Frequency Domain Fault Analysis of Low Sensitive BP Active Filter Structures

Dražen Jurišić and Neven Mijat

Faculty of electrical engineering and computing Zagreb
Unska 3, Zagreb, 10000, Croatia

Abstract -**This paper presents a fault location technique for testing analog filters using a fault dictionary. It is applied to various band pass (BP) active filter structures. Sensitivity analysis, and fault analysis is done for each structure, and a correspondence between the sensitivity and testability of different structures is investigated. It is shown that the structures with lower sensitivities need more parameters for efficient fault analysis than the high sensitive structures. As an illustration the sensitivity analysis and fault analysis are performed for an eight order Chebyshev narrow band pass filter realised as cascade (CAS), Follow-the-Leader-Feedback (FLF), and cascaded biquarts (CBQ) and Leap-Frog (LF) structure.**

1. INTRODUCTION

If a component value in some circuit deteriorate outside its tolerance bounds producing a circuit failure, the fault isolation procedure can be carried out to locate the faulty element. The reliability of come fault isolation procedure depends on various parameters: method used, complexity of a circuit, circuit structure etc.

The procedure described in this paper creates a dictionary containing a set of predetermined faults [1]. Since it can be applied in the frequency domain, it is very suitable for testing analog filters. In order to examine its efficiency it is applied to various narrow BP active filter structures with the same transfer function. They differ in the connections between the basic filter blocks, making them more or less sensible to component variations.

The purpose of this paper is to find the possible relation between the sensitivities and the efficiency of the fault analyses of these filter structures. The results obtained from the illustrative examples show that the low sensitivities may cause lower feasibility to fault isolation.

2. SENSITIVITY OF ACTIVE FILTERS

2.1 Sensitivity measure

The component values in electrical circuits can deviate from their nominal values due to ageing, temperature, tolerances, etc. Sensitivity analysis gives the information about network function changes caused by small deviations of component values [3].

Given the network function $F(s, r_1, \ldots, r_n)$, where s is complex variable and r_k; $k=1, \ldots, n$ are real parameters, the relative function deviation $\Delta F/F$ due to single parameter value relative deviation $\Delta r_k/r_k$ in given by

$$\frac{\Delta F}{F} \cong S_{r_k}^{F} \cdot \frac{\Delta r_k}{r_k}\,, \tag{1}$$

where $S_{r_k}^{F}$ represents the relative sensitivity of a function F to single parameter r_k, and equals to

$$S_{r_k}^{F} = \frac{r_k}{F}\frac{dF}{dr_k} \tag{2}$$

If more than one component deviates from the nominal value, a criterion for assessing function deviation due to change of many parameters must be used. Let $\Delta r_k/r_k$ be independent normal random variables with zero means and identical standard deviations equal to σ_r. The squared standard deviation σ_F of relative function change $\Delta F/F$ can be represented as

$$\sigma_F^2 = \sigma_r^2 \sum_{k=1}^{n}\left(S_{r_k}^{F}\right)^2 = \sigma_r^2 S_2\,, \tag{3}$$

where S_2 is so called Schoeffler sensitivity defined as

$$S_2 = \sum_{k=1}^{n}\left(S_{r_k}^{F}\right)^2\,. \tag{4}$$

The Schoeffler sensitivity is a reliable measure for estimation of different circuits from the sensitivity point, and it is used in this paper.

2.2 Low sensitive active filter structures

Active high order transfer function BP filters are usually realised as mutually interconnected second-order blocks. The manner in which this connection is accomplished is denoted as a filter structure, and it influences the filter transfer function sensitivity [3]. Four most often used structures, i.e. Follow the Leader Feedback (FLF), Cascade of Biquartic (CBQ) sections, and Leap Frog (LF) structure are shown in Fig. 1.

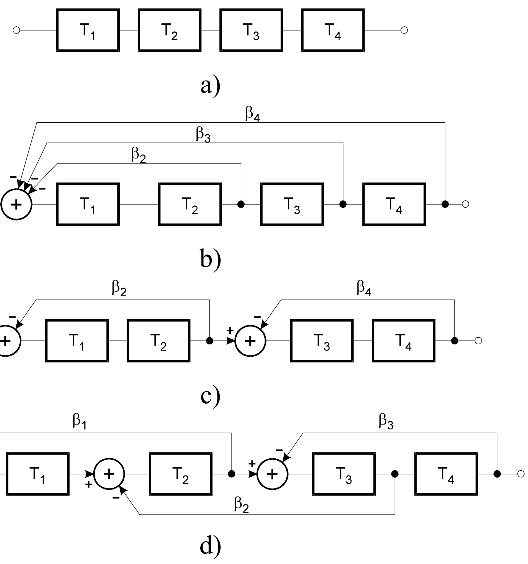

Fig. 1. a) CAS; (b) FLF; c) CBQ and d) LF structure

Second-order filter blocks used for the realization of above structures have the band pass transfer function

$$T_i(s) = \frac{k_i s(\omega_{pi}/Q_{pi})}{s^2 + s(\omega_{pi}/Q_{pi}) + \omega_{pi}^2}\;;\; i=1, \ldots, N, \tag{5}$$

where ω_{pi} is the transfer function pole frequency and Q_{pi} the pole Q- factor.

As an illustration an 8th order Chebyshev narrow band pass filter (bandwidth 0.1 and reflection coefficient 0.1) is realized by the structures form Fig. 1. Its transfer function magnitude $|F(j\omega)|$ [dB] is shown in Fig. 2. Normalised transfer function parameters are given in Table 1.

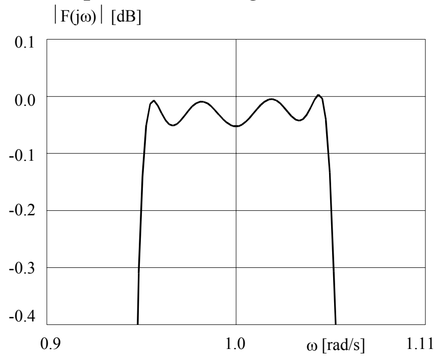

Fig. 2. Magnitude of narrow BP-filter

Table I Parameters of structures in Fig. 1.					
	i	Q_p	ω_p	k	β
CAS	1	13.202	0.9755	1.0000	
	2	13.202	1.0251	1.4274	
	3	31.919	0.9420	2.1733	
	4	31.919	1.0615	7.1188	
FLF*	1	18.665	1.0000	2.5933	0.0000
β_0=0.4582	2	18.665	1.0000	2.4669	0.8571
	3	18.665	1.0000	2.3572	0.2263
	4	18.665	1.0000	2.1840	0.1601
CBQ	1	13.198	1.0000	1.4482	
	2	13.198	1.0000	1.0363	0.2843
	3	31.862	1.0000	3.8230	
	4	31.862	1.0000	3.4848	1.0880
LF	1	9.357	1.0000	1.2085	0.8116
	2	∞	1.0000	0.07892*	0.7508
	3	∞	1.0000	0.08267*	0.6810
	4	9.307	1.0000	1.3737	

*Instead of k the value of $k\omega_p/Q_p$ is given

Second-order Transfer functions T_i; i=1, …,4 in (5) are realised by a general purpose (GP) section [8] shown in Fig. 3. The parameter definitions for that section are:

$$k = \frac{R_3}{R_1}\ ;\ \omega_p = \frac{R_6}{R_2 R_4 R_5 C_1 C_2}\ ;\ Q_p = R_3 C_1 \omega_p \qquad (6)$$

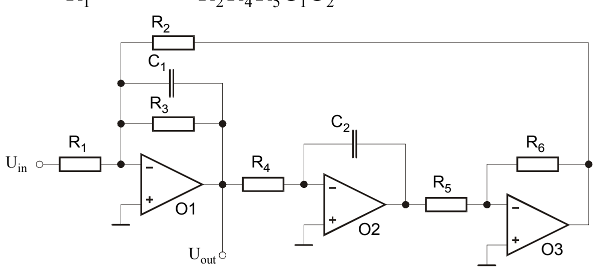

Fig. 3. GP section

Using (3) the standard deviation σ_F of the transfer function magnitude relative change $\Delta|F|/|F|$ is calculated [1, 2] assuming 1% standard deviations σ_r of passive elements relative changes $\Delta r_k/r_k$. The results are shown in Fig. 4. The influences of the feedback resistors to the overall sensitivities are not taken into consideration.

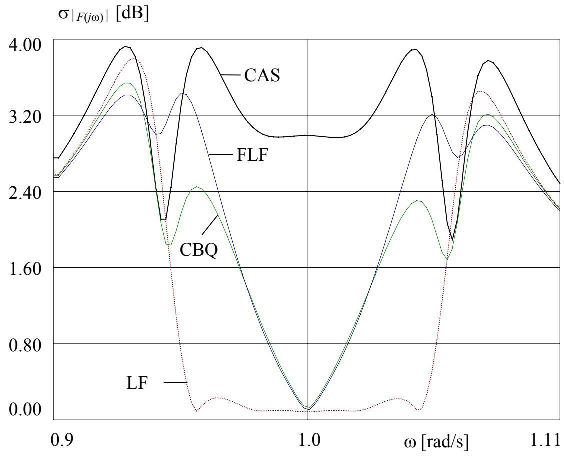

Fig. 4. Sensitivities of the structures from Fig. 1.

CAS structure has the worst sensitivity figure, while the structures with feedback loops have lower sensitivities. The LF structure gives the best results [3].

3. FAULT ISOLATION PROCEDURE

3.1 Categorisation of faults

By a fault one means a change of an element value, causing a circuit failure. It is catastrophic (*hard*) if the faulty element produces either a short or an open circuit. Otherwise, the fault is *soft*. One defective component produces a *single* fault [6]. Changes of several components produce *multiple* fault. The presented method deals with single hard faults of passive filter elements.

3.2 The technique for fault location using fault dictionary

The first step in fault isolation is fault definition [1]. In the early Seshu and Waxmann approach [7] +50% and -50% element changes are considered as the open and short circuits, denoted as for example R_1+ and R_1-.

In the presented example the magnitude is calculated in 100 discrete logarithmically spaced frequencies from 0.9 to 1.1 rad/s, denoted by numbers 0, …,99. Since it is expensive to carry out procedures in 100 frequency points, a subset of test frequencies for the initial fault dictionary can be chosen according to some optimisation criterion. As the initial set the following 14 test frequencies are chosen: 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90. Fig. 5 shows the influence of the ±50% deviation of the resistor R_1 in the first LF block to the filter magnitude.

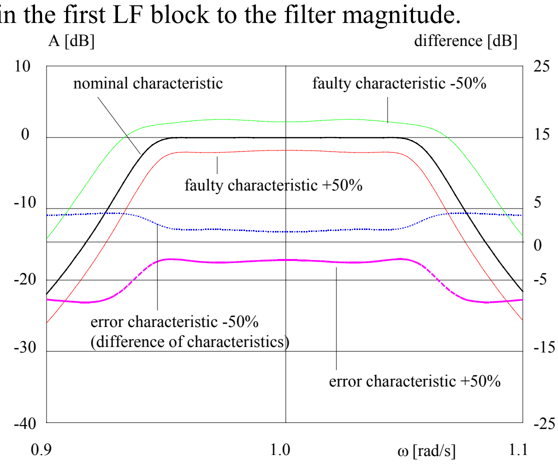

Fig. 5. Effects of ±50% change of R_1 in the 1st LF block

More or less similar influence have all other passive elements in the same block, as well as in other blocks. The error functions, i.e. the differences between faulty and nominal responses for +50% deviations of passive elements in the first filter blocks in all structures are shown in the Fig. 6.

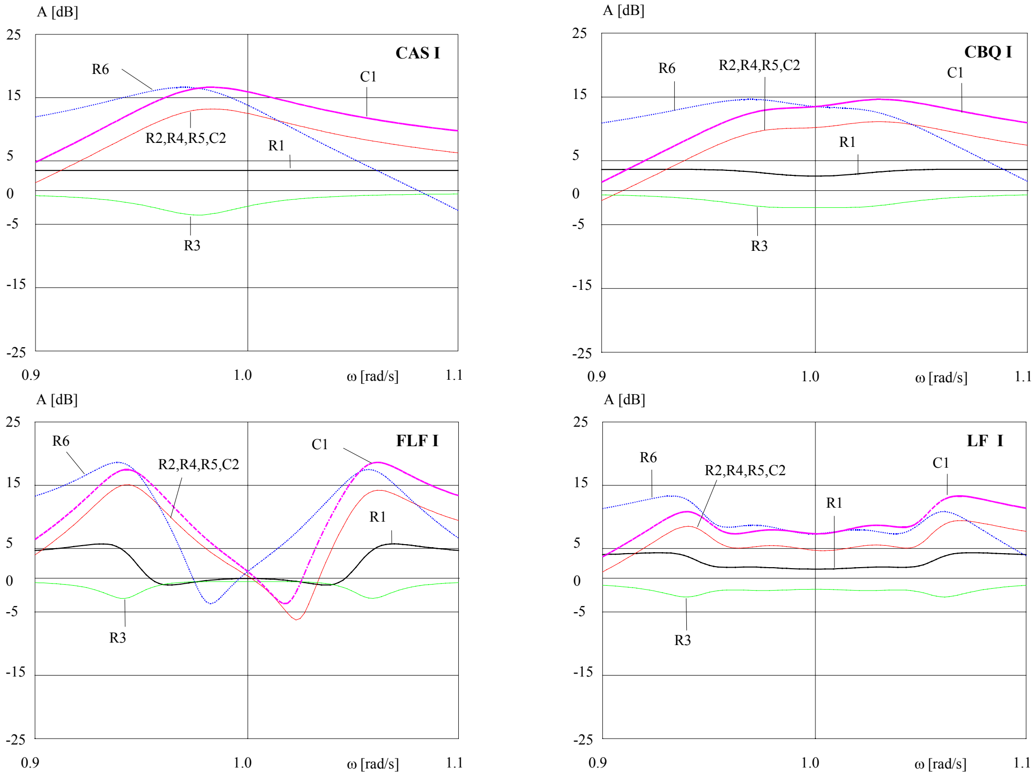

Fig. 6. Error functions for element changes in first filter blocks in structures from Fig. 1

Note that R_2, R_4, R_5 and C_2 produce the same error. The reason is in (6), i.e. in the nature of the network. These elements form the ambiguity group, and the isolation technique is not capable of breaking them apart.

Using the results from Fig. 6 one can establish the optimal frequency region to simulate the fault isolation in the first block. The most suitable is the region where the curves are the most spread. For the CAS structure it is below the central frequency, for FLF and LF optimal regions are at the passband edges, and for the CBQ they are closer to the center. It can be easily seen that these regions coincide with the regions of the maximum sensitivity in Fig. 4. The same procedure can be carried out for the second-order blocks within the structures. In CAS structure each block produces different error functions. In FLF 1st and 2nd block produce the same error function, while 3rd, and 4th produce different. In CBQ 1st and 2nd are the same and 3rd and 4th are the same, too. In LF structure 1st and 4th produce the same and 2nd and 3rd produce the same functions.

The records in the fault dictionary can be magnitudes or any other signature. Seshu and Waxmann proposed quantization of the error function using scale of marks. One such scale is shown in Fig. 7. It is usually defined by a test engineer. The errors in the interval [-2, 2] dB are marked as 0, in the interval [2, 5] dB as 1, etc.

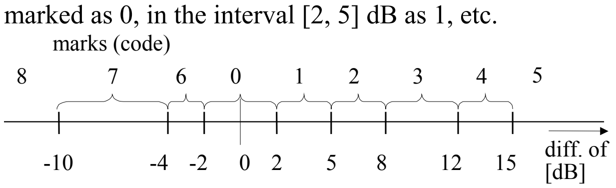

Fig. 7. Scale of marks associated with error functions.

The initial fault dictionary for the first block in FLF structure is given in Table II. Columns correspond to test frequencies and rows correspond to faults. Analogous initial dictionaries are constructed for other structures.

Table II 1st Block FLF Initial Fault Dictionary

Test Freq.		5	10	15	20	25	30	35	40	45	50	60	70	80	90
No.	Fault	Signature													
0	R_1+	2	2	2	2	0	0	0	0	0	0	0	0	2	2
1	R_1-	8	7	7	0	1	0	0	0	0	0	0	0	0	7
2	R_2+	2	3	4	4	4	3	2	1	1	0	7	2	4	3
3	R_2-	5	5	5	5	5	5	3	1	0	1	3	5	5	5
4	R_3+	0	0	0	6	0	0	0	0	0	0	0	0	6	0
5	R_3-	1	1	1	2	1	1	0	0	0	0	0	1	2	1
6	R_4+	2	3	4	4	4	3	2	1	1	0	7	2	4	3
7	R_4-	5	5	5	5	5	5	3	1	0	1	3	5	5	5
8	R_5+	2	3	4	4	4	3	2	1	1	0	7	2	4	3
9	R_5-	5	5	5	5	5	5	3	1	0	1	3	5	5	5
10	R_6+	4	5	5	5	5	3	1	6	0	0	2	4	5	3
11	R_6-	3	4	5	5	5	4	3	2	1	0	6	3	5	4
12	C_1+	3	3	4	5	5	4	3	2	1	0	6	3	5	5
13	C_1-	4	4	5	5	5	3	1	6	0	0	2	4	5	4
14	C_2+	2	3	4	4	4	3	2	1	1	0	7	2	4	3
15	C_2-	5	5	5	5	5	5	3	1	0	1	3	5	5	5

Finally, optimised fault dictionaries (Tables III-IV) are constructed containing magnitudes instead of marks. The ambiguous faults are particularly pointed out. The dictionaries contain all the parameters needed for testing, including the frequencies. Shaded areas indicate uniquely detected faults. Note that LF structure (Table IV) needs three test frequencies while for other structures two test frequencies are sufficient. Such dictionaries are constructed for testing 2nd, 3rd and 4th block using the same principles.

Table III 1st Block CAS Final Fault Dictionary			
Test Frequency		5 (0.9096 r/s)	80 (1.0662 r/s)
No.	Fault	Magnitudes [dB]	
0	R_1+	-2.1242780E+01	-6.3641390E+00
1	R_1-	-1.1700390E+01	3.1782750E+00
2	R_2+	-2.0928440E+01	-1.0892270E+01
3	R_2-	-3.5372810E+01	-1.4499230E+01
4	R_3+	-1.7136930E+01	-2.4559730E+00
5	R_3-	-1.9972430E+01	-4.4845550E+00
6	R_4+	-2.0928440E+01	-1.0892270E+01
7	R_4-	-3.5372820E+01	-1.4499220E+01
8	R_5+	-2.0928390E+01	-1.0892240E+01
9	R_5-	-3.5372650E+01	-1.4499000E+01
10	R_6+	-3.0338530E+01	-6.3376150E+00
11	R_6-	-2.5797260E+01	-1.3230810E+01
12	C_1+	-2.4181000E+01	-1.4355790E+01
13	C_1-	-2.9402600E+01	-8.6128650E+00
14	C_2+	-2.0928440E+01	-1.0892270E+01
15	C_2-	-3.5372820E+01	-1.4499260E+01
Ambiguous faults: (2,6,8,14), (3,7,9,15)			

Table IV 1st Block FLF Final Fault Dictionary			
Test Frequency		5 (0.9096 r/s)	10 (0.9127 r/s)
No.	Fault	Magnitudes [dB]	
0	R_1+	-2.2734240E+01	-1.8300880E+01
1	R_1-	-6.9357270E+00	-3.6536910E+00
2	R_2+	-2.4218070E+01	-2.2215550E+01
3	R_2-	-3.7461430E+01	-3.4309500E+01
4	R_3+	-1.7197360E+01	-1.2005130E+01
5	R_3-	-1.9756600E+01	-1.5801190E+01
6	R_4+	-2.4218070E+01	-2.2215550E+01
7	R_4-	-3.7461440E+01	-3.4309510E+01
8	R_5+	-2.4218010E+01	-2.2215490E+01
9	R_5-	-3.7461270E+01	-3.4309330E+01
10	R_6+	-3.2220230E+01	-2.8885370E+01
11	R_6-	-2.8748030E+01	-2.6384960E+01
12	C_1+	-2.6686560E+01	-2.4684780E+01
13	C_1-	-3.0883700E+01	-2.7636300E+01
14	C_2+	-2.4218070E+01	-2.2215550E+01
15	C_2-	-3.7461430E+01	-3.4309520E+01
Ambiguous faults: (2,6,8,14), (3,7,9,15)			

Table V 1st Block CBQ Final Fault Dictionary			
Test Frequency		5 (0.9096 r/s)	70 (1.0439 r/s)
No.	Fault	Magnitudes [dB]	
0	R_1+	-2.1377310E+01	-3.5233910E+00
1	R_1-	-1.1343350E+01	5.7550640E+00
2	R_2+	-1.8096310E+01	-1.0917920E+01
3	R_2-	-3.4042020E+01	-1.7901690E+01
4	R_3+	-1.7327290E+01	1.5369480E+00
5	R_3-	-1.9395730E+01	-3.9859070E+00
6	R_4+	-1.8096320E+01	-1.0917920E+01
7	R_4-	-3.4042030E+01	-1.7901690E+01
8	R_5+	-1.8096270E+01	-1.0917890E+01
9	R_5-	-3.4041870E+01	-1.7901490E+01
10	R_6+	-2.9193100E+01	-1.1329610E+01
11	R_6-	-2.3480830E+01	-1.3792790E+01
12	C_1+	-2.1068870E+01	-1.4431450E+01
13	C_1-	-2.7997490E+01	-1.2160670E+01
14	C_2+	-1.8096320E+01	-1.0917930E+01
15	C_2-	-3.4042020E+01	-1.7901680E+01
Ambiguous faults: (2,6,8,14), (3,7,9,15)			

Table VI 1st Block LF Final Fault Dictionary				
Test Fr.		5 (0.9096 r/s)	10 (0.9127 r/s)	70 (0.9389 r/s)
No.	Fault	Magnitudes [dB]		
0	R_1+	-2.1908660E+01	-1.7210670E+01	-6.0821670E+00
1	R_1-	-9.7016320E+00	-4.8478110E+00	1.3559500E+00
2	R_2+	-2.0926490E+01	-1.8124960E+01	-1.0910570E+01
3	R_2-	-3.4746760E+01	-3.0798390E+01	-2.0693880E+01
4	R_3+	-1.6709440E+01	-1.1473360E+01	2.5382340E-01
5	R_3-	-2.1007710E+01	-1.6871320E+01	-7.4590510E+00
6	R_4+	-2.0926500E+01	-1.8124970E+01	-1.0910580E+01
7	R_4-	-3.4746770E+01	-3.0798400E+01	-2.0693890E+01
8	R_5+	-2.0926460E+01	-1.8124930E+01	-1.0910550E+01
9	R_5-	-3.4746600E+01	-3.0798230E+01	-2.0693700E+01
10	R_6+	-2.9716180E+01	-2.5604080E+01	-1.5036100E+01
11	R_6-	-2.5451000E+01	-2.2306060E+01	-1.4289020E+01
12	C_1+	-2.3365350E+01	-2.0583330E+01	-1.3220440E+01
13	C_1-	-2.8462200E+01	-2.4437070E+01	-1.4054300E+01
14	C_2+	-2.0926500E+01	-1.8124970E+01	-1.0910580E+01
15	C_2-	-3.4746770E+01	-3.0798380E+01	-2.0693870E+01
Ambiguous faults: (2,6,8,14), (3,7,9,15)				

Simulation results are successfully applied to the real filter. The magnitude of the failed analog filter is measured in the same test frequencies as in the dictionaries in Tables III-VI. The fault isolation criterion is applied to the measured magnitudes and to the simulated magnitudes from the dictionary and faults were successfully located.

4. CONCLUSIONS

This paper presents fault location technique capable of locating single hard faults of filter passive elements. This technique is applied to filter structures with low sensitivities. It is shown that the sensitivity analysis can be used to find the optimum frequency range for performing the fault isolation procedure. Low sensitive structures are suitable to be tested using described technique, as well as the CAS structure, but they need more test frequencies than structures with higher sensitivities.

5. REFERENCES

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