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Fault Detection of Logic Circuit by Use of M-Sequence Correlation Method

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Abstract

In this paper, the estimation of the structure of a logic circuit under test is made from the observation of the input-output correlation function by use of M-sequence, from which we can estimate whether or not any fault exist in the logic circuit. Especially, investigation was made in case of the 2_stage logic circuit. We checked theoretically the sequence of correlation function, and we have shown that the correlation function is a function of period of M-sequence only, and the appearing number of correlation function in a period is a constant value depending on the logic circuit only. And by computer simulations we have shown that the structure of the circuit under test can be estimated from the observation of sequence of correlation function.

1. Introduction

One of the authors has developed an efficient method of fault detection by use of so-called M-sequence (We call this method as MSEC method)[1]. In the MSEC method, it is estimated that the circuit under test has a fault or not, by calculating the input-output correlation function with input M-sequence signal shifted one bit by one bit to certain numbers, and by the comparison between the correlation function of the fault logic circuit and that of normal circuit. This method has a characteristic that the undetected fault ratio is extremely small, whereas the fault position in the circuit can not be estimated[2].

In this study, the estimation of the fault position was made from the investigation of the correlation function obtained by the MSEC method. That is, we can estimate the fault position from the comparison between the structure of fault circuit and normal circuit.

We have shown in the previous report[3,4] that the structure of the 1-stage AND or OR logic circuit having 2 to 5 inputs can be estimated from the observation of the sequence of correlation function.

In this paper,we checked theoretically the sequence of correlation function in case of 2_stage logic circuit, such as logic circuit shown in Fig.1, and with computer simulations, we show that the structure of the circuit under test is estimated from the observation of sequence of correlation function. This method of fault detection of logic circuit is considered to be used widely in practical logical board testing.

2. Sequence of correlation function

Let any M-sequence signal be a basic signal $m0(\tau)$, and denote the delayed signal from the basic signal as $m_a(\tau)$, where a is the delay digit. For example,

τ : 0 1 2 3 4 5 6 7 8 · · · · · L-1

$m_0(\tau)$: 1 1 1 1 0 1 0 1 1 0 0 1 0 0 0

$m_3(\tau)$: 0 0 0 1 1 1 1 0 1 0 1 1 0 0 1

Here L is the period of M-sequence.

We consider a logic circuit under test whose inputs are any delay signals $m_a(\tau), m_b(\tau), \cdots$ as shown in Fig.1. The correlation functions C_q between the output $Y(\tau)$ (which is 0 or 1) and delayed basic signal $m_q(\tau)$ are calculated. We call C_0 to C_{L-1} as the sequence of correlation function. In the following, we investigate the relation between the sequence of correlation function and the logic circuit and/or input signals.

The correlation function C_q between output $Y(\tau)$ and delay signal $m_q(\tau)$ is written as

$$C_q = L - 2 \times \sum_{\tau=0}^{L-1} D_q(\tau) \qquad (1)$$

$$D_q(\tau) = Y(\tau) \oplus m_q(\tau) \qquad (2)$$

where $\oplus$ denotes an exclusive OR.

3. Correlation function in case of 2-stage logic circuit

As one of the 2-stage logic circuits, we consider a logic circuit shown in Fig.1. Delay signal $m_a(\tau), m_b(\tau), m_c(\tau), m_d(\tau)$ are added to the inputs, where a,b,c,d are arbitrary delay values from the basic signal $m_0(\tau)$, so the output signal $Y(\tau)$ is written as follow.

$$Y(\tau) = (m_a(\tau) \cdot m_b(\tau)) + (m_c(\tau) \cdot m_d(\tau))$$

where · denotes AND, + denotes OR.

Correlation function C_q indicated by Eq.(1) can be solved in the following cases. We write $m_a(\tau), Y(\tau), D_q(\tau), \cdots$ as $m_a, Y, D_q, \cdots$, for simplicity.

○ Relation of the 4 inputs m_a, m_b, m_c, m_d.

- A : 4 inputs are independent of each other.
- B : $m_a = m_b \oplus m_c$
- C : $m_a = m_c \oplus m_d$
- D : $m_a = m_b \oplus m_c \oplus m_d$

○ Relation between delay signal m_q and inputs.

- α : $m_q = m_a, m_b, m_c, m_d$
- β : $m_q = m_{a\_b}, m_{a\_c}, m_{a\_d}, m_{b\_c}, m_{b\_d}, m_{c\_d}$
- γ : $m_q = m_{a\_b\_c}, m_{a\_b\_d}, m_{a\_c\_d}, m_{b\_c\_d}$
- δ : $m_q = m_{a\_b\_c\_d}$
- ε : m_q is in other cases.

Here, m_{a_b} denotes $m_a \oplus m_b$, $m_{a\_b\_c}$ denotes $m_a \oplus m_b \oplus m_c$, and so on. For these cases ($A\alpha \sim A\varepsilon$, $B\alpha \sim B\varepsilon$, ··), the correlation functions C_q's were calculated as follows.

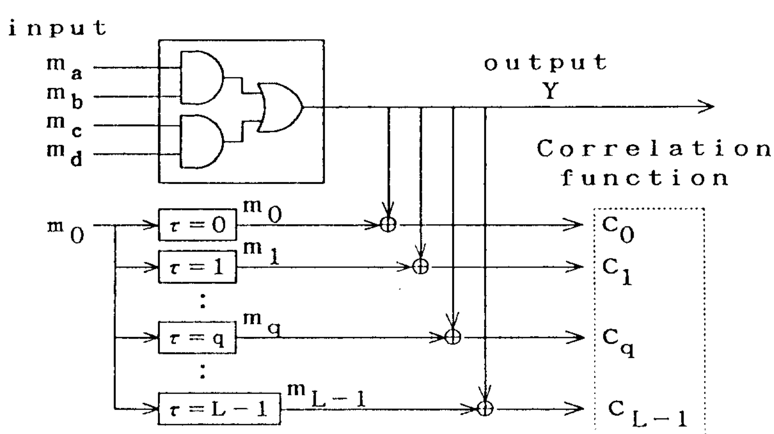

Fig.1 Block diagram for obtaining the sequence of Correlation function

3.1 In case of A

In this case, inputs are independent of each other, so the patterns [ma,mb,mc,md](in the following, this pattern is called as appearing pattern) in a period contain all patterns from [0000] to [1111] as shown in upper position of Table 1, and the numbers of the appearing pattern in a period (numbers Z) are all the same, except all zero pattern [0000] which is less than others by one, as shown in the number Z column of Table 1. These are one of the properties of M-sequence[5].

In Table 1, Y denotes output. In the line of $A\alpha \sim A\delta$ in Table 1, we see pattern of Dq, value of ΣDq, correlation function Cq, and appearing numbers in a period of M-sequence. In the following, we will describe these cases in detail.

Case $A\alpha$

In case of mq=ma, from Eq.(2), pattern of Da is as shown in Table 1, and $\Sigma Dq = 5s$, and so correlation function is $Ca = (3L-5)/8$ from Eq.(1).

In case of mq=mb, mq=mc, mq=md, the correlation function Cb,Cc,Cd is the same as Ca. Then the value (3L-5)/8 appears 4 times in a period, so the appearing number $n=4$.

Case $A\beta$

Calculating the same way as in the case of $A\alpha$, $Cq=-(3L+11)/8$ in the case of mq=ma_b and mc_d (so $n=2$).
$Cq=(L-7)/8$ in the case of mq=ma_c, ma_d, mb_c and mb_d (so $n=4$).

Case $A\gamma$ and $A\delta$

Calculating similarly, the result is in Table 1.

Case $A\varepsilon$

Signal ma,mb,mc,md and mq are independent of each other. So, pattern [ma,mb,mc,md,mq] in a period contain all patterns from [00000] to [11111] as shown in Table 2, and numbers Z are all the same expect the case of [00000]. Calculating similarly, $Cq=-1$ and $n=L-\Sigma$ (n in case of $A\alpha \sim A\delta$)

3.2 In case of B～D

In case of B～D, calculation was done similarly. The results in the case of A～D are shown in Table 3, which is arranged with respect to the correlation function ,appearing numbers, and appearing position. In this table, Cq with the period L=15 and L=31 are denoted as Corr(L=15,31).

Table 1 Pattern of input, output, Dq and Cq in case of logic
$Y = (ma \cdot mb) + (mc \cdot md)$ (case $A\alpha \sim A\delta$)

	signal	pattern	ΣDq	Correlation	n
	ma mb mc md Y	0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 0 0 1 0 0 0 1 0 0 0 1 1 1 1 1			
$A\alpha$	Da Db, Dc, Dd	0 0 0 1 0 0 0 1 1 1 1 0 0 0 0 0	5s	(3L-5)/8	4
$A\beta$	Da_b Dc_d	0 0 0 1 1 1 1 0 1 1 1 0 1 1 1 1	11s	-(3L+11)/8	2
	Da_c Da_d, Db_c, Db_d	0 0 1 0 0 0 1 0 1 1 0 1 0 0 1 1	7s	(L-7)/8	4
$A\gamma$	Da_b_c Da_b_d, Da_c_d, Db_c_d	0 0 1 0 1 1 0 1 1 1 0 1 1 1 0 0	9s	-(L+9)/8	4
$A\delta$	Da_b_c_d	0 1 1 1 1 0 0 0 1 0 0 0 1 0 0 1	7s	(L-7)/8	1
number Z		s-1 s s s s s s s s s s s s s s s	s=(L+1)/16		

Table 2 Pattern of input, output, Dq and Cq in case of logic $Y = (ma \cdot mb) + (mc \cdot md)$ (case ε)

	sig.	pattern (··· denotes omission)	ΣDq	Corr.
	ma	0 0 0 0 0 0 0 0 · · 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1		
	mb	0 0 0 0 0 0 0 0 · · 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1		
	mc	0 0 0 0 1 1 1 1 · · 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1		
	md	0 0 1 1 0 0 1 1 · · 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1		
	mq	0 1 0 1 0 1 0 1 · · 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1		
	Y	0 0 0 0 0 0 1 1 · · 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1		
Aε	Dq	0 1 0 1 0 1 1 0 · · 1 0 1 0 1 1 0 1 0 1 0 1 0 1 0	7s	-1
number Z		s-1 s s s s s s s · · s s s s s s s s s s s s s s s	s=(L+1)/32	

Table 3 Correlation function, appearing position, appearing numbers in case of $Y = (ma \cdot mb) + (mc \cdot md)$

A	Correlation appearing numb. appearing pos.	(3L-5)/8 4 a,b,c,d	-(3L+11)/8 2 a_b,c_d	(L-7)/8 5 a_c,a_d,b_c b_d,a_b_c_d	-(L+9)/8 4 a_b_c,a_b_d a_c_d,b_c_d	-1 L-15
	Corr.(L=15,31)	5,11	-7,-13	1,3	-3,-5	-1,-1
B	Correlation appearing numb. appearing pos.	(L-1)/2 3 a,b,d	-(L+3)/2 1 c_d			-1 L-4
	Corr.(L=15,31)	7,15	-9,-17			-1,-1
C	Correlation appearing numb. appearing pos.	(L-1)/2 3 b,c,d	-(L+3)/2 1 a_b			-1 L-4
	Corr.(L=15,31)	7,15	-9,-17			-1,-1
D	Correlation appearing numb. appearing pos.	(L-3)/4 6 a,b,c,d a_c,a_d	-(3L+7)/4 1 a_b			-1 L-7
	Corr.(L=15,31)	3,7	-13,-25			-1,-1

From Table 3, we see that in the sequence of correlation function, the value (3L-5)/8 at the position of q=a,b,c,d and the value -(3L+11)/8 is q=a_b,c_d and so on.

4. Other type of 2 stage logic circuit

We calculated similarly with the logic type $Y = (ma+mb) \cdot (mc+md)$, $Y = (ma+mb) + (mc \cdot md)$, $Y = (ma \cdot mb) \cdot (mc+md)$, and the result is shown in Table 4 in case of logic type $Y = (ma+mb) \cdot (mc+md)$.

These calculations are valid for any characteristic polynomial fx. So, we see the following facts from these tables.

1. Correlation function is a function of period of M-sequence only, and independent of characteristic polynomial fx.
2. Appearing number of correlation values is a constant value, and is independent of either fx or L, but it is determined by the logic type.
3. From the position of the specific correlation function whose appearing position contains the input delay values, the input signals can be estimated.

We will indicate how to estimate the input signals in the following section.

Table 4 Correlation function, appearing position, appearing numbers in case of $Y=(ma+mb)\cdot(mc+md)$

A	Correlation appearing numb. appearing pos.	(3L-5)/8 6 a,b,c,d a_b,c_d	-(L+9)/8 9 a_c,a_d,b_c,b_d,a_b_c a_b_d,a_c_d,b_c_d,a_b_c_d		-1 L-15
	Corr.(L=15,31)	5,11	-3,-5		-1,-1
B	Correlation appearing numb. appearing pos.	(3L-1)/4 1 c	(L-3)/4 4 a,b,d,c_d	-(L+5)/4 2 a_d,b_d	-1 L-7
	Corr.(L=15,31)	11,23	3,7	-5,-9	-1,-1
C	Correlation appearing numb. appearing pos.	(3L-1)/4 1 a	(L-3)/4 4 b,c,d,a_b	-(L+5)/4 2 b_c,b_d	-1 L-7
	Corr.(L=15,31)	11,23	3,7	-5,-9	-1,-1
D	Correlation appearing numb. appearing pos.	(3L-1)/4 1 a_b	(L-3)/4 4 a,b,c,d	-(L+5)/4 2 a_c,a_d	-1 L-7
	Corr.(L=15,31)	3,7	3,7	-5,-9	-1,-1

5. How to determine the logic circuit and input signals.

If the value and the appearing numbers in the sequence of correlation function observed from the logic circuit under test, agree with one of these tables, the structure of the circuit is estimated from the table. And from the appearing position of the specific correlation function, input signals can be estimated.

For example, we suppose that the logic circuit under test is $Y=(ma+mb)\cdot(mc+md)$, the delay value a,b,c,d are 0,1,2,3, and the characteristic polynomial is fx=23(in octal notation). Then the sequence of correlation function is observed as follows.

q	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Cq	5	5	5	5	-7	1	-7	-3	1	1	-3	-3	1	-3	1

Let us arrange the above sequence according to value[appearing number], then we obtain 5[4], -7[2], 1[5], -3[4]. Since the period of fx=23 is L=15, we compare the above sequence with corr.(L=15) and appearing numbers in the tables, we see that the corresponding table is Table 3 and the case is A. So, it is derived that the logic type under test is $Y=(ma+mb)\cdot(mc+md)$.

Next, from appearing position of the value (3L-5)/8 (=5), it is derived that the delay values a,b,c,d are 0,1,2,3. But it is not yet known which one out of a,b,c,d corresponds to 0,1,2,3.

These pairs are derived as follows. From Table 3, the appearing position of -(3L+11)/8 (=-7) are a_b,c_d, and from the sequence of correlation functions, these positions are 4,6. Since a_b denotes $ma\_b=ma\oplus mb$ and c_d denotes $mc\_d=mc\oplus md$, following equations are derived. $m4=m0\oplus m1$, $m6=m2\oplus m3$. Therefore, it is derived that input pairs are {m0, m1} and {m2, m3}. So, the logic under test is estimated as $Y=(m0+m1)\cdot(m2+m3)$.

But if the relation of inputs derived from the observed correlation function is in case B~D, the logic circuit and input signals are not determined uniquely, because the number of inputs are sometimes estimated as less than 4 such as $Y=(m0+m1)\cdot m2$. In these cases, it can be determined by changing fx until the relation of inputs becomes in the case A.

Table 5 shows a result of computer

simulations with the logic type $Y=(ma+mb)\cdot(mc+md)$.

In simulations we set a=0, and varied b,c,d from 1 to 14, so the number of combination we checked is 2184(=14*13*12). And fx we used are fx0=23, fx1=45,····fx8=211. The structure of the circuit under test was calculated from fx0 to fx8, until the structure was completely estimated. For example, in the Table 4, the low fx3=67 shows that the number of cases we have tested was 274, until the structure is estimated completely with fx3, and not determined correctly with fx1,fx2. Table 5 shows that, the structure of the circuit was correctly estimated by use of the characteristic polynomial fx up to fx5, in case of logic $Y=(ma+mb)\cdot(mc+md)$.

Table 5 Estimation process when the circuit is logic $Y=(ma\cdot mb)+(mc\cdot md)$

fx used		no. of combinations (ex. of input)
OK	fx0=23	0
	fx1=45	1086 (0 1 2 3)
	fx2=75	756 (0 1 2 4)
	fx3=67	274 (0 1 2 5)
	fx4=103	60 (0 1 4 14)
	fx5=147	8 (0 3 11 12)
	fx6=155	0
	fx7=203	0
	fx8=211	0
not completely determined		0
unable to determin		0
total number		2184

6. Conclusion

We checked theoretically the sequence of correlation function at the 2-stage logic circuits by use of M-sequence, and investigated the relation between input-output correlation function and the structure of the logic circuit. The main results are as follows.

1. Correlation function is a function of period of M-sequence only, and independent of characteristic polynomial fx.
2. Appearing number is a constant value, and is independent of either characteristic polynomial fx or a period of M-sequence L, and it is determined by the logic type.
3. From the appearing position of the specific correlation function, the input signals are estimated.
4. The structure of the logic circuit can be estimated from input-output correlation function, so the fault position can be estimated from the comparison between the structure of the fault logic circuit and that of normal circuit.

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