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IMPLEMENTATION OF THE BOARD-LEVEL OSCILLATION BUILD-IN SELF-TEST SCHEME FOR ANALOG CIRCUITS

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Abstract − The paper validates oscillation built-in self-test (OBIST) scheme for testing and measuring analog circuits assembled on a printed circuit board. This scheme uses both frequency, and time domain measurements in order to maximize the fault coverage. An implementation of the OBIST that comprises designing of oscillation-test structure and a measuring system based on microcontroller is presented. Special attention is being paid to the design of oscillatory circuit in such a way that leads to the orthogonal diagnostic process.

Keywords: self-testing, oscillation-test method.

1. INTRODUCTION

The proliferation of electronic systems stimulates an increased demand for simple and cost-effective means of testing and measuring. Build-in self-test (BIST) has gradually achieved a leading position as such solution [1,2,3].

Oscillation-based build-in self-test technique (OBIST) relies on being able to convert the circuit under test (CUT) functional blocks into oscillators one by one. The frequency of oscillation is related to the component values or the other circuit parameters. Therefore, changes of the frequency from its nominal value indicate faults in the CUT block. Oscillation-based testing has been promoted by many researchers for some years. The method based on an oscillator circuit has been proposed in [4] to estimate the ratio of the second pole to the gain-bandwidth product of matched operational amplifiers. To force the fast comparator to oscillate for voltage offset testing has been suggested in [5]. References [6,7,8] present and justify general idea of the OBIST throughout examples such as amplifiers, filters and analog-to-digital converters. In [9] oscillation approach has been applied to test switched-current biquadratic filters. In [10] an allpass equalizer has been used to fulfil the conditions for oscillation of the filter under test. Detailed case study of using the oscillation test methodology to test an active lowpass filter is presented in [11].

The drawback with the oscillation-based technique is that the measuring of frequency is not enough for full fault coverage and for fault isolation. In [12] the enhancement of the fault diagnostic resolution in term of the fault locating capability has been reached by combinational testing approach consists of oscillation-based tests, power supply current measurements and node voltage measurements. The approach comprises three separate phases.

In this paper, attention is paid to some aspects of oscillation-test methodology: orthogonalization of diagnostic process, fault coverage improvement and practical realization of microcontroller-based OBIST scheme.

Firstly, a step is made towards an orthogonal diagnostic process. In an orthogonal diagnostic process, each fault can be localized uniquely on the basis of measured symptoms. In order to achieve the orthogonal diagnostics a special attention is being paid to the design of oscillatory circuit.

Secondly, we come closer to the goal of 100% fault coverage. Combination of both frequency and time domain measurements are the key for improvement of fault coverage ratio. Two new measurands introduced in [13] are implemented in the testing scheme.

The proposed OBIST scheme employs the microcontroller-based test and measuring system which enables not only measurements of the oscillation frequency but also examination of variations in the amplitude step response parameters: rise time and steady-state error.

The scheme is dedicated to testing analog electronics assembled on a printed circuit board (PCB).

2. ANALOG CIRCUIT OBIST IMPLEMENTATION

2.1. Transformation of CUT to an oscillator

In some cases transformation of CUT to an oscillator can be done by minor circuit modification with additional switches [14]. More general approach is designing an external network that provides the required phase shift and gain to fulfil the Barkhausen criteria for oscillation. The external circuitry can be applied to CUT via the standard IEEE 1149.4 Mixed Signal Test Bus infrastructure [15].

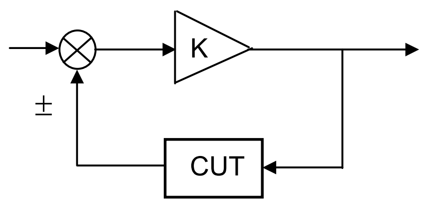

Fig. 1. Conversion of CUT into an oscillator.

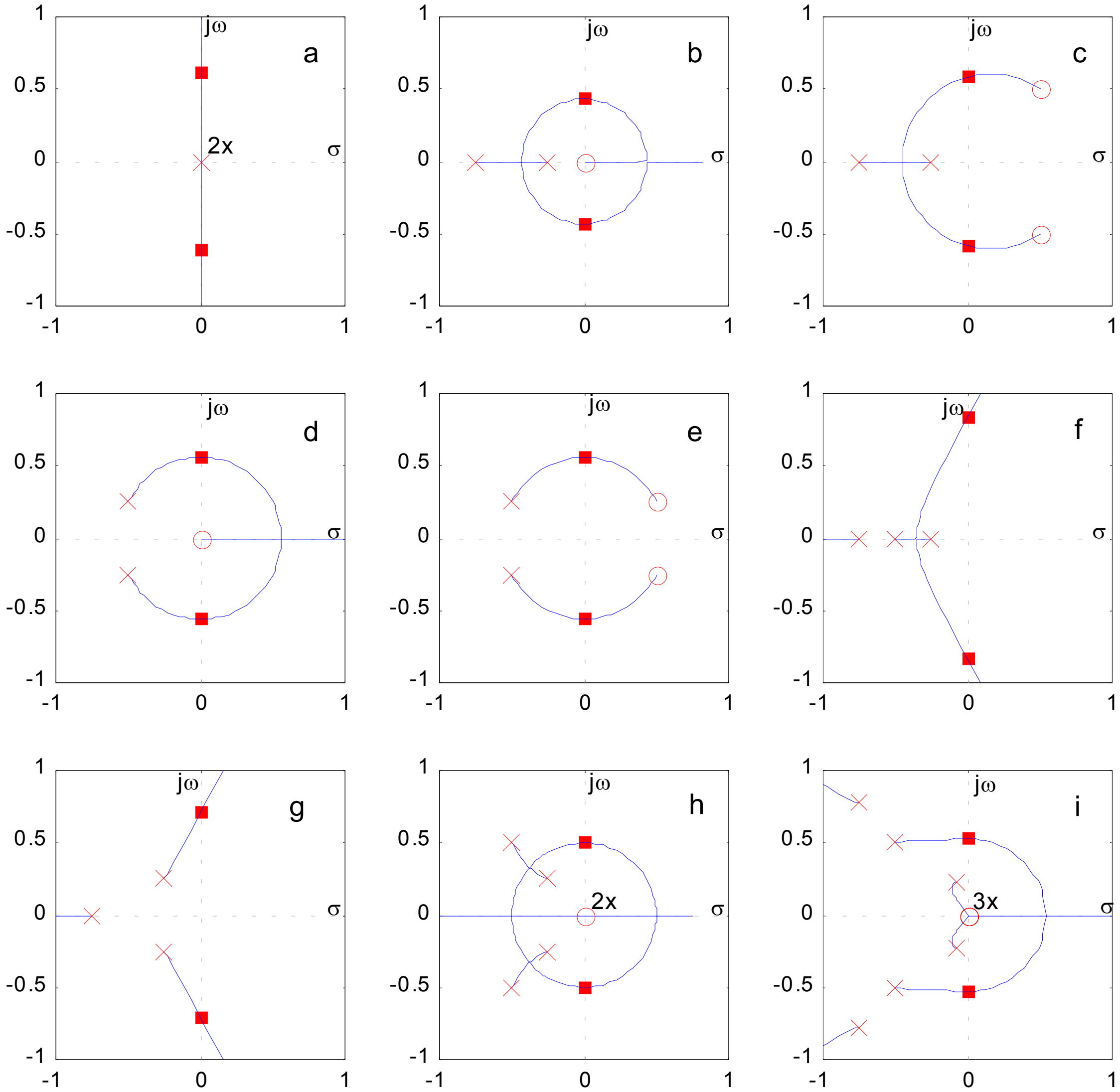

Fig. 2. The root loci of pole-zero patterns of some circuits under test that are transformed to an oscillator by inclusion in positive or negative feedback loop of an amplifier. (a) Cascade of two integrators in negative feedback loop. (b), (d) The second-order bandpass circuits in positive feedback loop. (c) A second-order bandstop circuit in negative feedback loop. (e) A second order allpass circuit in negative feedback loop. (f), (g) The third-order lowpass circuits in negative feedback loop. (h) A fourth-order bandpass circuit in positive feedback loop. (i) A sixth-order bandpass circuit in positive feedback loop.

At the highest level in the design of the oscillation-based test structures, characterisation of the CUT by its pole pattern and analysis of root locus is a very useful method. Consider the general form of the transfer function of the second, or higher-order, linear analog CUT

$$T_{CUT}(s) = \frac{K\prod_{i=1}^{m}(s - z_i)}{s^r \prod_{i=1}^{n-r}(s - p_i)} \qquad (1)$$

where: $m \le n$, z_i, p_i are zeros and poles respectively.

In order to force the CUT into harmonic oscillation with constant amplitude two complex conjugate poles must be placed on the imaginary axis on the s domain. The root locus method gives the designer a tool to make it easy to judge the possibility of putting the CUT into oscillation. For many pole-zero patterns a simple inclusion of CUT in the positive or negative feedback loop of an amplifier is sufficient (Fig. 1). Some of such, easily transformed to oscillator, second-order and higher-order pole-zero patterns are presented in Fig. 2. They are distinguished by the position of the poles (real or complex), and by the number of zeroes. It is shown, that in all cases depicted in Fig. 2 it is possible to drive the two poles of the CUT onto the imaginary axis, and therefore, to create a harmonic oscillator. The gain of amplifier required to place the poles onto the imaginary axis, as well as the frequency of oscillation, can be easy calculated with the aid of Routh array [13].

Taking a closer look at the root loci we can easily see that a way to bend the root locus of the two poles to the imaginary axis is to add one zero, two zeroes, or more poles to the pole pattern. From the fault localization point of view, the best strategy is to drive the root locus through the imaginary axis at an angle of 90 degrees. It is realized in the cases b, d, h, i, where zero or zeroes are placed at the origin and in the case e, where zeroes are placed symmetrically to poles. With this strategy, if the poles are near the imaginary axis, the loop causes them to move almost horizontally in the s-plane. That is, the frequency remains nearly constant as the damping changes. It is not true for pattern c, where location of zeroes is not correct and for patterns f, g, where due to the influence of the leftmost pole, two poles leave the real axis and cross the imaginary axis with a 30 degree angle.

Perpendicularity of the root locus and the imaginary axis is the main canon of oscillator design in our approach. It assures orthogonality of symptoms of those faults that have an effect on frequency, and those ones that exert influence on damping.

2.2. The provision of time domain measurements

In order to increase fault coverage, additional features of generated signal, for example amplitude, should be measured. Unfortunately, in any practical oscillator, output waveform is determined by non-linearities of some device, usually by the voltage saturation of the operational amplifier or by the slew rate. Non-linear bounding of the amplitude implies its small diagnostic sensitivity with respect to the parametric faults of the linear elements and contributes to harmonic distortion in the output waveform. The solution is using an amplitude stabilization loop that keeps the amplitude level in a linear region of CUT with greatly limited distortion, and without loss of diagnostic information contained in the signal.

The same stabilization loop can serve as the test and measuring system that measures frequency of generated signal and parameters of the time domain response. Fig. 3 illustrates the impulse and step response of the amplitude of oscillator created from the band-elimination circuit. Impulse response is monitored when oscillations are induced. Step response of the oscillator output is observed after change the value of setpoint.

For testing purposes, rise time of the stabilization loop impulse response or settle time of step response, as well as steady-state error can be measured. Rise time is taken as the time from 10% of the final value of the response, to when it achieves 90% of its final value (Fig. 4). The steady-state error is the difference between the demand input and the steady-state output.

The measuring system can be arranged as digital amplitude control loop. The analysis and design of digital controller is best performed by the z-transform representation. For this representation, s-plane pole pairs lying on the imaginary axis correspond to z-plane poles on the unit circle. In Fig. 5 representation in the z-plane of the second-order allpas circuit included in the negative feedback loop (from Fig. 2 e) is depicted.

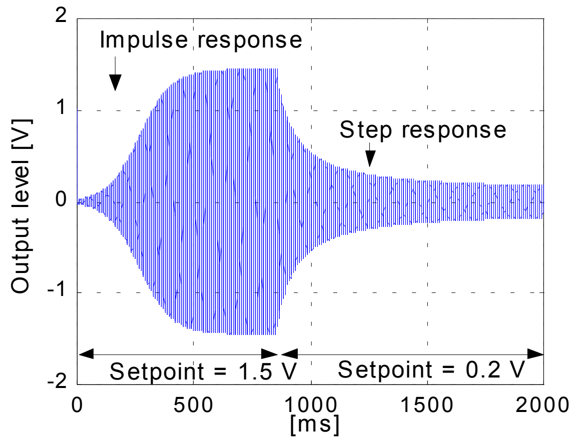

Fig. 3. Impulse and step responses of the amplitude of the band-elimination circuit transformed to oscillator.

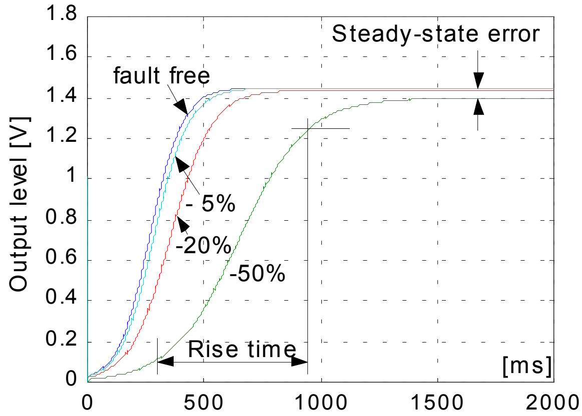

Fig. 4. Impulse response of the stabilization loop under fault-free and fault-producing conditions of element that has influence on damping (resistor R1 from Fig. 8). "–50%" means fifty percent deviation of resistance from its nominal value.

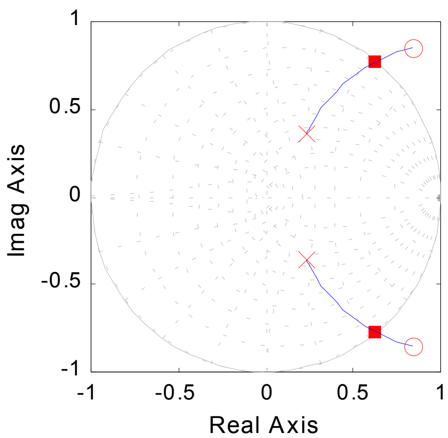

Fig. 5. Representation in the z-plane of the second order allpass circuit in negative feedback loop (compare Fig. 2 e). The unit circle corresponds to the s-plane imaginary axis.

2.3. Implementation in microcontroller

Fig. 6 shows a general scheme of the proposed OBIST. It consists of microcontroller, the amplitude detector (DET), analog to digital converter (A/D) and a four–quadrant multiplying digital to analog converter (D/A) arranged as a programmable amplifier/attenuator. The role of OBIST is twofold: to perform the digital automatic amplitude control and to measure frequency of generated signal and timing parameters of the impulse and step responses.

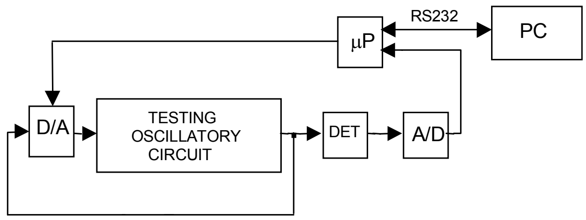

Fig. 6. General OBIST scheme.

Atmel AVR AT90S8515 microcontroller was applied. It has got several features allowing to create an efficient embedded system. High performance RISC architecture is fast and oriented for programming in high-level languages (C compiler has been used). High throughput is achieved at low clock speed, due to the fact, that instructions are mostly executed in one clock cycle. Program code is stored in internal 8k bytes of In-System Programmable (ISP) Flash ROM. The ISP brings possibility of rapid program code development without need of dissembling and assembling the µC from PCB – program code is downloaded to µC simple by a four-line interface connected to PC's parallel port. The internal 512 bytes of SRAM are sufficient for holding all the application data. Consequently, no external memory components are used and taking into consideration the high throughput at low clock rate (4Mhz oscillator is used) the emission of EMC by high-speed memory bus is avoided. Software-realized, parallel buses perform the communication with ADC and DAC, limiting the bus traffic to minimum. The on chip timer peripherals are used to measure period of oscillations, and indirectly – frequency.

In control mode microcontroller performs the following cycle of operations:

- It forms the error signal by subtracting the detector output from the value of setpoint (Fig. 7).

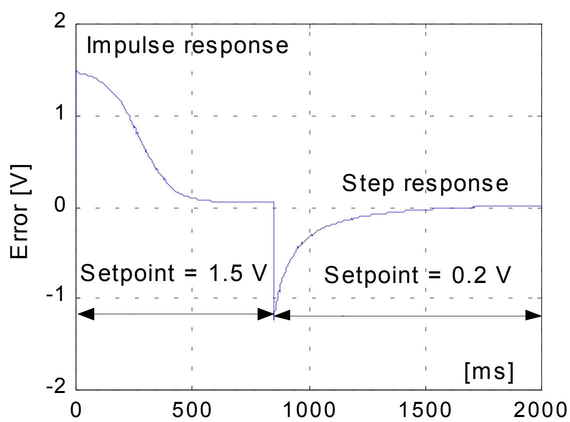

Fig. 7. An example of the error signal.

- It performs a calculation, based on the error value, to work out what its output should now be. In order to keep the diagnostic information contained in the amplitude steady-state error.
- It outputs and maintains that value until the next one is calculated.
- It waits for sampling interval timer to expire before restarting the cycle by forming the error signal again.

Sampling interval has been assumed fixed and equal to the oscillator period.

Although the controller module performs all the tasks in stand alone mode, it has the RS232 serial interface to communicate with PC. The virtual instrument on PC, build with LabWindows/CVI, performs the function of human-OBIST interface. It offers possibility of setting controller's coefficients, step stimulus parameters, controlling the system's behaviour, acquiring the impulse and step responses, visualising and post processing acquired data, saving and printing data and many more.

3. EXAMPLE OF APPLICATION

The second-order band-elimination (notch) filter (Fig. 8) has been used as test vehicle to examine the efficiency of the realised OBIST scheme.

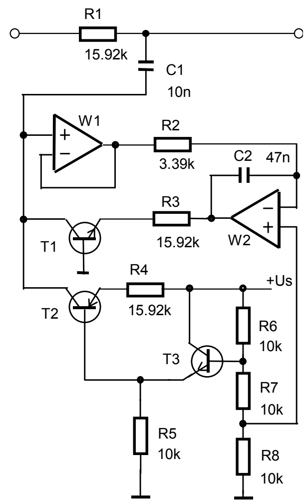

Fig. 8. A band-elimination (notch) filter under test.

3.1. Oscillation-based test structure

The input/output behaviour of filter is represented by a second-order transfer function model. Standard form of the notch filter transfer function possesses tree parameters: angular frequency ω_0, and two quality factors: Q_z in numerator and Q in denominator. For ω_0 normalized to 1 we have

$$T(s) = \frac{s^2 + (1/Q_z)s + 1}{s^2 + (1/Q)s + 1} \tag{2}$$

Fig. 10 a illustrates the pole-zero pattern of *T(s)*. It consist two poles and two zeroes located in a short distance to imaginary axis.

The band-elimination circuit can be converted into an oscillator by inclusion in negative feedback loop of the operational amplifier and then application of the outer positive feedback loop (Fig. 9).

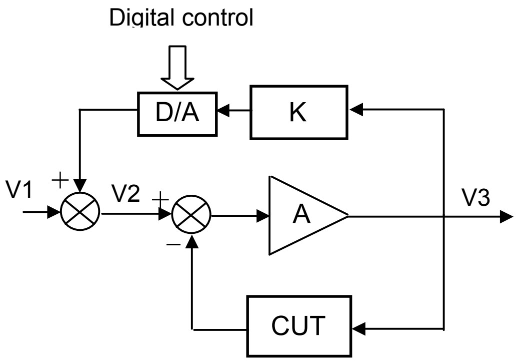

Fig. 9. Multiloop oscillation-based test structure for band–elimination filter under test.

A part of the structure encircled by the inner negative feedback loop possesses transfer function

$$T_1(s) = \frac{V3}{V2} = \frac{A[s^2 + (1/Q)s + 1]}{s^2 + (1/Q)s + 1 + As^2 + A(1/Q_z)s + A} \quad (3)$$

According to very high amplification factor A of operational amplifier, (3) can be reduced to the form

$$T_1(s) = \frac{s^2 + (1/Q)s + 1}{s^2 + (1/Q_z)s + 1} \quad \text{for A} \to \infty \quad (4)$$

Pole-zero pattern of transfer function (4) is presented in Fig. 10 b. It can be seen that poles and zeroes interchange their positions.

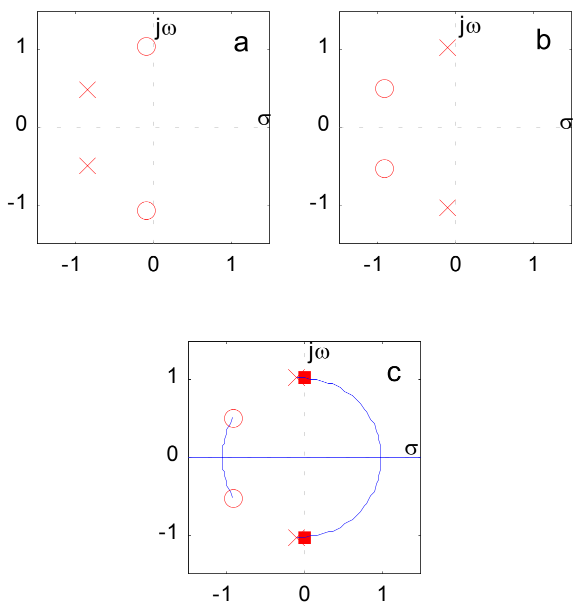

Fig. 10. Pole-zero patterns; a) filter under test, b) filter under test included in negative feedback loop of the operational amplifier, c) root locus of the test structure depicted in Fig. 9.

Because of short distance between poles and imaginary axis, additional positive feedback loop with low tranfer factor K is required to push the poles of (4) onto the imaginary axis. By selection of the value of $K = \frac{Q}{Q_z}$ the coefficient of the term s in the denominator of overall transfer function is forced to zero. Finally, the transfer function of the test structure depicted in Fig. 9 is given by

$$T_2(s) = \frac{V3}{V1} = \frac{Q_z}{(Q_z - Q)} \frac{s^2 + (1/Q)s + 1}{(s^2 + 1)}. \quad (5)$$

A digitally controlled attenuator was used to regulate the output amplitude by adjusting an outer feedback loop transfer factor. The magnitude and sign of this feedback are determined by microcontroller. When the amplitude of the oscillation is too low, it can control feedback transfer factor such that the poles of the circuit are pulled to the right half plane for a short time (Fig. 10 c), so that the amplitude of the oscillation can increase. When the oscillation amplitude is too high, it can control the feedback transfer factor to pull the poles to the left half plane.

3.2. Eksperimental results

In order to determine the fault coverage, both catastrophic faults (shorts and opens) and parametric faults (50% of deviations from the nominal value in both directions, introduced for passive components of CUT) have been injected to the circuit under test. The majority of injected catastrophic faults resulted in the absence of oscillations and therefore can be immediately detected. The injected parametric faults cause deviation of measured parameters: (a) frequency, (b) impulse response rise time, (c) amplitude level steady-state error.

TABLE 1. Deviation of measured parameters (symptoms) for the injected parametric faults in the CUT; (a) oscillation frequency, (b) impulse response rise time, (c) amplitude level steady-state error.

Fault	Deviation of parameter		
50%	a %	b %	c mV
R1↓	0	+108,3	-118
R1↑	0	-35,8	+34
R2↓	+41,4	-52	0
R2↑	-18,4	+45,8	0
R3↓	+41,4	-52	0
R3↑	-18,4	+45,8	0
R4↓	0	0	-76
R4↑	0	0	+30
C1↓	+41,4	0	0
C1↑	-18,4	0	0
C2↓	+41,4	-52	0
C2↑	-18,4	+45,8	0

As the results presented in Tab. 1 indicate, the fault coverage can be considerably increased by combining frequency (a) and time domain (b, c) measurements. In example, frequency measurements alone give results in 66% coverage of considered set of faults. Combined measurements result in a full fault coverage.

One can observe that measured parameters (symptoms) have different diagnostic sensitivity with respect to the different faults. For example, faulty capacitor C1 exerts an influence on frequency only. On the other hand, faulty resistor R4 has an effect on steady-state amplitude level only. When resistor R1 is perturbed, the frequency remains constant, as the time domain parameters change. Each faulty element from the set: R2, R3, C2 shifts both the frequency of oscillation and impulse response rise time, but does not change the amplitude level steady-state error. Such orthogonality of symptoms is favourable for fault isolation.

4. CONCLUSIONS

The presented oscillation built-in self-test with amplitude stabilization loop is capable of performing frequency and time domain measurements. Monitoring the response of the stabilization loop provides more diagnostically relevant information than it is obtainable with the method exploiting only frequency measurements. The goal of extended measurements is to improve the fault coverage and fault localization capability.

The authors have developed canonical rule for the design of oscillation-based test structure. The rule states that perpendicularity of root locus and imaginary axis is the best strategy for facilitation of the fault isolation process.

Microcontroller implementation of OBIST has a number of advantages: in particular, microcontroller technology becomes cheaper as well as faster all the time and the major costs of digital implementation are in software development. The restrictions of the approach are mainly connected with the limited speed of the microcontroller-based implementation.

A prototype realization of the proposed OBIST was demonstrated to perform testing on the band-elimination filter example with increased fault coverage and some possibilities of fault isolation.

Presented results validate the design of the oscillatory circuit and BIST scheme. It has possibility of application for production testing of the assembled PCB as well as for diagnostics testing in the field.

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