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OSCILLATION BASED DIAGNOSIS IMPLEMENTATION IN ACTIVE RC NOTCH FILTERS

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Abstract – *The Oscillation Based Testing (OBT) method represents an effective and simple solution to the testing problem of discrete continuous time analog electronic filters. Here for the first time diagnosis based on OBT will be described. It will be referred to as OBD. Fault dictionary was created and based on it, diagnosis was performed using artificial neural networks (ANNs). The implementation of the new concept will be demonstrated by testing and diagnosis of a second order notch cell realized with one operational amplifier. Single soft and catastrophic faults are considered with more detail while double soft faults are exemplified only.*

1. INTRODUCTION

One of the fundamental problems in analog testing is the synthesis of the test signal. One has to choose among virtually unlimited possible variants. Analog testing may be done by DC signals, in the frequency domain, and in the time domain. Of course, if necessary, test signals from several domains may be used simultaneously. The DC signals are usually checking for fault effects related to the quiescent conditions and nonlinearities, while in the frequency domain one has to find the spectrum of the testing signal in order to activate the fault effect. In the time domain one is to search for a signal waveform or several of them that will enable testing in the shortest possible time so optimizing the production and decreasing the price of the product.

On the other side one may observe the problem of response measurement. Namely, it is always a question as to how many test (measurement) points are needed and which quantities are to be extracted as a favourable measure of the state of the circuit.

There exists, however, a technique that needs no test signal. It is known as the oscillation based testing (OBT) [1]. The basic idea behind this powerful method is to create a redundant feed-back loop that is to be activated during testing only. By measurement of the output signal and by comparison with the response of the fault-free circuit, one may conclude whether there are defects in the circuit or not. Note, while usually one creates test signals targeting specific faults, here all possible defects are targeted with only one measurement that makes OBT very effective.

The implementation of OBT depends on the very circuit under test. The main reason for that is the necessity to create an oscillator out of a given circuit. That is one of the difficulties related to the implementation of the method. In addition, some of the faults, especially the soft ones, create fault effects that are not easily discernible. Moreover, while mainly the number of test points is reduced to one, the oscillator's output, the problem of measurement is still not fully solved since one has to decide which and how many parameters of the response are to be extracted. Finally, the method needs to bring the oscillator into a steady state what frequently slows down the testing process.

To the authors best knowledge no implementation of the OBT method for diagnosis was published in the literature.

In this paper we describe our experience on implementation of the OBT for testing and, for the first time, in diagnosis (OBD) the second order notch cell of discrete analog active filters. This cell is the most frequently used one when cascade synthesis of active filters is considered. Hence the importance of the case study.

A fault dictionary will be created by simulation. Discrete operational amplifiers available on the market will be implemented. An exhaustive list of single faults and a list of most probable double faults will be used. The problem of feed-back circuit synthesis will be solved in the simplest manner.

2. THE OSCILLATION BASED TESTING METHOD

When proper feed-back circuit is added to an analog building block one may create an oscillator. By measuring the output voltage (or some other responses) of that circuit one may extract quantities, such as the oscillation frequency, the amplitudes of the first and other harmonics, the DC value of the output voltage, etc. that may contain information on the presence of a fault in the circuit. Main advantage of this method is avoidance of the search for input stimuli and appropriate mode of operation of the circuit; independence of the type of faults that provoke the circuit's malfunction (soft or catastrophic); and simplified selection of the test point and measured quantity at the output [1], [2], [3], [4].

As a case study for implementation of the OBT, the Sallen-Key non-inverting second order notch filter cell will be used. The schematic of the cell is depicted in Fig. 1 [5].

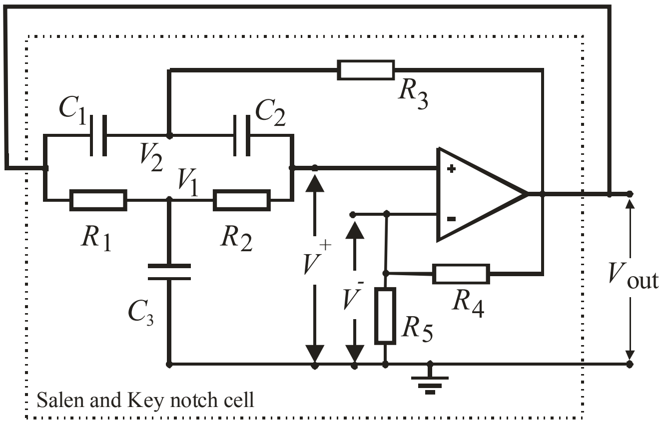

Fig. 1. *RC oscillator based on the Notch filter cell*

The oscillator circuit so obtained is depicted in Fig. 1. The fault free circuit will oscillate at f_0. When defects are present one may observe three different situations: a) The faulty circuit oscillates at f_0, b) the faulty circuit oscillates at some other frequency $\hat{f}_0$, and c) there are no oscillations in the circuit. The testing will be successful if there is any difference between the oscillating frequencies and if there are no oscillations. Unfortunately, that is not enough for diagnosis. One needs distinctive information in order to create the diagnostic hypothesis.

When parametric faults are considered, the oscillator is treated as a linear circuit so one may use the usual oscillator analysis method to get the expected oscillation frequencies. Namely, by writing the modified nodal equations [6] for the circuit of Fig. 1, and equating the system determinant to zero, after separating the real and imaginary part, one obtains the following two expressions for the possible oscillation frequencies:

$$\omega_0{}^2 = \frac{A-1}{(A-1)C_3(R_2R_3C_2 + R_1R_3C_2 + R_1R_2C_1) - R_1R_3C_1(C_2 + C_3)} \quad (1)$$

and

$$\omega_0{}^2 = \frac{R_2C_3 + R_1C_3 + R_3C_2 + R_3C_3 - \dfrac{R_1C_1}{A-1}}{R_1R_2R_3C_1C_2C_3}, \quad (2)$$

where $A = k = 1 + R_4 / R_5$. One of these expressions is usually required for frequency calculations while the other is needed to find the necessary value of A for sustained oscillation.

The above expressions were derived under condition that the operational amplifiers are ideal with infinite gain which is not true in a real circuit. This is important since the closed-loop-gain of the oscillator circuit is characterized by both modulus and phase. Both are frequency dependent and fundamentally determine the oscillation frequency. The operational amplifier's phase shift becomes of main importance in this situation and has to be taken into account. So, the expressions given by (1) or (2), may be used as reference only. This will be shown after experiments with simulation are performed. It is worth mentioning that the need to include the operational amplifiers phase shift was earlier mentioned in the literature [7]. The idea was, however, implemented in the frequency domain and led to conclusions quite different than the ones we are reporting here.

3. FAULT SIMULATION

Our goal is to create a fault dictionary that is a table containing faults and fault effects. To get it a large number (As large as the number of defects conceived in advance is.) of repetitive simulations is to be performed. For every simulation a fault is to be inserted in the original oscillator circuit so creating a new oscillator. Note that simulation of an oscillator is not a straightforward task since one usually implements an A-stable integration rule (such as Euler-backward) for solving the differential equations of the oscillator [6]. Here however, since the circuit is unstable, one needs to use an integration rule that is not A-stable.

For correct simulation one needs to use a complete schematic of the operational amplifier or a qualified model that performs well from the phase-shift point of view. To illustrate how successful the modelling of the phase difference inserted by the operational amplifier is, the simulation results for a fault free circuit (oscillator) are depicted in Fig. 2. Two signals are drawn, the operational amplifier input (non-inverting terminal) and its output. We can deduce from the simulation that a phase shift is 12.3^o.

The defects here are categorized in several groups:

- Catastrophic defects within the RC circuit.
- Parametric defects within the RC circuit.
- Separate examples of multiple parametric defects.

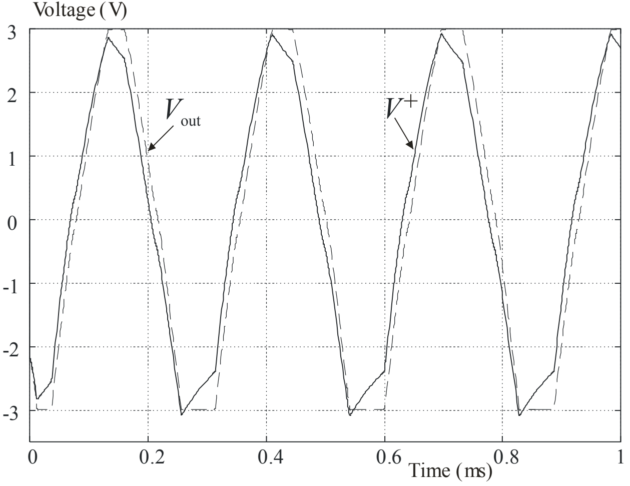

Fig. 2. *Responses of the fault free oscillator of Fig. 1 demonstrating the phase shift introduced by the op-amp*

A table containing a set of faults and the corresponding responses of the system is referred to as fault dictionary. These are important not only for testing but also for diagnostic purposes. Since the number of possible faults in a system may be very large, when creating the fault dictionary, one generally chooses a set of most probable faults. If so, one claims that the structured approach to testing is applied. Search through the fault dictionary, in general, enables fault coverage to be established and the test signal to be qualified.

For every passive element within the RC circuit short- and open circuit is considered as a catastrophic fault. After insertion, the resulting schematic was simulated and the results are shown in Table 1. The resistors in the negative feed-back circuit were chosen to be R_4=2kΩ, and R_5=20kΩ, leading to a gain A=1.1.

Table 1. Catastrophic defects (SC stands for: short circuit. OP stands for: open circuit. NO stands for: no oscillations)

No.	*Defect type*	*Element value*	*Oscillating frequency* (kHz)
1	Fault free		3.5
2	SC: R_1	R_1=0 Ω	NO
3	SC: R_2	R_2=0 Ω	42.167
4	SC: R_3	R_3=0 Ω	2.167
5	OP: R_1	R_1=∞ Ω	3.167
6	OP: R_2	R_2=∞ Ω	NO
7	OP: R_3	R_3=∞ Ω	3.333
8	SC: C_1	C_1=∞ F	2.833
9	SC: C_2	C_2=∞ F	2.167
10	SC: C_3	C_3=∞ F	2.4
11	OP: C_1	C_1=0 F	NO
12	OP: C_2	C_2=0 F	NO
13	OP: C_3	C_3=0 F	NO

The first experiment was creation of a fault dictionary for the catastrophic faults. To get the „oscillating frequency" f_0, simulation of the oscillator with the fault inserted was performed. The results are shown in Table 1. By comparison of the first and the rest of the rows in Table 1 one may conclude that one may get almost perfect fault coverage of catastrophic faults making this method convenient for testing.

Table 2. Parametric defects

No.	*Defect type*	*Oscillating frequency* (kHz)
1	$1.2 \cdot R_1$	3.5
2	$0.8 \cdot R_1$	3.5
3	$1.2 \cdot R_2$	3.166
4	$0.8 \cdot R_2$	4
5	$1.2 \cdot R_3$	3.5
6	$0.8 \cdot R_3$	3.5
7	$1.2 \cdot C_1$	3.333
8	$0.8 \cdot C_1$	3.667
9	$1.2 \cdot C_2$	3.333
10	$0.8 \cdot C_2$	3.833
11	$1.2 \cdot C_3$	3.333
12	$0.8 \cdot C_3$	3.667

Here, a parametric defect will be seen when the element value within the RC-circuit is changed for 20% in comparison to its nominal value. Both positive and negative changes are taken into account. Table 2 contains the faults and the fault effects for all conceived soft faults in the RC-circuit. Here similar conclusion stands as for Table 1.

The possible number of double soft defects is much larger than in the case of the single faults. This is why a reduced set of pairs of soft faults was considered as shown in Table 3. One may observe that in 10 out of 12 cases the faulty circuit exhibits new value for f_0. In five cases the change in the frequency value is also small (4.8%).

Table 3. Two defects present simultaneously

No.	*Defect type*	*Oscillating frequency*(kHz)
1	$1.2 \cdot C_2$; $1.2 \cdot C_3$	3.167
2	$0.8 \cdot C_2$; $0.8 \cdot C_3$	4
3	$1.2 \cdot C_2$; $0.8 \cdot C_3$	3.5
4	$0.8 \cdot C_2$; $1.2 \cdot C_3$	3.667
5	$1.2 \cdot R_1$; $1.2 \cdot C_1$	3.333
6	$0.8 \cdot R_1$; $0.8 \cdot C_1$	3.667
7	$1.2 \cdot R_1$; $0.8 \cdot C_1$	3.667
8	$0.8 \cdot R_1$; $1.2 \cdot C_1$	3.5
9	$1.2 \cdot R_2$; $1.2 \cdot C_2$	2.833
10	$0.8 \cdot R_2$; $0.8 \cdot C_2$	4.333
11	$1.2 \cdot R_2$; $0.8 \cdot C_2$	3.333
12	$0.8 \cdot R_2$; $1.2 \cdot C_2$	3.833

When evaluating the OBT approach implemented to the notch filter cell we have to consider the following. First of all, no test signal was needed to be found. That is a big advantage for the test engineer. Second, only one test point was observed i.e. the circuits output, what is the most natural way of access for measurement. Finally, only one quantity was extracted as a measure of fault coverage: the oscillation frequency. With such a simple procedure a waste number of faults was covered that leads to a conclusion that the OBT method, for this example, is an excellent testing concept.

4. FAULT DIAGNOSIS

In the previous text we considered testing and fault coverage, and the only important issue was if there existed fault coverage or not. When we come to the diagnosis matter, the previous fault dictionaries are not satisfactory for generation of diagnostic statements since oscillating frequencies are the same for groups of several defects, so we cannot make distinction among the defects that are to be identified based on these data.

The idea in this paper is to demonstrate how these defects can be diagnosed using ANNs. This, first, brings in fore an important aspect of diagnosis, the number and location of the test points. Simply, we can say that internal test points should be avoided and measurements on the primary inputs and outputs are preferred. This is not only related to their automatic accessibility but also to the nature of the diagnostic reasoning. Namely, one looks for functionality to diagnose something, and the function is seen at the primary terminals.

So, keeping the circuit‘s output as the only measured quantity we tried to get some additional parameters of the output signal that can be extracted from the same measurement, and by inspection, we found two: total harmonic distortion (*THD*) and DC output voltage (*DC Vo*).

Table 4. The fault dictionary

Fault code	*Defect type*	*Oscillating frequency*(kHz)	*DC Vo* (V)	THD (%)
0	Fault free	3.5	0.025	6.88
1	$1.2 \cdot C_1$	3.333	0.0073	7.69
2	OP: C_2	NO	-0.007	NO
3	SC: R_3 SC: C_2	2.167	-0.297	21.41
4	$0.8 \cdot R_2$; $0.8 \cdot C_2$	4.333	-0.017	7.64
5	SC: R_2	42.167	-0.687	7.37
6	$0.8 \cdot R_2$; $1.2 \cdot C_2$	3.833	0.0335	6.98
7	SC: C_1	2.833	0.0138	12.37
8	$1.2 \cdot R_1$; $0.8 \cdot C_1$	3.667	-0.112	6.04
9	$0.8 \cdot R_3$	3.5	-0.07	5.82
10	$1.2 \cdot R_1$; $1.2 \cdot C_1$	3.333	-0.06	7.76
11	OP: C_3	NO	-0.541	NO
12	$1.2 \cdot R_2$	3.166	-0.146	20.94
13	$0.8 \cdot C_2$; $0.8 \cdot C_3$	4	-0.032	5.71
14	$1.2 \cdot R_2$; $1.2 \cdot C_2$	2.833	0.079	12.4
15	SC: R_1 OP: R_2 OP: C_1	NO	-3.3	NO
16	$1.2 \cdot R_1$	3.5	-0.017	6.93
17	SC: C_3	2.4	-0.591	24.78
18	$0.8 \cdot C_1$	3.667	-0.028	6.52
19	$0.8 \cdot C_2$; $1.2 \cdot C_3$	3.667	0.017	6.27
20	$0.8 \cdot R_1$; $1.2 \cdot C_1$	3.5	-0.005	6.78
21	$1.2 \cdot C_2$	3.333	-0.057	8.07
22	$0.8 \cdot R_1$; $0.8 \cdot C_1$	3.667	-0.037	5.8
23	$1.2 \cdot R_2$; $0.8 \cdot C_2$	3.333	-0.0086	8.55
24	OP: R_1	3.167	0.054	9.93
25	OP: R_3	3.333	-0.022	7.68
26	$1.2 \cdot C_2$; $0.8 \cdot C_3$	3.5	-0.0061	6.74
27	$1.2 \cdot C_2$; $1.2 \cdot C_3$	3.167	-0.048	11.09
28	$0.8 \cdot R_2$	4	-0.0027	6.03
29	$0.8 \cdot C_2$	3.833	0.024	6.21
30	$0.8 \cdot R_1$	3.5	0.014	6.97
31	$1.2 \cdot R_3$	3.5	-0.022	7.03
32	$0.8 \cdot C_3$	3.667	0.059	7.48
33	$1.2 \cdot C_3$	3.333	-0.071	7.69

We created a merged fault dictionary (Table 4) including defects from the previous tables, containing two more columns with values of parameters *DC Vo* and *THD*. From the Table 4 we can deduce that values for *DC Vo* and *THD* have different values for different faults, so the diagnosis is possible. Also, from the Table 4 we can notice that some defects have the same values for *DC V*o and *THD* (defects from the groups 3 and 15). These groups of defects are referred to as ambiguity groups or functionally equivalent faults (FEF). Here, we can say that an ambiguity group consists of a set of *faults* that propagate identical signatures to the output, making the faults detectable and the circuit testable, but no distinction between the individual faults is possible making them undiagnosable.

The first column of the Table denotes the Fault code (m). In general, faults are coded randomly, so that faults with similar effects are unlikely to have similar codes, and if that happens, the codes are reordered in order to make bigger distinction. This approach is proven to be good, because the way of coding influenced the training time, and also, the training error.

With two pieces of data for each fault, the neural network input structure was restricted to two input terminals. The ANN diagnoses the fault by outputting the fault-code as a signal level, so we needed only one output neuron. The number of hidden neurons, n, was found by trial and error after several iterations starting with an estimation based on that in [8]. The goal was to find the optimum n that leads to a satisfactory classification. Using too many neurons would increase the training time, but using too few would starve the network of the resources needed to solve the problem. Also, an excessive number of hidden neurons may cause the *overfitting* problem [9], when a network has so much information capability that it learns insignificant aspects of the training sets, irrelevant to the general population. In practice, 36 hidden neurons were used.

The effectiveness of the training process of the obtained ANN was verified by exciting the ANN with faulty inputs. Responses of the ANN show that there were no errors in identifying the faults what is partly presented in Table 5. The ANN response was considered to be correct when its value was in the range [(m-0.5), (m+0.5)]. We can see that all faults can be diagnosed successfully.

Table 5. ANN responses-partly presented

Fault code	*Defect type*	*ANN response*
0	Fault free	0.153
2	OP: C_2	2.03
5	SC: R_2	4.992
7	SC: C_1	6.985
10	$1.2 \cdot R_1$; $1.2 \cdot C_1$	9.741
13	$0.8 \cdot C_2$; $0.8 \cdot C_3$	13.027
18	$0.8 \cdot C_1$	17.907
20	$0.8 \cdot R_1$; $1.2 \cdot C_1$	19.97
22	$0.8 \cdot R_1$; $0.8 \cdot C_1$	22.13
24	OP: R_1	23.926
26	$1.2 \cdot C_2$; $0.8 \cdot C_3$	25.98
30	$0.8 \cdot R_1$	30.049
33	$1.2 \cdot C_3$	32.73

5. CONCLUSION

Implementation of the oscillation based method to diagnosis was introduced for the first time. It was referred to as the oscillation based diagnosis. The method was implemented on the second order Sallen and Key notch cell. Minimum number of test points and, accordingly, measurements were used: just the output terminal. The measured output signal was processed in order to obtain the following parameters: frequency of the first harmonic, total harmonic distortions, and the DC voltage at the output. These were used for creation of fault dictionaries. The latter were memorized as artificial neural networks. Diagnosis was performed by running the neural network after measurement of the faulty circuit. It was shown that OBD may be successfully used for diagnosis of the notch cell.

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Abstract – Metod testiranja oscilacijama (OBT) predstavlja jednostavno i efikasno sredstvo za testiranje diskretnih analognih električnih filtara. Ovde će po prvi put biti opisana dijagnostika istih kola zasnovana na oscilacijama - OBD. Kreirani su rečnici defekata i na osnovu njih ostvarena je dijagnostika pomoću veštačkih neuronskih mreža (ANNs). Primenjeni koncepti demonstrirani su na sekciji drugog reda filtra prigušnika opsega frekvencija koji je realizovan sa jednim operacionim pojačavačem. Uzeti su u račun meki i tvrdi defekti s tim što je razmatran i skraćeni skup dvostrukih defekata.

PRIMENA METODA OSCILACIJA ZA DIJAGNOSTIKU AKTIVNOG FILTRA PRIGUŠNIKA OPSEGA

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