A Fault Diagnosis Method for Analog Parts of Embedded Systems Based on Time Response and Identification Curves in the 3-D Space

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Abstract – A new 3-D version of the new fault diagnosis method of analog parts in embedded mixed microsystems based on microcontrollers is presented. It has the following advantages: measurements of the CUT can be made using only internal resources of popular microcontrollers, the diagnosis procedure does not require big computing power and the codes of its procedure do not occupy much space in the program memory of the microcontroller.

I. Introduction

At present, simple embedded systems consist of not only a digital part, used for control and processing of data, but also an analog part mostly used for adjustment of input signals e.g. from sensors. Moreover, in many cases microcontrollers control the operation of these embedded systems.

Hence, testing or automated testing of analog parts of is needed using microcontrollers mounted in the system.

So in the paper describes a new 3-D version of the diagnosis method elaborated by the author [1], which enables the detection and localisation of single parametric (soft) faults and which can be used for testing of analog parts of these embedded systems.

It was assumed that the method should not require excess hardware in the embedded system. Therefore, to exclude the hardware, the resources of microcontrollers accessible in the embedded systems should be used for measuring and processing of data.

At present the microcontrollers generally used in practice (e.g. Atmega8/16/32/64/128, ADuC8xx) have advanced timers/counters enabling precise measurement of time, counting of external pulses, generating programmed square impulses and they have 8, 10, 12-bits SAR-type A/D converters with sample & hold circuits which enable the measurement of temporary values of a 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 3-D method

The above requirements are satisfied by the new 3-D version of the new fault diagnosis method. It consists of two stages, see also [1]. In the first pre-testing stage, a fault dictionary in the form of a family of identification curves in the 3-D space is generated in a simulated way on a PC computer. Next, it is placed in the program memory of the microcontroller.

In the second stage, three samples u_1, u_2 and u_3 of voltages of the time response of a circuit to a square impulse for three precise moments t_1, t_2 and t_3 are probed (for instance, a square impulse is generated at the output of the microcontroller, the voltages are probed by its A/D converter at moments established by the internal timer). The measurement result in the form of a measurement point P_m is placed into the map with a family of identification curves (e.g. Fig. 1b). In a similar way as described in [2,3,4], the faulty element can be localised by location of 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 idea of the 3-D method

It was tested that the responses of the linear circuit to a square impulse for the assumed range of change of elements for different elements do not fall on each other. Therefore it is possible to discern and to assign these responses to given elements and to their given values.

In Fig. 1a the responses of the low pass filter (e.g. the 3-rd order low Butterworth filter shown in Fig. 2) to a square impulse for changes from 0.1 to 6 of the nominal value of R1, C1 and C2 elements and moments of probing t_1, t_2 and t_3 are shown.

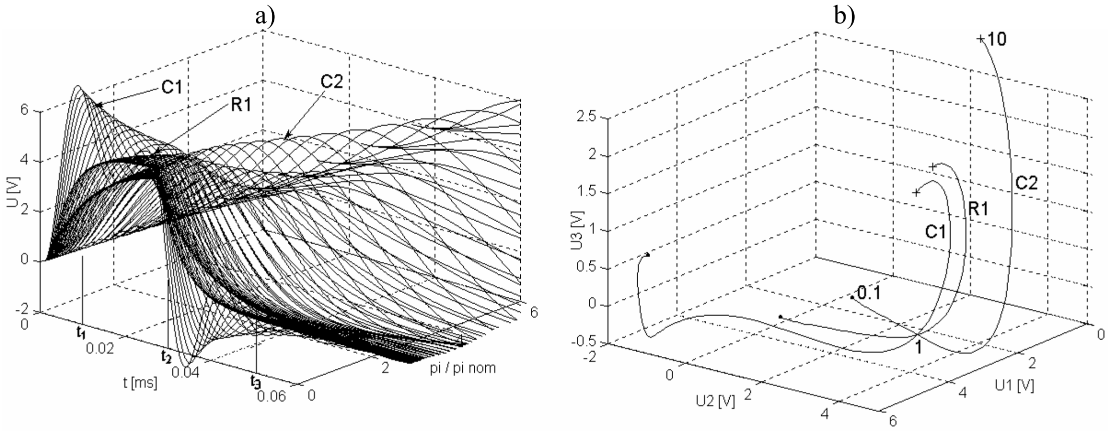

Figure 1. a) Time response of the analog part of the embedded system (Fig. 2) for changes from 0.1 to 6 of nominal values of R1, C1 and C2 elements, b) the map of identification curves of the analog part

We assumed that the voltage probed at a moment t_1 (u_1) is the first co-ordinate, the voltage probed at the moment t_2 (u_2) is the second one and the voltage probed at the moment t_3 (u_3) is the third one. Successively changing the value of a particular element p_i (where i=1,..,I, I - the number of elements of the analog circuit) from $0.1p_{i\ nom}$ to $10p_{i\ nom}$ ($p_{i\ nom}$ - the nominal value of i-th element) the particular curves are drawn in the 3-D space U1,U2,U3. In this way we obtain a family of identification curves (Fig. 1b).

We can present the above operation in the form of the transformation:

$$T_i(p_i) = u(p_i,t_1)\cdot \mathbf{i} + u(p_i,t_2)\cdot \mathbf{j} + u(p_i,t_3)\cdot \mathbf{k} \tag{1}$$

where: **i**, **j**, **k** - are versors.

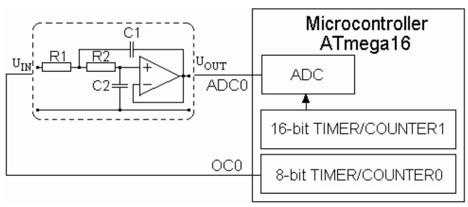

Fig. 2. The embedded system with the tested analog part, where: R1=R2=10kΩ, C1=560pF, C2=1.1nF

The transformation (1) maps changes of values of p_i elements into the identification curves in the 3-D space. This map of identification curves can be transformed to the fault dictionary and stored in the program memory of the microcontroller, which will be described in the next paragraph.

B. Assignment of duration time of the stimulant square impulse

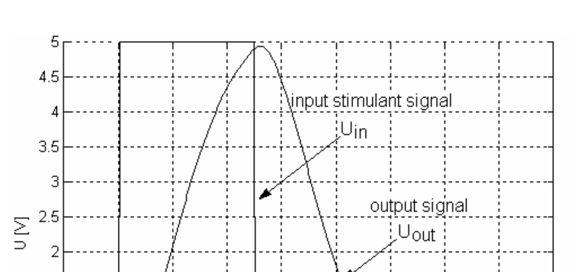

Fig. 3. The stimulant and response signals of the tested analog part

Duration time of the stimulant square impulse is determined in two steps. In the first step this time is assigned to a value $T = 1/f_c$, where f_c is the cut-off frequency of the low pass filter (Fig. 2). In the second one we fix the maximum value of the output signal $U_{OUT}=\xi \cdot U_{IN}$ for the nominal values of elements of the circuit, where a coefficient $\xi \in <0, 1>$. Next we fit duration time T by simulation to obtain a given maximum value U_{OUT} of the output signal (It was chosen ξ = 1). The Fig. 3. shows the input stimulant signal U_{IN} and the response signal U_{OUT} of the circuit for ξ = 1.

For the circuit in Fig. 2 the duration time T of the stimulant impulse was set to 25μs.

C. Assignment of moments of voltage samples of the response signal

The fault diagnosis method needs determination of three moments t_1, t_2 and t_3 of voltage samples of the response signal. Location and shape of the curves exclusively depend on these moments. So they should be chosen in a way enabling the best localisation resolution of the faults. Thus, the identification curves should have similar length, and they should be as distant from themselves as it is possible. Based on these assumptions and results of simulation investigations criteria and a procedure of determination of the three moments of voltage samples were elaborated.

The procedure consists of two stages. In the first stage two moments are determined, t_1 and t_2, based on criteria of the best localisation resolution of identification curves on a plane. In the second stage the moment t_3 is assigned. It determines the third co-ordinate U3 of a measurement space with the family of the identification curves. It bases on criteria of additional increase of the localisation resolution.

The moments t_1 and t_2 are determined in the following way. It is known, that the response of the tested circuit consists of two steps (see Fig. 2):

- cumulation of energy (loading of capacitors) during duration of the stimulant signal $(0, T)$,
- emission of energy (discharge of capacitors) after the stimulant signal, during $(T, \nu T)$ time (where $\nu = 1, 2, ..$).

Therefore, we observe two different behaviours of the circuit. Taking into account, the moment t_1 is determined in first step $t_1 \in (0, T)$, and the moment t_2 in the second one $t_2 \in (T, \nu T)$.

To determine of moments t_1 and t_2, for which we obtain the best localisation resolution, a coefficient of the localisation resolution λ_i of p_i element is introduced and is defined in the following way:

$$\lambda_i(t_k) = \max_{j=1,..,J}\{u(p_{ij}, t_k)\} - \min_{j=1,..,J}\{u(p_{ij}, t_k)\}, \tag{2}$$

where J – the number of values of element p_i, t_k – the moment of the k-th sample, $k = 1, .., K$ and $t_k \in (0, \nu T)$, K – the number of samples.

This coefficient describes the difference between the maximum and minimum values of voltage of the circuit response at the moment t_k for defined range of values of p_i element.

The coefficient λ has the form:

$$\lambda(t) = \frac{1}{I}\sum_{i=1}^{I}\frac{\lambda_i(t)}{\max\limits_{k=1,..,K}\{\lambda_i(t)\}} \tag{3}$$

The coefficient λ is an average value of normalised coefficients λ_i, then its maximum value represents the optimum sensitivity of the circuit response to changes of values of all elements. Thus we can define:

$$\lambda_{\max 1} = \max_{k=1,..,K1,\ t_k \in (0,T)}\{\lambda(t_k)\} \quad \text{and} \quad \lambda_{\max 2} = \max_{k=K1,..,K,\ t_k \in (T,\nu T)}\{\lambda(t_k)\} \tag{4}$$

where $K1$ – the number of samples for time range $(0, T)$.

So, the solutions of (4) determines the two moments of voltage samples:

$$\lambda_{\max 1} \to t_1 \quad \text{and} \quad \lambda_{\max 2} \to t_2 \tag{5}$$

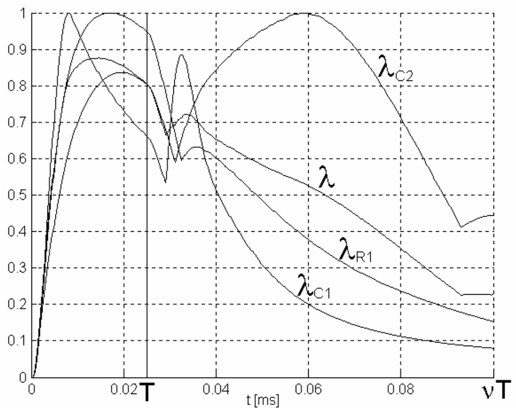

Fig. 4. The chart of the coefficient λ for the analog part of the embedded system (Fig. 2)

Fig. 4 shows charts of all coefficients λ_i and coefficient λ. It is seen that in the first step (loading of capacitors) properties of the circuit significantly depend on the values of R1 and C1 elements. However, in the second step (discharge of capacitors) the values of the capacitor C2 mainly influences on the form of identification curves.

For the analog part (Fig. 2) it was determined following moments of voltage samples t_1 = 14.8μs and t_2 = 33.6μs.

Knowing these times, it is possible to draw the identification curves on the plane U1, U2 (Fig. 5).

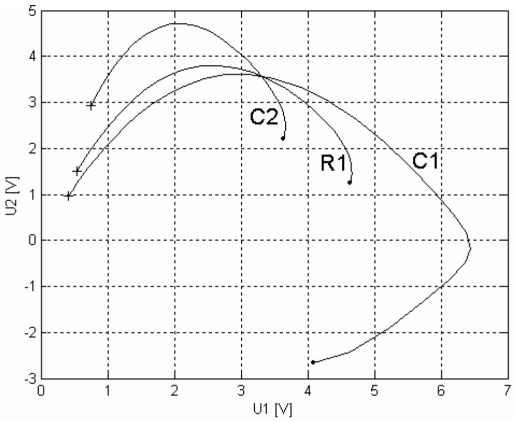

Fig. 5. The map of identification curves of the analog part on the plane

It is seen, that curves R1 and C1 are situated too close to each other. In this case measurement errors can make difficult the correct fault localisation. So a third dimension U3 was introduced (Fig. 1b). It causes an increase of distances among identification curves, and the same improvement of the fault localisation resolution.

Assignation of moment t_3 of the voltage sample can be realised in many ways depending on established criteria. The following criteria were elaborated:

- maximum difference of time between t_3 and t_1 and t_2,
- improvement of identification accuracy of i-th identification curve, where the curve can be chosen by us or it can be the shorter curve,
- improvement of localisation resolution by drawing aside neighbouring curves chosen by us or neighbouring curves placed too close to each other.

In this paper the first criterion is described. Assurance of maximum difference among moment t_3 and moments t_1 and t_2 allows the observation of the response signal at the moment, for which the signal is maximally different. It ensures getting maximum information from the response signal from the third sample at the t_3 moment.

At the beginning of determination of the moment t_3 maximum values of coefficients λ_i for all p_i elements are calculated:

$$\lambda_{i1} = \max_{k=1,..,K1,\ t_k\in(0,T)} \{\lambda_i(t_k)\} \quad \text{and} \quad \lambda_{i2} = \max_{k=K1,..,K,\ t_k\in(T,vT)} \{\lambda_i(t_k)\} \tag{6}$$

Based on these coefficients moments of samples are fixed:

$$\lambda_{i1} \rightarrow t_{i1} \quad \text{and} \quad \lambda_{i2} \rightarrow t_{i2} \tag{7}$$

Next, the maximum difference between moment t_3 and moments t_1 and t_2 is assigned:

$$\Delta t_3 = \max\{\max_{i=1,..,N}\{|t_1 - t_{i1}|\}, \max_{i=1,..,N}\{|t_2 - t_{i2}|\}\} \tag{8}$$

If $\max_{i=1,..,I}\{|t_1 - t_{i1}|\} > \max_{i=1,..,I}\{|t_2 - t_{i2}|\}$ that $\Delta t_3 \rightarrow t_{i1} = t_3$, else $\Delta t_3 \rightarrow t_{i2} = t_3$.

For the tested circuit the moment t_3 of third sample is equal to 59.2μs and it represents the moment at which the coefficient λ_{C2} has its maximum value. Thus the curve of the C2 element is more distinguished then the other ones (compare Fig. 1b and Fig. 5). But also the distances among all identification curves are larger. So, moving of the identification curves from the plane to the 3-D space improves the fault localisation resolution.

III. An application of the 3-D method

The new 3-D method was illustrated on the example of a microsystem (Fig. 2) based on an ATmega16 microcontroller [5]. This microcontroller contains the resources required by the method: two 8-bit Timers/Counters (T0 and T2) and one 16-bit Timer/Counter (T1), and an 8-channel, 10-bit ADC with a S&H circuit.

A. Creating the fault dictionary

The fault dictionary is generated in the same way as described in [1]. But in this case points $\{q_{ij}\}_{j=1,...,J}$, where J=32, which represent the i-th identification curve of the p_i element (i=1, 2, .. I, I – the number of elements of the tested circuit), have three co-ordinates (u_{1ij}, u_{2ij}, u_{3ij}). So each curve is described by 96 bytes (three bytes include co-ordinates of each q_{ij} point). It gives the fault dictionary with the dimension $I * J * 3 + 3 + 1 = 388$ bytes, where 3 co-ordinates belong to a nominal point, one byte contains a coefficient ε_{nom} [6], which represents a size of a nominal area. It is still small in relation to the size of the program memory of the microcontroller (ATmega16 has 16kB of FLASH memory).

At the end of creating the fault dictionary, it is 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 similar to that described in [1]. In this case three samples u_1, u_2, and u_3 of the output signal are measured by the AD converter of the microcontroller. Generally this procedure consists of six steps as shown in Fig. 6. In the first step the tested circuit is introduced in an initial state. After about $5T$ a stimulant signal is put out on OC0 line (step 2), and its duration time is counted by the Timer 0. In this step the Timer 1 is started to count time t_1. The overflow of the Timer 1 (step 3) triggers the AD converter, which measures u_1 sample, and loaded value t_2 to the Timer 1 and again starts the Timer 1. At the step 4 the Timer 0 overflows and stops to generate stimulant signal on OC0. Second overflow of the Timer 1 (step 5) activates the AD converter to measure the u_2 sample. At the end (step 6) third overflow of the Timer 1 triggers measurement of the u_3 sample.

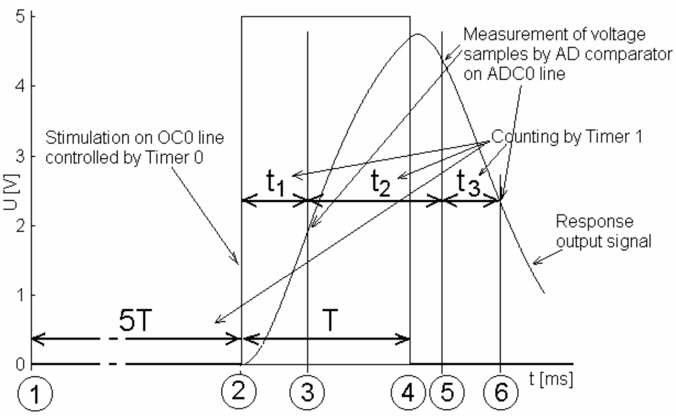

Fig. 6. The measurement procedure

The ATmega16 has a rich set of multifunctional, flexible end extended peripheral devices. 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 minimization of space occupied in the program memory by the diagnosis procedure.

Using the interrupt system, for which each interrupt has a separate program vector in the program memory space, and using the AD converter with source triggers: Timer/Counter1 Compare Match B, Timer/Counter1 Overflow, it is possible to count exactly T, t_1, t_2 and t_3 times with the precision of a crystal oscillator without errors introduced by program delays.

C. The fault diagnosis procedure

When the measurement procedure is finished, the microcontroller performs the detection and the localisation of single soft faults, based on the measurement results – the measurement point P_m (u_{1ij}, u_{2ij}, u_{3ij}) and the fault dictionary $S_{IJ} = \{(u_{1ij}, u_{2ij}, u_{i3ij}), (u_{1\,nom}, u_{2\,nom}, u_{3\,nom}), \varepsilon_{nom}\}_{i=1,..,I,\, j=1,..,J}$, where ($u_{1\,nom}$, $u_{2\,nom}$, $u_{3\,nom}$) are co-ordinates of the nominal point P_{nom}.

The code of the fault diagnosis procedure is contained in the function faultdiagnosis, the graph of which is shown in Fig. 7. This function consists of two parts. In the first part the fault detection is made. In the second one, if a fault is detected, its localisation is done.

In the first fragment of the function, which deals with the fault detection, the distance d_{nom} between the measurement point P_m and the nominal point P_{nom} is calculated. If distance d_{nom} is less than the coefficient ε_{nom}, the tested circuit is fault-free and the functions faultdiagnosis is finished with a variable *fault* = 0. Else the microcontroller runs the fault localisation part.

Also in this case (see [1]) the definition of the distance between two points P_1 (u_1 , u_2 , u_3) and P_2 (v_1 , v_2 , v_3) is assumed in the following way:

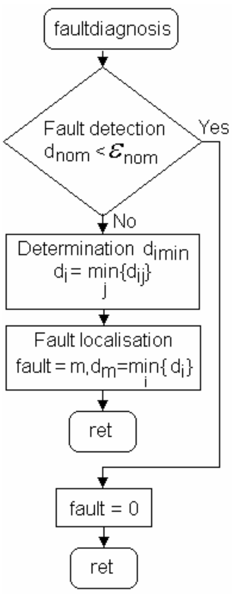

Fig. 7. The graph of the fault diagnosis procedure

$$d = |u_1 - v_1| + |u_2 - v_2| + |u_3 - v_3| \quad (9)$$

This calculation (9) is realised by the function distance. This function is "fast" and consists of only 18 assembler instructions. These advantages are very important, because this function is called by function faultdiagnosis $I*J + 1 = 129$ times.

In the fragment which deals with the fault localisation, for all elements p_i the distances d_{ij} among the point P_m and points q_{ij} are calculated. Next, the distances d_i among the point P_m and i-th identification curves are determined based on the relationship: $d_i = \min_{j=J}\{d_{ij}\}$. Next the minimum distance $d_m = \min_{i=1,..,I}\{d_i\}$ is determined and the variable *fault* gets a value m, where $m = 1, .., I$. It points to a faulty element p_m.

After the fault diagnosis procedure, the localisation results can be e.g. displayed on an 8 LED line connected to a port of the microcontroller (the simple way) or they can be transmitted via the UART interface to the PC.

IV. Conclusions

The new 3-D version of the new fault diagnosis method has better fault resolution as well as robustness against non-faulty component tolerances and measurement errors than the basic 2-D method presented in [1]. Because these methods were elaborated for fault diagnosis of analog parts of mixed signal embedded systems based on microcontrollers, they have the following advantages:

- Measurements of the analog parts can be made using only internal resources of popular microcontrollers (timers and AD converters).
- The diagnosis procedure does not require a big computing power. It is written in an assembler code and all calculations base on only an integer subtraction, an integer addition and a one's complement.
- The size of the fault dictionary is small in relation to the program memory of the microcontroller.
- The codes of the measurement and the diagnosis procedures do not occupy much place in the program memory.

Because the methods do not require a big place in the program memory, their codes (with the fault dictionary) can be added to a main program, which controls the embedded microsystems, without the risk of exceeding of the program memory size of the microcontroller.

Thus, these methods, especially the 3-D version of the method, can be used in practice for self-testing or automated testing of mixed signal embedded systems or it can be also used for parametric identification of technical or biomedical objects modelled by electrical circuits.

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