based on an ATmega16 microcontroller [6]. This microcontroller contains the resources required by the method: two 8-bit Timers/Counters (T0 and T2) and one 16-bit Timer/Counter (T1) which enable the generation of square impulses with programmable length and precise measurement of time, and an 8-channel, 10-bit ADC with S&H circuit used to probe the time response of the CUT.

In the Fig. 5 the microsystem in the testing mode of an analog part (CUT) is shown.

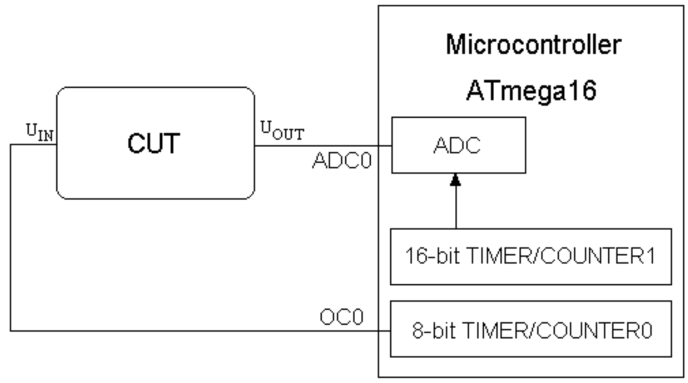

Fig. 5. The microsystem in the testing mode of the analog part (CUT)

It is seen (Fig. 5) that the CUT is tested by the microcontroller already contained in the microsystem and controlled by this microsystem. Hence, the testing of the CUT is an additional task or the microcontroller. The method does not require additional hardware.

A. Creating the fault dictionary

With regard to the limited size of the program memory of the microcontroller, which is destined mainly for a program controlling the microsystem, the code of the diagnosis procedure should be as small as possible. This code contains procedures realising the measurement-diagnosis algorithms and the fault dictionary. Thus the fault dictionary should have the smallest size while keeping an adequate level of location resolution.

For that reason, from the proprieties of the microcontrollers, simulation tests and previous works [5] the following assumptions result:

- 8-bit measurement resolution,
- the *i*-th identification curve of the p_i element is represented by a set of points $\{q_{ij}\}_{j=1,..,J}$, where J=64, which are calculated from the set of values of elements $\{p_{ij}\}$and equally placed on this curve.

Hence, each curve is described by 128 bytes (two bytes include co-ordinates (u_{1ij}, u_{2ij}) of the q_{ij} point), which gives a fault dictionary with the dimension $N * J$ = 384 bytes. It is small in relation to the size of the program memory of the microcontroller (ATmega16 has 16kB of FLASH memory).

The fault dictionary is generated on a PC computer using the Matlab program. For the assumed range of changes from 0.1 to 10 $p_{i\ nom}$ the values of respective elements are chosen using the logspace function. It gives an as far as possible equal location of approximation points on identification curves. For each value of a p_{ij} element, simulation of the time response of the CUT to a square impulse with the same parameters which the real impulse has at the input of the CUT (Fig. 3) is performed using the Control Toolbox. Next, the fault dictionary created in this way is converted and placed into the HEX file with the full program code. In the last step the microcontroller is programmed in the ISP mode.

B. The measurement procedure

The measurement procedure is running according to following steps:

- Writing a logical zero to the output OC0 and keeping this value ("Lo" level) for at least the duration of 5T to assure zero initial conditions of the CUT.
- After this time, the configuration of the internal resources of the microcontroller is:
  - the 8-bit Timer/Counter0 (T0) – Compare Output Mode (clear OC0 on compare match). Writing to Output Compare Register (OCR0) the value corresponding to time T,
  - the 16-bit Timer/Counter1 (T1) – Clear Timer on Compare Mode (normal port operation). Writing to Output Compare Register A (OCR1A) the value 0xFFFF, to Output Compare Register B (OCR1B) the value corresponding to time t_1, and to Timer/Counter1 Register (TCNT1) the complement to the value suiting to time t_2,
  - the Analog to Digital Converter (ADC) – probing the voltage at the ADC0 input, taking the reference voltage from the AVCC line connected to the supply voltage Vcc, trigger source: the Timer/Counter1 Compare Match B.
- Writing a logical one to the output OC0 („Hi" level) and starting counters T0 and T1.
- When the contents of the T1 counter (register TCNT1) equal the contents of OCR1B register (time t_j), the comparator of T1 signals a match. The match triggers the ADC converter (using the hardware).

- The end of measurement of the ADC voltage causes an interrupt in which:
  - the result is written in the u_{1m} variable,
  - a new ADC trigger source is selected: Timer/Counter1 Overflow.
- When the contents of T0 counter (TCNT0 register) equal the contents of OCR0 register, it signals a compare match, which clears the OC0 output (writing the „Lo" level) by the hardware.
- The overflow of the T1 counter (measurement of time t_2) triggers the measurement of voltage by the ADC and generates the TIMER1 OVF interrupt, in which the T1counter is stopped.
- Termination of the measurement of the ADC voltage triggers an interrupt in which:
  - the result is written in the u_{2m} variable,
  - the flag informing of the finishing of the measurement procedure is set.

The ATmega16 microcontroller has a rich set of multifunctional, flexible end extended peripheral devices (e.g. three flexible Timer/Counters with compare modes 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. Hence, the code of the measurement procedure is short and satisfies the accepted condition of minimisation of space occupied in the program memory by the diagnosis procedure.

This code consists of the part in which the T0, the T1 and the ADC are configured to work and the part involved with interrupt services. The service of the Timer/Counter1 Overflow is trivial – it only stops the T1 counter. The most important part of the code of the measurement procedure is included in the ADC Conversion Complete interrupt service and it occupies only less then twenty assembler instructions.

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 Compare Match B, Timer/Counter1 Overflow, it is possible to count exactly T, t_1 and t_2 times with the precision of a crystal oscillator without errors introduced by program delays.

C. The location of single soft faults

When the measurement procedure is finished, the microcontroller performs the detection and the location of single soft faults, according to the new algorithm proposed below.

With regard to the computing capability of the microcontrollers, we define the distance d between two points $P_1(x_1,y_1)$ and $P_2(x_2,y_2)$ in the following way:

$$d = |x_1 - x_2| + |y_1 - y_2| \tag{2}$$

Hence, the microcontroller, in the course of computing the distances realises only an integer subtraction (SUB R_d,R_r), when the result is negative (the N flag is set – tested by the BRMI instruction) realizes a one's complement (COM R_d) and next an integer addition (ADD R_d,R_r).

The diagnosis algorithm consists of the following steps:

1. Fault detection – checking that the distance $d_{m\ nom}$ between the measurement point $P_m(u_{1m},u_{2m})$ and the nominal point $P_{nom}(u_{1nom},u_{2nom})$ is less than the assumed *Epsilon* number. If this condition is satisfied, the CUT is fault-free and the algorithm is stopped. Otherwise, the next steps have to be executed for fault location.
2. Fault location – finding the minimum distance d_{min} between the measuring point P_m and the i-th identification curve points at the faulty element. The location is performed in the following steps:
   - for each i-th identification curve the minimum distance $d_i = \min_{j=1,..,J} \{d_{ij}\}$ is determined in the way shown in Fig. 6a, where d_{ij} – the distance between point P_m and the j-th point $q_{ij}(u_{1ij},u_{2ij})$ on the i-th identification curve,
   - next the minimum distance $d_{min} = \min_{i=1,..,N} \{d_i\}$ and the index of the faulty element i are determined (as shown in Fig. 6b).

As described above and as shown in Fig. 6, the microcontroller does not perform complicated arithmetic operations. It was obtained by realisation of the fault dictionary in the form of a table of vectors representing the identification curves and by assumption of the definition of distance (2). The only arithmetic operations made by the microcontroller are included in the DISTANCE function (written in Assembler). The procedures of determination of the minimum distance are short (Fig. 6). Hence the whole code of the diagnosis procedure is small, and like it was for the measurement procedure, it satisfies the assumed condition of minimisation of the place occupied by the code in the program memory.

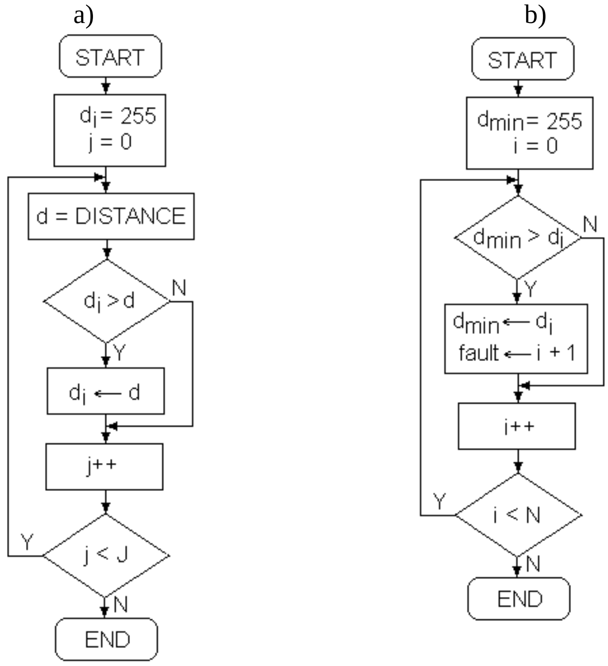

Fig. 6. a) Determination of the distance d_i between the *i*-th curve and the P_m point. b) Location – finding the minimum distance d_{min} among curves and the P_m point

III. Conclusions

The new method was elaborated for the fault diagnosis of analog parts of mixed signal microsystems based on microcontrollers. Hence, it has the following advantages:

- the measurement signal with a precisely established duration time is generated by the microcontroller,
- measurements of the response of the CUT can be made using only internal resources of popular microcontrollers (the ADC circuit triggered by the T1 timer),
- duration time of the excitation and moments of probes of the response are precise, without program delays – due to the internal timers of the microcontroller,
- the diagnosis procedure does not require large computing powers,
- in addition, the codes of the diagnosis procedure and the fault dictionary do not occupy much place in the program memory.

Thus, this method can be used in practice for example for self-testing or automated testing of mixed signal microsystems or it can be also used in monitoring devices for parametric identification of technical or biomedical objects modelled by electrical circuits.

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