Fault Coverage Improvement Based On Error Signal Analysis

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Abstract - Fault-tolerant design of analog circuits is more difficult than that of digital circuits. Abhijit Chatterjee has proposed a continuous checksum-based technique to design fault-tolerant linear analog circuits. However, some faults in the passive elements cannot be detected if the checker has not been designed appropriately. This paper addresses the fault coverage issue in the continuous checksum based technique and proposes an error signal analysis based method for improving fault coverage of the checker.

I . INTRODUCTION

A lot of studies have been done on how to design fault-tolerant digital systems [1-2]. Although many results on analog test methodologies have been published recently [3-5], only a small amount of literature can be found on how to design fault-tolerant analog systems, especially on self-checking in analog circuits. Since Huang and Abraham [6] opened a research field called algorithm-based fault-tolerance for matrix related arithmetic, there has been significant research in the field [7-10], but it is on the digital aspect. Abhijit Chatterjee [11] first applies the concepts from algorithm-based fault-tolerance to the design of linear analog circuits. Recently Zhou *et al* [12] propose the first algorithm to effectively reduce hardware overhead in the checker. The multiple error diagnosability of the continuous checksum based scheme is studied by Zhou *et al* [13]. However, some faults in the functional block are undetectable in this scheme if the error detection circuit is not designed appropriately. Hence, how to design such an error detection circuit that has a higher fault coverage is an important issue. In this paper, we propose a method for improving fault coverage in the error detection circuit based on error signal analysis.

II. CONCURRENT ERROR DETECTION AND CORRECTION IN LINEAR ANALOG CIRCUITS

The behavior of a linear analog circuit can be described by a system of state equations in terms of state variables as follows [11-12]:

$$X(s) = \sum_{j=1}^{n} \left(A(j) \frac{X(s)}{s^j} + B(j) \frac{U(s)}{s^j} \right) + D \times U(s) \qquad (1)$$

where n is the largest degree of the denominator polynomials of the transfer functions at all stages; $X(s) = [x_1(s),\ x_2(s),\ \ldots,\ x_N(s)]^T$ is an $N\times 1$ matrix of state variables; $U(s) = [u_1(s),\ u_2(s),\ \ldots,\ u_m(s)]^T$ is an $m\times 1$ matrix of external inputs; $A(j)$, $B(j)$ and D are $N\times N$, $N\times m$ and $N\times m$ matrices respectively.

In order to detect and diagnose a single error in a state variable, a $2\times N$ coding matrix

$$CM = \begin{bmatrix} \alpha_{11},\ \alpha_{12},\ \ldots,\ \alpha_{1N} \\ \alpha_{21},\ \alpha_{22},\ \ldots,\ \alpha_{2N} \end{bmatrix}$$

and check variables $c_1(s)$ and $c_2(s)$ are introduced, where each α_{ki} is a real number. $c_1(s)$ and $c_2(s)$ are given by

$$[c_1(s),\ c_2(s)]^T = \sum_{j=1}^{n} \left(R(j) \frac{X(s)}{s^j} + Q(j) \frac{U(s)}{s^j} \right) + H \times U(s) \qquad (2)$$

where, $R(j)=CM\times A(j)$, $Q(j)=CM\times B(j)$, $H=CM\times D$, $j=1,\ldots, n$. Let $e_1(s)$ and $e_2(s)$ be two error signals such that, $e_k(s) = c_k(s) - \sum_{i=1}^{N} \alpha_{ki} x_i(s)$, $k=1,2$. It has been proved in [11] that in the fault-free case, $c_k(s) = \alpha_{k1}x_1(s) + \alpha_{k2}x_2(s) + \ldots + \alpha_{kN}x_N(s)$, $k=1,2$, and that in the presence of an error in state variable $x_i(s)$, $\frac{e_1(s)}{e_2(s)} = \frac{\alpha_{1i}}{\alpha_{2i}}$. Therefore, if the coding matrix is chosen such that $\frac{\alpha_{1i}}{\alpha_{2i}} \neq \frac{\alpha_{1j}}{\alpha_{2j}}$, $i \neq j$, then error diagnosis can be realized.

By feeding $e_1(s)$ back to the ith stage which has been diagnosed to be faulty, the error resulting from this faulty stage can be corrected [11]. The structure of a general linear analog circuit with a concurrent error detection and correction

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checker is shown in Figure 1. The checker is shown in the dotted block. The error detection circuitry is used to generate the two error signals. The diagnosis and feedback circuitry is used to implement error diagnosis and feedback.

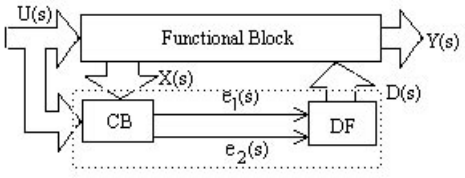

Figure 1: Scheme of an analog circuit with concurrent error detection and correction capability
CB—Checking Block DF—Diagnosis & Feedback

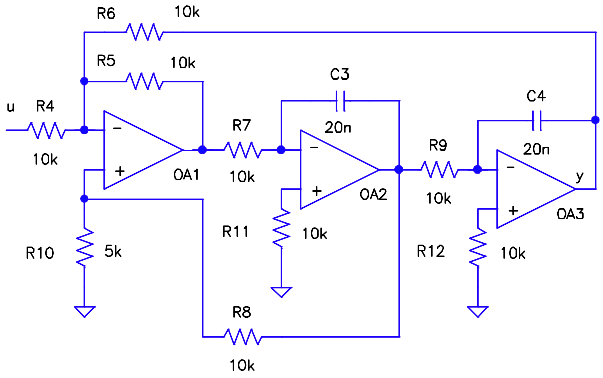

Figure 2: The active low-pass filter

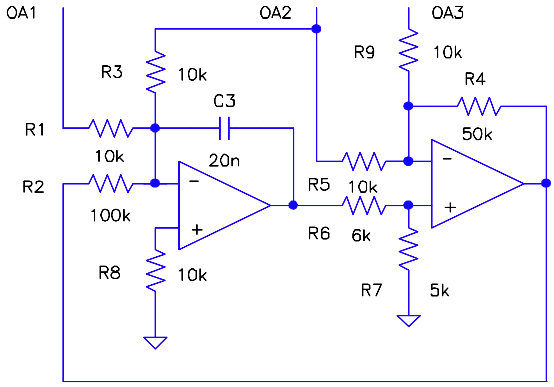

Figure 3: The error detection circuit

III. FAULT MODELING AND FAULT COVERAGE

. In this paper, we only consider faults in the passive elements. Assume that we accept deviations within $\pm x\%$ (x=10), and deviations beyond this range are considered to have caused faults.

In the digital field, fault coverage is defined as the ratio of the number of detected faults to the total number of faults in the circuit. For even a simple analog circuit, one can count its hard faults, but impossible to get the number of soft faults. Thereafter, for one element, we do not distinguish its soft faults and simply regard all of its soft faults as one fault which is still called soft fault without confusion. Consequently, for any passive element, the number of its possible faults equals to that of hard faults plus one. For example, the possible faults of a resistor consist of three faults: open, short and soft. A capacitor usually may have two possible faults: open and soft. Under the above simplification of faults, the concept of fault coverage in digital field can also be applied to analog field as a criterion to evaluate an error detection circuit. Consider an active low-pass filter as shown in Figure 2 with its error detect circuit in Figure 3 when the coding vector is taken to be (1, 1) [11]. In Figure 2, the total number of passive elements is 11. Only faults of four of them can be detected when they fail individually. These elements include two resistors, R_7 and R_9, and two capacitors, C_3 and C_4. For the others, the errors in the state variables due to the faulty elements cannot be observed from the error signal. Since R11 and R12 do not appear in the state equations, we call them theoretically undetectable. Table 1 shows the detail. The fault coverage is estimated to be 45%. Obviously, to improve the applicability of the continuous checksum based scheme, strategy on fault coverage improvement should be worked out.

TABLE 1

FAULT	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	R_{11}	R_{12}	C_3	C_4
Open	0	0	0	1	0	1	0	0	0	1	1
Short	0	0	0	1	0	1	0	0	0	N	N
Parametric	0	0	0	1	0	1	0	0	0	1	1

DETECTABILITY OF FAULTS CORRESPONDING TO FIG. 3

0 - Undetectable 1 - Detectable N - Not applicable

IV. ERROR DETECTION CIRCUIT DESIGN WITH FAULT COVERAGE IMPROVEMENT

In the proposed method for error detection circuit design with fault coverage improvement, single fault in the functional circuitry is assumed. For simplicity, we only consider one coding vector.

A . Method for Fault Coverage Improvement

Detectability of a fault depends on the magnitude of the error signal. When a fault occurs in the *i*th stage, the error signal can be calculated through the following formula [11]:

$$e(s) = -\alpha_i \left(\sum_j \sum_l \Delta A(j)_{il} \frac{x_l(s)}{s^j} + \sum_j \sum_l \Delta B(j)_{il} \frac{u_l(s)}{s^j} + \sum_l \Delta D_{il} u_l(s) \right)$$
$$= -\alpha_i E(s) \quad (3)$$

Obviously, $E(s)$ is determined by the component values and topology of the functional circuitry as well as the external inputs. Eq.(3) shows that the magnitude of the error signal only depends on $E(s)$ and the ith entry (α_i) in the coding vector CV=(α_1, α_2, ..., α_N), and it is proportional to α_i. It reminds us that an appropriate selection of α_i can make the magnitude of the error signal be equal or above its threshold (say, $|e_0|$) so that the error is observable and hence the fault becomes detectable. If α_i is selected such that the error for each possible fault of the passive components is in the ith stage SC_i, then all these faults will be detectable. Consequently, we proceed to investigate the method for coding vector determination so that the resulting checker can have higher fault coverage.

B . Coding Vector Determination

In [14], a brief description of a possible method for selection of a coding vector to improve fault coverage is given. However, the selected coding vector can not guarantee the detectability of other faults with changes larger than x percent and less than $-x$ percent. For mission critical applications, the uncorrected and nonstoped malfunction of the functional circuitry may result in disaster, in which case, error detection circuitries with higher fault coverage are necessary. The method proposed in this paper for coding vector determination is based on error signal analysis. To do so, the error signal is expressed as a function of the component values, external inputs and s, as shown in the following expression rather than the state variable representation in Section II:

$$e(s) = F(r_1,\ r_2,\ \ldots,\ r_p,\ s,\ u_1(s),\ u_2(s),\ \ldots,\ u_m(s))$$

where r_i is the value of the ith component and $u_i(s)$ is the ith external input.

When component r_{ki} in SC_i is faulty and its value changes from its nominal value r_{ki} into $r_{ki}+\Delta r_{ki}$, the magnitude of the error signal is noted as $|e(\Delta r_{ki}, f)|$, where f is the frequency which satisfies $s=j2\pi f$. Because the other components except for r_{ki} are fault-free, there are only two variables (Δr_{ki}, f) in $|e(\Delta r_{ki}, f)|$. The ith entry α_i in the coding vector can be selected by the following procedure:

ALGORITHM Coverage(α_i)
BEGIN
x_{ki}:=maximum permitted relative deviation of the kith component (tolerance);
$|e_0|$:=threshold of |e(s)|;
$\Re$:=range of the operational frequencies of the functional circuitry;
z:=number of passive components in SC_i;
FOR k:=1 **TO** z **DO**

$$V_{ki} = \min_{\substack{|\Delta r_{ki}| > r_{ki} x_{ki} \\ f \in \Re}} \left\{ \frac{|e(\Delta r_{ki}, f)|}{|\alpha_i|} \right\};$$

$$V_i = \min_{k=1,\ldots,z} \{V_{ki}\};$$

Select non-zero $|\alpha_i|$ such that $V_i |\alpha_i| \geq |e_0|$;
END

For every component r_{ki} in SC_i, if its value is beyond the nominal value r_{ki} by a deviation Δr_{ki} such that $|\Delta r_{ki}| \geq r_{ki} x\%$, then $|e(\Delta r_{ki}, f)| \geq |e_0|$. Therefore, at every operational frequency, the error due to the fault can be observed at the error signal. Repeating the procedure can find out all the entries in the coding vector. If the coding vector is selected using the above method, the fault can be observed at all the operational frequencies. This is very important for a real time system. Once a fault occurs, it can be observed immediately so that necessary correction or maintenance can be made in time.

The above algorithm results in such a coding vector that can make any fault detectable at any operational frequency. The only drawback occurs when there is a large difference between the maximum value and the minimum value of the magnitude of the error signal in the case of a fault. In this case, for each component r_{ki} in SC_i, note that

$$MAXE_{ki}(\Delta r_{ki}) = \frac{|e(\Delta r_{ki}, f_{ki}(\Delta r_{ki}))|}{|\alpha_i|} = \max_{f \in \Re} \left\{ \frac{|e(\Delta r_{ki}, f)|}{|\alpha_i|} \right\}$$

where function $\frac{|e(\Delta r_{ki}, f)|}{|\alpha_i|}$ reaches its maximum value at frequency $f_{ki}(\Delta r_{ki})$ when Δr_{ki} is regarded as a parameter. The following alternative algorithm can be used to determine α_i.

ALGORITHM Coverage_Alt(α_i)
BEGIN
x_{ki}:=maximum permitted relative deviation of the kith component (tolerance);
$|e_0|$:=threshold of |e(s)|;
$\Re$:=range of the operational frequencies of the functional circuitry;
z:=number of passive components in SC_i;
FOR k:=1 **TO** z **DO**

$$V_{ki}^{(Alt)} = \min_{|\Delta r_{ki}| > r_{ki} x_{ki}} \{MAXE_{ki}(\Delta r_{ki})\};$$

$$V_i^{(Alt)} = \min_{k=1,\ldots,z} \{V_{ki}^{(Alt)}\};$$

Select non-zero $|\alpha_i|$ such that $V_i^{(Alt)} |\alpha_i| \geq |e_0|$;
END

There are several ways to get the local minimum / maximum value of a function with multiple variables over a

range. One can use the existing tools such as Mathematica, MATLAB and MATHCAD. A program in programming languages such as C can also be written to calculate the minimum / maximum value.

V. AN EXAMPLE

We take the active low-pass filter shown in Figure 2 as an example. Its range of operational frequencies is $\Re$=[0, 1KHz] approximately. Table 2 lists the minimum values V_{ki} calculated by algorithm Coverage(α_i) as well as the maximum values $V_{ki}^{(max)}$ calculated in the similar way as V_{ki} for each component except for R_{11} and R_{12} which do not appear in the state equations. It is obvious that there is a large difference between V_{ki} and $V_{ki}^{(max)}$. Therefore, the second algorithm is used to determine the coding vector. It yields that V_1=0.00110895 and V_2=0.00159956. Under the assumption that the threshold of the error signal is $0.01V_P$ where V_P=1V is the amplitude of the input signal in this example, the coding vector can be selected to be (10, 8) which can be used to construct the corresponding error detection circuitry as shown in Figure 5. Algorithm Coverage(α_i) can guarantee that every fault for each component is detectable by the error detection circuitry except for theoretically undetectable components.

VI . CONCLUSIONS

Fault coverage is an important performance index of an error detection scheme. This paper addresses the fault coverage issue of the continuous checksum-based concurrent error detection and correction scheme for linear analog systems. A method for improving fault coverage of the scheme is proposed by means of error signal analysis. The method can be combined with the hardware overhead reduction algorithm to design a more practical analog checker.

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Table 2: MINIMUM AND MAXIMUM VALUES

VALUE	R_4	R_5	R_6
V_{ki}	5.84621e-5	5.16238e-6	4.22342e-5
$V_{ki}^{(max)}$	0.123983	0.0168351	0.0619899

R_7	R_8	R_{10}	C_3
1.05119e-6	1.04684e-5	1.08006e-5	1.05119e-6
0.0165408	0.0375665	0.0369173	0.0422155

(a) The first stage

VALUE	R_9	C_4
V_{ki}	1.6745e-005	1.6745e-005
$V_{ki}^{(max)}$	0.0185082	0.00917067

(b) The second stage

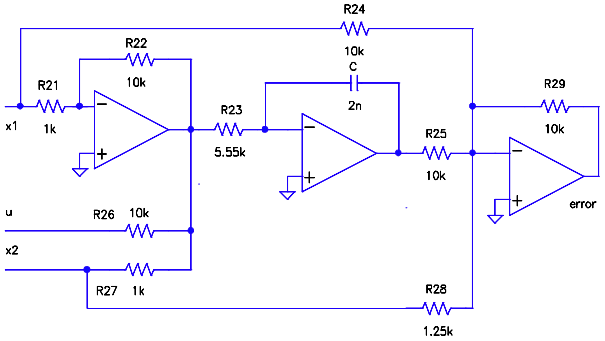

Figure 5: The alternative error detection circuit