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FAULT DIAGNOSIS OF A LOGICAL CIRCUIT BY USE OF INPUT GROUPING METHOD

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Abstracts The authors have already proposed a method for grouping of inputs of a logical circuit under test (LCUT) by use of M-sequence correlation. We call this method as input grouping (IG) method. In this paper, the authors propose a new method to estimate the faulty part in the circuit by use of IG when some information on the candidate of faulty part can be obtained beforehand. The relationship between IG and fault probabilities of a LCUT, and undetected fault ratios are investigated for various cases. Especially the investigation was made in case where the IG was calculated by use of n correlation functions (IG $_{inp}$). From the thoretical study and simulation results it is shown that the estimation error ratio of fault probabilities and undetected fault ratio of LCUT are suficiently small even when only a part of correlation functions are used. It is shown that the number of correlation functions which are to be memorized to calculate IG can be considerably reducible from $2^n - 1$ to n by use of IG $_{inp}$. So this method would be very usefull for a fault diagnosis of actual logic circuit.

Key words Correlation function, M-sequence, Logical circuit, Input grouping, Fault diagnosis

1. INTRODUCTION

The authors have already proposed a method for grouping of relevant and equivalent inputs of a logical circuit under test (LCUT) by use of M-sequence correlation [3]. We call this method as input grouping (IG) method. Relevant input implies those inputs which give some influence to the output, and equivalent input means those input pairs for which the output pattern does not change when they are exchanged. Input grouping shows the relation between the inputs and output, so this method is one of the method to represent the logical structure of the LCUT. The relevant inputs and equivalent inputs are calculated from the correlation functions between the input and output, when pseudorandom M-sequences are applied to the LCUT.

On the other hand, IG can also be calculated from a truth table. The authors showed that IG by use of correlation functions stated above, is far advantageous over the truth table method [4]. This is due to the fact that the number of correlation functions necessary to calculate IG can be considerably reducible, if we admit small parcentage of error.

In this paper, the relationship between IG and fault probabilities of a LCUT are investigated for various cases, and the undetected fault ratio by use of this IG are calculated. Especially the investigation was made in case where the input grouping by use of a part of correlation functions are carried out. And simulations were carried out for various kind of actual logical circuits, and it is shown that the undetected fault ratios of fault positions are suficiently small even when a part of correlation functions are used.

2. INPUT GROUPING

Fig. 1 shows block diagram of this IG method. Here $m_0(\tau)$ denotes any M-sequence signal and $m_i(\tau)$ denotes i digit delayed signal from $m_0(\tau)$. Crosscorrelation function C_i between the delayed signal m_i and the output Y is written as

$$C_i = \sum_{k=1}^{L} \{ 1 - 2 \times m_i(k) \oplus Y(k) \}$$

where ⊕ denotes an exclusive OR[2], and L denotes M-sequence period [1, 2].

Let's call input signals which are relevant to output as

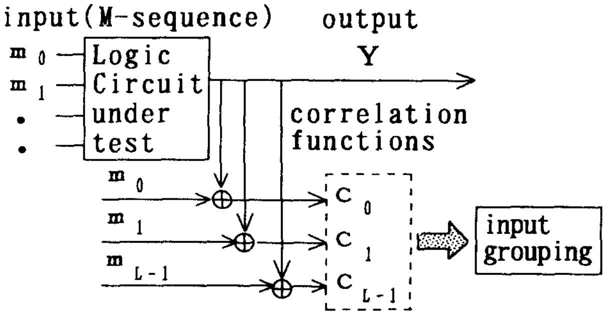

Fig. 1 Logic diagram of input grouping method

relevant signals, and as equivalent signals when these input signals are changed each other, the output signal doesn't change [3].

Grouping of inputs of a LCUT can be made by use of relevant and equivalent input. We call this grouping of inputs as Input Grouping (IG). For example IG of a logical circuit shown in Fig. 2 is (A B)(C D)(E), since {A, B} and {C, D} are equivalent input sets, E is a relevant input, and F is an irrelevant input.

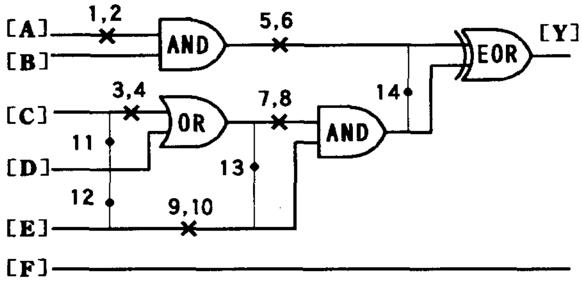

Fig. 2 Logic diagram of test logic circuit

3. APPLICATION OF IG FOR FAULT DIAGNOSIS

The authors propose a new method to estimate faulty parts in the circuit by use of IG when some information on the candidate of faulty part can be obtained beforehand. Let's call these locations where fault may occure as fault candidates. For example in Fig. 2 fault candidates are from 1 to 14, where from 1to 5 denotes stack-at-0 faults, from 6 to 10 stack-at-1 faults, and from 11 to 15 contact faults, respectively. Value 1 of fault candidate means there exists fault in this place, whereas value 0 denotes there is no fault. Let p be the number of fault candidates, then the number of all kind of fault logic circuits N becomes $N=2^p$. Let's call p bit 01 pattern of all the candidates as fault pattern.

Let's call the fault occurrence number at a candidate for arbitrary IG pattern as fault frequency of the candidate. Fault occurrence fequencies concerned with some IG pattern IG_i are calculated by the sum of the fault patterns whose IG are IG_i. Fault prpbability of each candidate is calculated as the fault ocurrence frequency devided by the number of IG_i. Fault positions in a faulty logic circut can be estimated as the fault probabilities of fault candidates.

The authors showed previously that IG can be calculated by use of a part of correlation functions when we admit small parcentage of error, and this IG method would be very useful because the number of correlation functions which are to be memorized to calculate IG can be considerably reducible. Therefore if we use only a part of correlation functions and in addition if fault probability of each candidate can be derived from IG calculated by use of a part of correlation functions, this method of fault diagnosis would be very useful.

In the next section, the authors have calculated theoretically the estimation error ratio of this fault probability of fault candidates of general circuit.

4. THEORETICAL STUDY OF FAULT PROBABILITY BY USE OF IG_{inp}

Let's call IG_{inp} as IG calculated by use of a part of correlation functions from C_0 to C_{n-1}, here n denotes the number of inputs of a logical circuit. And let's call IG_{norm} as IG by use of all correlation functions.

The theoretical calculations are carried out on the fault probabilities of the LCUT in case of IG_{inp}. And, the estimation error ratio of fault probabilities at the candidates, and the undetected fault ratio are obtained.

4.1 Estimation Error Ratio of Fault Probabilities by use of IG_{inp}

Let p be the number of fault candidates in LCUT, and these candidates be pos_1, pos_2, … pos_p. Table 1 shows fault occurrence frequency at the individual candidates when IG_{norm} was used, and Table 2 shows that of IG_{inp}. In Table 1, 2, pat=A ~ Z denotes kind of IG patterns, and freq=n_a ~ n_z, i_a ~ i_z means occurrence frequency of individual IG patterns. n_{jk} (j=a, b, …, z k=1, 2, …, p) denotes fault occurrence frequency at pat=J, pos_k in IG_{norm}, and i_{jk} demotes that of IG_{inp}.

Calculation error ratio of fault occurrence frequency by use of IG_{inp}, that is denoted as err, is defined as Eq. (1).

$$err = \frac{1}{N\cdot p} \sum_{j=a}^{Z} \sum_{k=1}^{p} |e_{jk}| \qquad (1)$$

$$e_{jk} = \left(\frac{n_{jk}}{n_j} - \frac{i_{jk}}{i_j} \right) n_j \qquad (2)$$

Here e_{jk} means wrongly estimated fault occurrence frequency by use of IG_{inp} at pat=J, pos_k. To calculate Eq. (1) it is necessary to estimate individual values of Table 1 and 2, but it is very difficult because they are affected by the locations of fault candidates and kind of logic circuits. So we will estimate Eq. (1) under the following assumptions from A1 to A6. In the following let pat=z be the IG pattern having no equivalent input.

(A1) When the number of all kind of n-input logic circuits is denoted as N, $N=2^{2^n}$.

(A2) E_{At} which is the number of logic circuits having no equivalent input in case where IG_{norm} is used is defined as Eq. (3) and n_z described by Eq. (4) denotes the same quantity for E_{At} in case where IG$_{inp}$ is used [3].

$$E_{At} = \binom{n}{2} 2^{-2^{n-2}} N \tag{3}$$

$$n_z = N - E_{At} \tag{4}$$

(A3) Assume that occurrence frequencies for several patterns of IG$_{norm}$ n_j's are all the same except pat=Z.

(A4) Assume that estimation error of IG$_{inp}$ against IG$_{norm}$ occurs only when the circuit is wrongly estimated as there exists equivalent inputs although there doesn't.

Let ε be estimation error ratio of IG$_{inp}$, then the following equation is derived [3].

$$n_z - i_z = \varepsilon N$$

From assumption A4, i_j's which are the occurrence frequencies for several patterns of IG$_{inp}$ are all the same except pat=z.

(A5) Assume that the kind of IG patterns of IG$_{inp}$ and that of IG$_{norm}$ are the same, and let w be that number.

To estimate Eq.(2), the following two cases are considered.

1) pat = A, B, … $\neq$ Z

In this case e_{jk} becomes as Eq.(5).

$$e_{jk} = \left(\frac{n_{jk}}{n_j} - \frac{n_{zk}}{n_z} \right) \frac{\varepsilon N}{w-1} \frac{E_{At}}{E_{At} + \varepsilon N} \tag{5}$$

In Eq.(5) n_{jk}/n_j, n_{zk}/n_z denotes fault ratio at pat=J, pos$_k$ and pat=Z, pos$_k$ by use of IG$_{norm}$ respectively, and they are values from 0% to 100% which are determined by the kind of LCUT and locations of fault candidates. Here we introduce the following 6th assumption.

(A6) Assume that the value of fault ratio n_{jk}/n_j, n_{zk}/n_z is one of 0%, 50% 100%, and appearance frequencies of these ratios are the same.

From assumption A6, Eq.(6) is derived.

$$E\left[\frac{n_{jk}}{n_j} - \frac{n_{zk}}{n_z} \right] = \frac{4}{9} \tag{6}$$

Here notation E[ ] denotes expected value.

2) pat = Z

In this case, e_{zk} is described by Eq.(7).

$$e_{zk} = \left(\frac{n_{zk}}{n_z} - \frac{i_{zk}}{i_z} \right) n_z \tag{7}$$

By using of assumption A6, Eq.(8) is derived.

$$E\left[\left| \frac{n_{zk}}{n_z} - \frac{i_{zk}}{i_z} \right| \right] = \frac{1}{9} \min \left(\frac{\varepsilon}{1-\varepsilon}, 1 \right) \tag{8}$$

Here min (A, B) means minimum value of A, B. From Eq.(1), Eq.(5) through Eq.(8) calculation error ratio of fault probability (denoted as err) is derived as Eq.(9). Calculation result of Eq.(9) is shown in Table 3.

$$err = \frac{4}{9} \varepsilon \frac{E_{At}}{E_{At} + \varepsilon N} + \frac{1}{9} \min \left(\frac{\varepsilon}{1-\varepsilon}, 1 \right) \tag{9}$$

Table 1 Fault frequencies concerned with IG$_{norm}$

pat.	freq.	pos$_1$	pos$_2$	pos$_3$	…	pos$_p$
A	n_a	n_{a1}	n_{a2}	n_{a3}	…	n_{ap}
B	n_b	n_{b1}	n_{b2}	n_{b3}	…	n_{bp}
:	:	:	:	:	:	:
Z	n_z	n_{z1}	n_{z2}	n_{z3}	…	n_{zp}

Table 2 Fault frequencies concerned with IG$_{inp}$

pat.	freq.	pos$_1$	pos$_2$	pos$_3$	…	pos$_p$
A	i_a	i_{a1}	i_{a2}	i_{a3}	…	i_{ap}
B	i_b	i_{b1}	i_{b2}	i_{b3}	…	i_{bp}
:	:	:	:	:	:	:
Z	i_z	i_{z1}	i_{z2}	i_{z3}	…	i_{zp}

Table 3 Calculation result of err and miss concerned with IG$_{inp}$

n	ε (%)	err(%)	miss(%)
4	50.0	20.6	1.56
5	50.0	12.7	1.56
≧6	50.0	11.1	1.56
4	5.0	2.55	0.16
5	5.0	1.56	0.16
≧6	5.0	0.59	0.16
≧6	3.0	0.35	0.09
5	0.5	0.25	0.02

4.2 Undetected fault ratio by use of IG$_{inp}$

Undetected fault occurs at the candidate whose fault probability is calculated as >0 by use of IG$_{norm}$, but it becomes 0 by use of IG$_{inp}$. From above assumptions undetected fault occurs in case where pat=Z only.

Let's consider the case when a part of pat=Z is wrongly eatimated as pat=J by use of IG_{inp}. Assume that fault occurs at pos_k, then the case that the fault position pos_k is not detected is only the case that the following two cases occur simultaneously. Here α is a frequency of both a part of n_{zk} and included in εN, where εN means the number of estimation error of IG_{inp}.

① $n_{zk} \neq 0$ and fault frequency at pos_k in α is 0.
② $n_{zk} \neq 0$ and $n_{jk} = 0$

The ratio of ①,② becomes $\varepsilon/9$, 1/4 respectively. So the undetected fault ratio (denoted as miss) can be described as Eq.(10).

$$\text{miss} = \frac{1}{36}\varepsilon \qquad (10)$$

Calculated result of Eq.(10) is shown in Table 3. For example in Table 3, err = 11% and miss = 1.6% in case of $n \geqq 6$ and $\varepsilon = 50\%$. From Table 3 it is shown that err (the calculation error ratio of fault probability) is smaller than ε (IG estimation error ratio of IG_{inp}), and miss (undetected fault ratio) is much smaller than ε.

5. SIMULATION RESULT

Simulations were carried out by use of 5 kinds of logic circuit and the results are shown in Table 4. EXAM is the logic circuit shown in Fig.2. 74145, 7482,… are the logic circuits of 74 series. In Table 4 fault denotes the number of fault candidates. Fx and length denotes characteristic equation and length of M-sequence applied to the logic circuit respectively. From Table 4, we can say that the theoretical results are in good agreement with simulation results in spite of the fact that many assumptions were used in theoretical consideration.

From above discussions it is shown that the fault probabilities of the LCUT can be calculated by use of IG_{inp}. It is also shown that the number of correlation functions which are to be memorized to calculate IG can be considerably reducible from $2^n - 1$ to n by use of IG_{inp}. So this method would be very usefull for a fault diagnousis of actual logic circuit.

6.CONCLUSION

As an application of Input Grouping (IG), the authors proposed a new method to estimate the fault probabilities of individual fault candidates in LCUT.

Table 4 Simulation result of err and miss

Logic	EXAM	7464	7482	74138	74145
input(n)	5	11	5	6	4
output	1	1	3	8	10
fault(P)	15	13	14	14	12
fx	45	4005	45	103	23
length	31	2047	31	63	15
ε(%)	0.50	3.02	4.47	0.00	0.00
err(%)	0.12	0.00	1.99	0.00	0.00
miss(%)	0.01	0.00	0.32	0.00	0.00

Estimation error ratio of fault probability and undetected fault ratio of the LCUT by use of IG_{inp} were calculated theoretically, and simulations were carried out. Here IG_{inp} denotes IG calculated by use of a part of correlation functions from C_0 to C_{n-1}. The following results were obtained.

① Estimation error ratio of fault probability (err) is indicated by Eq.(9).
② Undetected fault ratio (miss) is indicated by Eq.(10).
③ Simulation results are in good agreement with thoretical results.

From the above investigations we see that the estimation error ratio of fault probability is smaller than ε (estimation error ratio of IG_{inp}), and undetected fault ratio is much smaller than ε. Therefore we can say that the fault probabilities of the LCUT can be calculated by use of IG_{inp}.

It is also shown that the number of correlation functions which are to be memorized to calculate IG can be considerably reducible from $2^n - 1$ to n by use of IG_{inp}. So this method would be very usefull for a fault diagnousis of actual logic circuit.

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