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Citation for published version (APA):

You, Z., Sanchez-Sinencio, E., & Pineda de Gyvez, J. (1995). Analog system-level fault diagnosis based on a symbolic method in the frequency domain. *IEEE Transactions on Instrumentation and Measurement*, 44(1), 28-35. <https://doi.org/10.1109/19.368107>

DOI:

[10.1109/19.368107](https://doi.org/10.1109/19.368107)

Document status and date:

Published: 01/01/1995

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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- The final published version features the final layout of the paper including the volume, issue and page numbers.

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Analog System-Level Fault Diagnosis Based on a Symbolic Method in the Frequency Domain

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Abstract— Concurrently, a symbolic approach for analog system-level fault diagnosis and a systematic approach to maximize the fault location capability are proposed. This unified approach is realized as a result of combining the simulation before test (SBT) fault dictionary diagnosis method with a symbolic approach. The traditional SBT fault dictionary method is often costly and inefficient because of a high number of simulations, but it can become very efficient when a symbolic approach is employed. This symbolic approach only requires one analysis for circuit topology to generate the network transfer function and a parameter substitution to obtain the frequency response (or time response) of the system. An efficient program is developed to deal with the frequency responses of the system to provide the optimum testing point set, and to automatically generate the fault dictionary. The “distance” between the measurement data and the frequency responses from the fault dictionary is evaluated to determine the diagnosis results. A practical example is presented in order to illustrate the main features of this proposed analog system fault diagnosis approach.

I. INTRODUCTION

THE problem of analog circuit fault diagnosis first attracted researchers’ attention in the 1960’s, and later became a flourishing research activity because of the advent of modern, complex analog circuits and systems. However, the progress has been slow because there is not any user-oriented, publicly available computer program for analog circuit fault diagnosis such as those for digital circuit diagnosis [1]. The main factors [2]–[4] that make analog circuit fault diagnosis difficult can be summarized as follows:

- 1) Analog systems are usually nonlinear and have widely spread parameter values. Thus, deterministic methods are often inefficient for modeling these systems. At the same time, analog systems have a continuum of possible failures. It is also difficult to have the same simple, discrete models to cover all possible analog network faults.
- 2) In analog circuits, a good component may be within tolerance, but not nominal. This implies that an extremely large number of simulations, or a complicated calculation method is often required for analog circuit fault diagnosis.

- 3) Relations between input and output signals in analog circuits are sometimes more complicated as compared to those in digital circuits. These relations in analog circuits are more difficult to model than digital circuit representations, which are based on classical truth tables, and thus, are precise and easy to model.
- 4) The number of I/O’s in analog circuits is small. This implies that analog circuit fault diagnosis requires a great amount of computer time and computer storage as the number of observable/controllable pins is small.
- 5) There are some inherent interactions between various circuit parameters, which will impede efficient functional verification and diagnosis.

There are many problem formulations depending on the systems under test, e.g., fault models, measurement conditions and the final objective of the fault diagnosis [5]. The key factors in the classification of diagnostic problems are the following:

- 1) Systems under test [1], [5]
 - a) Elements contained in the system: RLC or RC; controlled sources; operational amplifiers (OP AMP); operational transconductance amplifiers (OTA); switches and nonlinear elements.
 - b) Excitation of the systems: DC excitation; sinusoidal excitation, which includes single frequency or multifrequency.
 - c) Number of exciting sources (independent sources or inputs): Single exciting sources; multiple exciting sources.
- 2) Fault models [4], [5]

By a fault we mean, in general, any change in the value of an element with respect to its nominal value which can cause the failure of the whole circuit. The fault could be catastrophic (HARD fault) when the faulty element produces either a short circuit or an open circuit, or parametric (SOFT fault) when the faulty element just deviates from its nominal value for a specific design tolerance range. These soft faults could result from manufacturing tolerances, aging, or parasitic effects. Several fault location techniques only address the cases when just one parameter causes the fault. This is referred to as a single fault. In practice the multiple-fault case, which is caused by several faulty parameters, could occur, and recent techniques address this as a difficult case [1], [2].

Manuscript received February 21, 1994; revised June 12, 1994.

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IEEE Log Number 940775.

3) Measurements

The measurements can be carried out in DC, frequency or time domains. Within the different domains, voltage measurements or current measurements can be chosen.

4) Final objective of fault diagnosis [3], [4], [6]

In general, analog circuit fault diagnosis has three main objectives: fault detection, fault location and fault identification. Fault detection is the minimum requirement for the fault diagnosis; it answers WHETHER an analog circuit's functionality falls outside design specification. Fault location is the necessary requirement for repairing faulty parts at a later time; it addresses WHERE the faults are. Fault identification is necessary for tuning and adjustment; it answers WHAT the exact value of the deviation is. For these purposes, many fault diagnosis ideas have been developed. The major characteristics of these ideas can be classified into the pattern recognition, parameter identification, fault verification, and approximation techniques.

Two basic methods of analog fault diagnosis are the simulation-before-test (SBT) and the simulation-after-test (SAT) methods [2]. The SBT techniques use a pattern recognition concept [2], which is implemented by simulating the circuit with the possible fault conditions before the actual testing; the results are stored in look-up tables. It can effectively detect and locate hard faults. The fault simulation plays a very important role in this approach. The application of SBT techniques is usually limited to circuits of small or moderate size for the detection of only hard faults. The fault dictionary technique is an SBT method.

All parameter identification and fault verification techniques belong to the SAT approach, which simulates the circuit at the testing time or after the testing time. Parameter identification techniques identify all circuit parameters under the assumption that enough independent measurements are available [7], [8]. These techniques are classified as linear or nonlinear according to the nature of the diagnosis equations. Fault verification techniques can only identify a few faulty elements under the assumption that a few elements are faulty and the rest of the network elements are within design tolerances. Based on this idea, several algorithms have been developed such as the substitution theorem-based technique, the failure bound technique and the network decomposition approach [1], [9]. In the SAT approach there have been various methods which may locate single or multiple, hard or soft faults in circuits of small or relatively large size. However, the complexity and computer time required usually limits its applicability.

The motivation of the research hereby presented is to improve the traditional SBT fault dictionary approach. It is known that the traditional SBT fault dictionary technique is very time consuming and costly because a high number of numerical simulations are required to construct the fault dictionaries of the system under test. But, it might be rendered more useful if an efficient approach could be found to generate fault dictionaries in reasonable amounts of computer time. For this reason, a symbolic approach is introduced during the fault dictionary generation.

Fig. 1. Symbolic fault diagnosis flow diagram.

The proposed approach uses the symbolic simulator (ASAP) [13] to generate the requested network functions of the circuit under test [15], and then only expression evaluations are required to obtain all the possible faulty responses. Compared to a traditional approach, which uses a numerical simulator (SPICE) to obtain the faulty responses, the proposed approach is more efficient and less costly. It can also deal with single/multiple faults, soft/hard faults at the same time. This reduction in computation time to evaluate the faulty responses is a key contribution of this paper. The other practical contribution is the systematic approach to maximize the fault location capability.

II. PROPOSED FAULT DIAGNOSIS APPROACH

Nowadays, two main classes of simulators exist. One class is the numerical simulator, such as SPICE, which can be used for nonlinear dc, nonlinear transient and linear ac analysis problems. Even though it is very efficient, it only returns a collection of numbers, in tabular or plot forms. The other class is the symbolic simulator. It can yield the network function in which some, or all, of the circuit elements, $p_1, p_2, \dots, p_m$, along with the complex frequency s , are represented by symbolic parameters, as shown in (1)

$$H(s_1, p_1, p_2, \dots, p_m) = \frac{N(s_1, p_1, p_2, \dots, p_m)}{D(s_1, p_1, p_2, \dots, p_m)}. \quad (1)$$

The symbolic simulation has noteworthy advantages with respect to the numerical simulation for those applications which require the repetition of a high number of simulations performed on the same circuit topology with the variation of component values and/or frequency [14]–[15]. In these types of applications, the symbolic approach can be used to generate the requested network functions of the analyzed circuit in parametric form. In this way, the circuit analysis is performed only once and, during the fault dictionary generation phase, only a parameter substitution and an expression evaluation are required to obtain the numerical results. Evidently, the function evaluation is much easier and faster than working repeatedly with a network analysis program to perform a full ac analysis.

The flow diagram of the proposed symbolic fault dictionary diagnosis approach is shown in Fig. 1. The dashed lines are

Fig. 2. OTA-C leapfrog lowpass filter.

Fig. 3. A simple macromodel for an OTA.

related to SPICE simulations. All these parts (dashed arrows) are only used to verify the new symbolic fault dictionary approach during the research stage. In actual use, SPICE will not be used.

For a system under test, it is necessary to have macromodels for dealing with the system-level faults. These macromodels focus on building-block performance parameters of OP AMP's and OTA's rather than on transistor-level parameters.

Next, a detailed explanation of Fig. 1 is given. Once the macromodels are generated, the symbolic simulator, ASAP, is used to generate the network transfer function, $H(s)$, in which some, or all, of the circuit elements, along with the complex frequency, are represented by symbolic parameters. At the same time, the system-level faults¹ are determined based on the macromodel circuit, and the initial testing frequencies are chosen according to the Seshu and Waxman theory [2]. Then, a parameter substitution and an expression evaluation are performed to obtain the required numerical frequency responses. The output frequency responses, under all faulty conditions, and together with the frequency testing points, form a recognition matrix. Each column of the recognition matrix is related to a testing frequency point, and each row of the matrix is related to a specific faulty case. An optimum testing-point selection technique [18] is used to make the new approach self-contained. The testing-point selection is a choice with the minimum testing frequency points to maximize the fault diagnosability. Based on the optimum testing points, the fault dictionary can be generated automatically. At this point, the off-line computation is finished.

During the on-line computation, the nearest neighbor rule is used to locate the faults. This rule is based on the idea that a faulty case which has the minimum Euclidean distance with the testing data will be the most likely fault. For an analog system, there are several accessible nodes which can provide different information for fault diagnosis. This fact leads us to propose a systematic fault location approach, which is developed to maximize the fault location capability.

¹ System-level faults are those faults that do not consider actual transistors.

Fig. 4. Comparison between the OTA-C leapfrog lowpass filter with the real OTA and with its macromodel.

Based on the above discussion, it is evident that the proposed symbolic fault diagnosis approach can save the off-line computation time invested in the fault dictionary generation. Undoubtedly, this proposed approach can be more efficient and practical than conventional techniques. Also, fault location capabilities can be maximized using a systematic technique.

III. SYMBOLIC FAULT DIAGNOSIS

A. System Under Test

In this presentation, we address continuous-time, linear, time-invariant systems, which are composed of lumped passive elements and active devices. These systems can be characterized by (2) or (3) in the Laplace domain:

$$H(s) = \frac{Y(s)}{X(s)} = \frac{a_m s^m + a_{m-1} s^{m-1} + \dots + a_0}{b_n s^n + b_{n-1} s^{n-1} + \dots + b_0} \quad (2)$$

$$H(s) = \frac{Y(s)}{X(s)} = \frac{a_m (s - Z_1)(s - Z_2) \dots k(s - Z_m)}{b_n (s - p_1)(s - p_2) \dots (s - p_n)} \quad (3)$$

An OTA-C leapfrog lowpass filter is chosen as an example to illustrate the proposed fault diagnosis symbolic method. The topology of the OTA-C leapfrog lowpass filter is shown in Fig. 2. The real OTA used in the OTA-C filter is a tunable OTA [11], which uses the voltage V_{C_i} to control the transconductance g_m of the OTA, for $i = 1, \dots, 5$.

This approach can address system-level faults, which focus on the behavioral performance of the OP AMP and the OTA. To deal with system-level faults, simple macromodels for the OP AMP and the OTA need to be built. These macromodels should include typical parameters: namely, gain, dominant pole, input impedance and output impedance, to accurately represent the performance of the circuit or subcircuit under test for all faulty conditions.

For the OTA-C leapfrog lowpass filter, the typical one-dominant-pole macromodel is shown in Fig. 3. Here, $G_1(V_{C_i}) = G_m$ represents the transconductance gain; the dominant transconductance pole is $\omega_p = 1/(R_{dp} * C_{dp})$, $G_{buf} = 1$ and; R_{in} and R_{out} characterize the input and output resistances, respectively. When this simple, one-dominant-pole macromodel² is included in a closed-loop configuration, it matches well with the real OTA at the transistor level. Fig. 4 shows the comparison between the OTA-C leapfrog lowpass filter

² A more complex OTA macromodel could be used for higher frequency applications.

TABLE I
COMPARISON OF THE EXTRACTED POLES/ZEROS FROM ASAP AND SPICE FOR THE OTA-C LEAPFROG LOWPASS FILTER

Poles/Zeros from ASAP (rad/sec)	Poles/Zeros from SPICE (rad/sec)
Symbolic pole extraction root[0] = -488.841e+3 + 1.239e + 6 i root[1] = -488.841e+3 - 1.239e + 6 i root[2] = -968.288e+3 + 0 i Symbolic zero extraction root[0] = -666.6667e+6 + 21.838 i root[1] = -666.6667e+6 - 21.838 i root[2] = 9.014e+12 + 1.561e+13 i root[3] = 9.014e+12 + 1.561e-13 i	Poles root[0] = -488.838e+3 + 1.239e + 6 i root[1] = -488.838e+3 - 1.239e + 6 i root[2] = -968.281e+3 + 0 i root[3] = -665.7278e+6 + 0 i root[4] = -666.200e+6 + 1.242e + 6 i root[5] = -666.200e+6 - 1.242e + 6 i Zeros root[0] = -666.6667e+6 + 0 i root[1] = -666.6667e+6 - 0 i

with the real OTA subcircuit and with its macromodel. The standard deviation of the difference between the two responses is 0.053. The CPU time used for the simulation with the OTA macromodel is about 10 times faster than for the simulation with the OTA at the transistor level.

B. Feasibility Analysis of Using ASAP to Substitute for SPICE

One of the main advantages of the proposed fault diagnosis approach is to use a symbolic simulator to substitute for the use of numerical simulations during the generation of the fault dictionaries. This will reduce the computational time and make the approach more practical. However, it is necessary to analyze the feasibility of using symbolic simulations to substitute for numerical simulations. We present two sufficient and necessary conditions to do the feasibility analysis.

Condition 1: Poles and Zeros Comparison: Each continuous-time linear time-invariant system can be represented by (3), which is the transfer function characterized by the poles and zeros, and concurrently all these poles/zeros are functions of some, or all, circuit parameters. Parameter deviations change the locations of the poles and zeros, and consequently change the magnitude of the transfer function. This fact implies that the feasibility analysis of using a symbolic simulator can be verified by comparing the numerically and symbolically extracted poles and zeros. Table I shows the comparison of poles/zeros from ASAP and HSPICE for the OTA-C leapfrog

lowpass filter. The results show that there are some differences between the larger poles and zeros. This is due to the fact that we are using a simple OTA macromodel. However, the critical poles and zeros of this system are matching very well with a standard deviations of less than 1.0e-6, see Fig. 4. Based on the fact that mainly the critical poles and zeros affect the system performance, one can conclude that good matching between the poles and zeros from ASAP and SPICE is obtained.

Condition 2: Numerical Frequency Response Comparison: The symbolic transfer function from ASAP can be represented by (2). When $s = j\omega$, the magnitude frequency responses can be calculated by (4), shown at the bottom of the page.

Here, "INT" means integer, and all a_i and b_j are functions of the circuit parameters.

The flow chart for calculating the frequency response of the system under test is shown in Fig. 5. Two libraries are set to automate the calculation. One is the element library, which includes all possible elements of the system under test. They are capacitors, resistors, OP AMP's and OTA's. The other library is the faulty case library, which includes several possible faulty cases for each kind of element. For example, each OP AMP has several faulty cases, namely, voltage gain "e" deviations from their nominal value, input impedance reductions, and output impedance changes to open circuits. For a given system under test, the faulty cases can be generated automatically by searching the faulty case library. Using the

$$|H(j\omega)| = \left(\frac{\left[a_o + \sum_{i=1}^{INT(N/2)} (-1)^i a_{2i} \omega^{2i} \right]^2 + \left[\sum_{i=1}^{INT(N/2)} (-1)^{2i-1} a_{2i-1} \omega^{1i-1} \right]^2}{\left[b_o + \sum_{j=1}^{INT(N/2)} (-1)^j b_{2j} \omega^{2j} \right]^2 + \left[\sum_{j=1}^{INT(N/2)} (-1)^{2j-1} b_{2j-1} \omega^{2j-1} \right]^2} \right)^{1/2} \quad (4)$$

Fig. 5. Flow chart for calculating frequency response.

faulty cases and the testing frequency points, the evaluation of the symbolic transfer function can be done to obtain the frequency responses of the system.

The comparison between ASAP calculations and SPICE simulations using the OTA-C leapfrog lowpass filter are shown in Fig. 6. The standard deviation of the difference is about 0.0003. These results verify that the symbolic simulator can be used to substitute for SPICE numerical simulations.

C. Optimum Testing-Point Selection

One of the most important aspects in the design of fault diagnosis schemes is the testing-point selection. With proper and efficient testing-point selection, diagnosability of faulty components can be increased considerably. Improper or ineffective testing points will increase the number of frequency points needed for testing, thereby increasing the testing time and/or computational facilities required. It will also increase confusion and errors in diagnosability [2]. Testing-point selection [23] is the optimal choice of the minimum number of measurement points while maintaining and/or maximizing the probability of correct diagnosis. The initial testing features are chosen according to the Seshu and Waxman theory, which requires that there must be at least one test break point below the "lowest nonzero" break point, and one between the successive break points [2], [18]. The rationale behind this choice is that all poles and zeros of the network are functions of the network parameters. Parameter deviations cause changes in the locations of the poles and zeros, and consequently change the magnitude of the transfer function. Here the "lowest nonzero" and the "highest finite" frequency break points depend on the particular poles/zeros distribution and the range of frequencies over which the system is active.

A heuristic optimum testing-point selection, proposed in [18], is used in this symbolic approach for the sake of completeness. This procedure selects a set of testing points without performing the exhaustive search of all subsets of frequency points.

For a given circuit, the fault dictionaries for some accessible nodes are built and stored in a dictionary library. After obtaining measurement data, the corresponding fault dictionary

Fig. 6. Comparison between frequency responses from ASAP and SPICE for the OTA-C leapfrog lowpass filter.

Fig. 7. Flow chart for systematic fault location.

is chosen. Then, the nearest neighbor rule is used to locate the most likely faulty case based on the minimum "distance" concept. Possible faulty cases which fail within the tolerance window can be identified and grouped together. If the fault family only has one faulty case, the process is finished; if not, a different dictionary for a different node is chosen, and another fault family is obtained. See Fig. 7 for a flow chart of this procedure. The same procedure is carried out k times, where k is the number of accessible nodes. The final fault location result can be determined as follows:

$$\text{Fault} = \text{fault family (node 1)} \cap \text{fault family (node 2)} \\ \cap \dots \cap \text{fault family (node } k\text{)}. \quad (5)$$

This approach is similar to the ambiguity sets concept introduced in [24]. Rather than using fixed constraints to isolate the faults, the method we implemented makes use of tolerance windows. That is to say, the output responses are considered within a certain standard deviation. This allows us to consider the effect of component tolerances in the final result. Obviously, the wider this window is, the more fault cases it can include. But on the other hand, a window allows taking into account the regular variations of the fault-free response. Cases in which an element is considered faulty under the fixed-constraint value approach, may actually not be faulty if they fall within the tolerance window of the fault-free response. Furthermore, our fault diagnosis approach uses a symbolic analysis not used in [24].

TABLE II
INITIAL TESTING-POINT SET FOR THE OTA-C LEAPFROG LOWPASS FILTER (kHz)

1	2	3	4	5	6
7	8	9	10	50	100
150	200	250	300	350	400
450	500	550	600	650	700
750	800	850	900	950	1000
3250	5500	7750	10000		

TABLE III
OPTIMUM TESTING-POINT SET FOR THE OTA-C LEAPFROG LOWPASS FILTER (kHz)

Node	Optimum Testing Point Set					No. of Points
1	10	50	100	150	200	15
	250	300	350	400	450	
	500	3250	5500	7750	10000	
	4	6	9	150	250	
2	3250					6
3	2	50	100	150	200	9
	250	300	3250	10000		

D. Diagnosis Results

Based on the rationale presented before, the fault dictionary should be built for each accessible node of the circuit. After the fault dictionaries of all accessible nodes in the circuit are built, the off-line computation has been finished. Then, the on-line computation of testing data can be carried out to locate the faults.

Step 1: Off-Line Computation Results: Based on Seshu and Waxman's theory, the initial testing-point set for the OTA-C leapfrog lowpass filter is shown in Table II, which totally includes 34 frequency points. Table III shows the optimum frequency testing-point set for each accessible node in the OTA-C leapfrog lowpass filter, which is shown in Fig. 2. After the optimum testing-point sets are determined, the fault dictionary for each node is generated automatically.

Step 2: On-Line Computation Results: In this presentation, two kinds of testing data are discussed. One of them, generated from SPICE simulations using the real OTA, is used to test the theoretical feasibility of the proposed solution.

In the data set 38 faults were generated consisting of short circuits, opens, and excessive parameter value variations. The other testing data was obtained from actual measurements of a test chip to verify the practicality.

1) Using SPICE Simulation Data: For the OTA-C leapfrog lowpass filter, the simulation data is generated from the filter with the real OTA subcircuit. Some diagnosis results are shown in Table IV.

In an analog system, the output response has its specification tolerance range because of the circuit parameter tolerance and the inaccuracies in the measurement [19]. The tolerance column in Table IV shows the specification tolerance range (also called tolerance window).

2) Using Measurement Data of OTA-C Leapfrog Lowpass Filter: In order to verify the practicality of this proposed symbolic fault diagnosis approach, the actual testing data of the OTA-C leapfrog lowpass filter is used. During the on-line testing, several possible faulty cases are produced. For a capacitor, a fault can be produced by adding or reducing one or more capacitors to make its value change. For an OTA, the control voltage can be used to adjust the gain to a faulty

TABLE IV
SOME DIAGNOSIS RESULTS FOR THE OTA-C LEAPFROG LOWPASS FILTER WITH SPICE SIMULATION DATA

Faulty case of testing data	Program diagnosis results			
	Tolerance	Node	Fault families	Final result
F0	$\pm 20\%$	1 2 3	F0 F0, F25 F0, F5, F6, F22, F25	F0
F1	$\pm 5\%$	1 2 3	F1, F5 F1 F1	F1
F14	$\pm 20\%$	1 2 3	F14 F14 F14	F14
F18	$\pm 20\%$	1 2 3	F18 F8, F18, F24, F36, F37 F12, F18, F35	F18
F27	$\pm 20\%$	1 2 3	F27 F27 F27	F27

F0	fault free case	F22	+50% variation in g_{m4}
F1	+50% variation in C_1	F24	-90% variation in g_{m4}
F5	+50% variation in C_2	F25	+50% variation in g_{m5}
F8	+10,000% variation in C_2	F27	-90% variation in g_{m5}
F12	+10,000% variation in C_3	F35	r_{o3} set to 100
F14	-50% variation in g_{m1}	F36	r_{o4} set to 100
F18	-90% variation in g_{m2}	F37	r_{o5} set to 100

Fig. 8. Diagnosis for actual testing data.

case. After a certain faulty case is generated, the magnitude frequency responses under the optimum feature points are tested for each accessible node, and then diagnosed by using the corresponding dictionary.

The fault case F1, corresponding to a 50% variation of C_1 from its nominal value, is chosen to illustrate the approach. Fig. 8 shows the magnitude frequency response for node 1 under the optimum feature set, which has 15 frequency points. By using the fault location approach with the +40% specification tolerance window, the most likely faulty case and its fault family are obtained. Here, the diagnosis result shows that the most likely faulty case is F1, and the fault family includes F1, F5, F9, and F32. Diagnosis results for the OTA-C leapfrog lowpass filter from actual measurement data are shown in Table V. These results verify the feasibility of the proposed approach.

IV. CONCLUSIONS

A new symbolic method based on a conventional analog system fault diagnosis approach has been presented. This approach combines the SBT fault dictionary diagnosis method with a symbolic simulator, ASAP, to locate system-level faults

TABLE V
SOME DIAGNOSIS RESULTS FOR THE OTA-C LEAPFROG
LOWPASS FILTER FROM ACTUAL MEASUREMENT DATA

Faulty case of testing data	Program diagnosis results			
	Tolerance	Node	Fault families	Final result
F0	± 30%	1 2 3	F0, F16, F25 F0, F6, F16, F22, F29, F31 F0	F0
F1	± 40%	1 2 3	F1, F5, F9, F32 F1, F9, F14 F1, F7, F29, F30, F31	F1
F14	± 20%	1 2 3	F14 F14 F14	F14
F18	± 20%	1 2 3	F18 F8, F18, F24, F36, F37 F12, F18, F35	F18
F27	± 50%	1 2 3	F22, F26, F27 F27 F27	F27

F0	fault free case	F24	-90% variation in g_{m4}
F1	+50% variation in C_1	F25	+50% variation in g_{m5}
F5	+50% variation in C_2	F26	-50% variation in g_{m5}
F6	-50% variation in C_2	F27	-90% variation in g_{m5}
F7	-100% variation in C_2	F29	r_{in2} set to 10,000
F9	+50% variation in C_3	F30	r_{in3} set to 10,000
F12	+10,000% variation in C_3	F31	r_{in4} set to 10,000
F14	-50% variation in g_{m1}	F35	r_{o3} set to 100
F16	+50% variation in g_{m2}	F36	r_{o4} set to 100
F18	-90% variation in g_{m2}	F37	r_{o5} set to 100
F22	+50% variation in g_{m4}		

TABLE VI
CPU TIME FOR OFF-LINE COMPUTATION (OTA-C LEAPFROG LOWPASS FILTER)

	Symbolic method	General SBT fault dictionary method
Transfer function	ASAP 0.3 sec	—
Initial recognition matrix	reading netlist 0.4 sec ckt. evaluation 2.2 sec	HSPICE 38 x 2.0 sec + t _l
Optimum feature set and fault dictionary	OPTIMUMF 0.2 sec	OPTIMUMF 0.2 sec
Total	3.1 sec	76.2 sec + t _l

in continuous-time, linear, and time-invariant systems. The conventional SBT fault dictionary method can be costly and inefficient because of the immense number of simulations. But, it becomes very efficient when a symbolic approach is used. This approach permits us to automatically obtain the optimum measurement feature set and generate the fault dictionaries. The nearest neighbor rule is used for fault isolation, and a systematic approach has been developed to maximize the fault isolation capability.

Efficiency of this new symbolic approach can be assessed from Table VI, which shows the measured CPU times for off-line computation compared to the conventional SBT fault dictionary method. READCF and CIRCUIT are two C-programs to edit the ASAP symbolic results and to generate the initial recognition matrix, respectively. It is clear that the new symbolic approach can deal with hard/soft faults at the same time and reduce off-line computation.

The above CPU times are measured for the OTA-C leapfrog lowpass filter. Its initial recognition matrix includes 38 faulty cases, which means that 38 SPICE simulations have to be done

TABLE VII
COMPARISON BETWEEN THE NEW SYMBOLIC APPROACH AND
THE GENERAL SBT FAULT DICTIONARY APPROACH

	On-line computation	Off-line computation	Test nodes	Types of faults	Network type
General fault dictionary	minimal	high	limited	single hard	linear/ nonlinear
New symbolic approach	minimal	moderate	limited	multiple hard/soft	linear
Goals	minimal	moderate	limited	multiple	general

when using the conventional SBT fault dictionary method. Table VI shows that the symbolic approach is more than 20 times faster than the conventional method. In Table VI, t_l is the time needed for editing SPICE results to generate the recognition matrix. A general comparison between the common SBT fault dictionary method and this new approach is shown in Table VII.

ACKNOWLEDGMENT

The authors want to thank the Analog Microelectronics Group from the Centro Nacional Microelectronica, Seville, and in particular, Dr. Angel Rodríguez-Vázquez for giving us access to a preliminary version of ASAP.

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