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OBSERVABILITY ESTIMATION OF A STATE VARIABLE WHEN THE LOS TECHNIQUE IS APPLIED

Structural scan based delay testing is used for detecting the circuit delays. Because of architectural limitations not an each test pair can be applied through a scan delay test. Enhanced scan techniques were developed to remove these restrictions on vector pairs. Unfortunately these techniques have rarely been used in practice because of the near doubling of the flip-flop area. Most promising are partial enhanced scan approaches based on partial selection of flip-flops for including them in enhanced scan chains. The problem is how to select proper flip-flops. In this paper we suggest to estimate flip-flop observability as a probability of robust PDF manifestation for paths connected with corresponding state variable in the frame of the LOS technique. It is desirable to include in enhanced scan chains flip-flops with low observabilities of corresponding state variables. The algorithm of observability calculation is developed and experimental results are presented.

Keywords: path delay fault (PDF); robust PDF; equivalent normal form (ENF); Launch-on-Shift (LOS) scan technique.

Because of architectural limitations not an each test pair $v_1, v_2$ can be applied through a scan delay test. Enhanced scan techniques were developed to remove these restrictions on vector pairs. Unfortunately these techniques have rarely been used in practice because of the near doubling of the flip-flop area. Most promising are partial enhanced scan approaches based on proper selection of flip-flops for including them in enhanced scan chains [1].

In the paper [2] it was suggested to include flip-flops with low estimations of controllability of corresponding state variables in scan chains. Facilities of signal change propagation from an input to an output of a circuit (observability) are not considered. In the paper [3] estimations oriented to cutting the test length and improving the test coverage were developed for both controllability and observability. In both papers estimations are related to providing the constant value for the state variable but not to providing the change of its value.

1. Calculation of observability estimation of a state variable

Suppose we have a synchronous circuit (Fig. 1) in which $x_1, ..., x_n$ are input variables, $y_1, ..., y_p$ are state variables, $z_1, ..., z_m$ are output variables, and $d_1, ..., d_p$ are flip-flops. Circuit $C$ is a combinational part of a sequential circuit.

Random input sequence of a sequential circuit is described with a probability distribution $\rho(x_1), ..., \rho(x_n)$. Here $\rho(x_i), i = 1, ..., n$, is a probability an input variable $x_i$ takes the 1 value on a random input vector. Assume that a probability distribution $\rho(y_1), ..., \rho(y_p)$ of state variables is also known.

The problem of probability calculation of robust PDF manifestation (calculation of observability estimation) for the state variable was considered in the paper [4] under
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suggestion that the vector $v_1$ of the test pair is a unit of random sequence with the given probability distribution of 1 values of input and state variables. Moreover each test pair $v_1, v_2$ can be applied through a delay test. The algorithm of observability estimation is based on deriving a ROBDD representation of all robust PDF test pairs for the path. Remind that ROBDD paths from its root to the 1 value terminal node represent a Disjoint Sum of Products (DSoP). In a DSoP all products are pairwise orthogonal. When the LOS technique is applied we also consider that the vector $v_1$ in the test pair is a unit of the random sequence but the vector $v_2$ is obtained by single right cyclic shift among state variables of the vector $v_1$. The latter means that not an each test pair $v_1, v_2$ can be applied in the frame of the LOS technique. In that case we first suggest deriving a ROBDD representation of all robust PDF test pairs for each product (of the Equivalent Normal Form) that generates test pairs. Then we derive prime products for each function represented by a ROBDD. After that we correct prime products in order to provide existence of test pairs in the frame of the LOS technique.

Consider ENF products containing the literal representing the path $\alpha$. In line with theorems 1, 2 [4] such products may originate robust PDF test pairs. Find all robust test paths both for rising and falling transitions of the given path originated by one product of ENF [4]. For that we have to find product $K$ that does not contain repeated variable $x_i$. Analyzing ENF we don’t pay attention to index sequences of literals representing paths of the circuit. All roots of the special equation [4] $D = 0$ are represented as ROBDD $R$. $R$ is compact description of a disjoint sum of products (DSoP). Exclude the variable $x_i$ from $K$ and obtain the product $K^*$. Represent the expression $K^* \& DSoP$ as ROBDD $R^*$. Each path of $R^*$ from the root till the 1 terminal node represents the product corresponding to $2^{n-r-1}$ robust test pairs consisting of neighboring Boolean vectors. Here $r$ is a rank of the product originated by the $R^*$ path and $n$ is the number of ENF variables.

Extract from the $R^*$ sum of all prime products and denote it as a SoPP. Any product of the SoPP represents conditions for forming test pairs: each test pair must have same a) among variables of $K^*$ (theorems 1, 2, point 4, [4]) and b) among subset of the rest variables (except $x_i$) which provide orthogonality to products of the set $K$ (theorems 1, 2, point 3[4]). Notice that all minimal subsets are represented with prime products of the SoPP and we need them all in order to keep all test pairs. Experimental results showed that SoPPs as a rule are rather simple.

Let $K_j$ be the product of the SoPP. Consider the following proposals.

**Proposal 1.** Product $K_j$ from the SoPP with literals $y_k, y_{k+1}$ ($y_k, y_{k+1}$), $k \neq i-1$, does not originate robust test pairs (if $k = n$, then $k+1 = 1$).

**Proof.** Really both vectors $v_1, v_2$ must turn the product $K_j$ into the 1 but it is impossible if the $K_j$ contains literals $y_k, y_{k+1}$ ($y_k, y_{k+1}$), $k \neq i-1$, as $v_2$ is obtained from $v_1$ by single right cyclic shift among state variables. The proposal is proved.

**Proposal 2.** The product $K_j$ from the SoPP with literals $y_{i-1}, y_{i+1}$ ($\overline{y}_{i-1}, \overline{y}_{i+1}$) does not originate robust test pairs. If $i = n$ we should consider literals $y_{n-1}, y_1$ ($\overline{y}_{n-1}, \overline{y}_1$), if $i = 1$ – literals $y_n, y_2$ ($\overline{y}_n, \overline{y}_2$).
Proof. Really both vectors \(v_1, v_2\) must turn the product \(K_j\) into the 1 and at the same time provide the value change of the variable \(y_i\). But it is impossible if the \(K_j\) contains above mentioned literals as \(v_2\) is obtained from \(v_1\) by single right cyclic shift among state variables. The proposal is proved.

If a product \(K^*\) in accordance with proposals 1 and 2 does not originate robust test pairs it must be excluded from the consideration. Consider \(K^*\) that may originate robust test pairs.

Find the proper \(R^*\) and the SoPP. Exclude from the SoPP products which don’t originate robust test pairs. Denote the result as the SoPP*. Consider the SoPP* and find all test pairs originated by these products when the LOS technique is used. Represent them as a ROBDD \(R(K_j)\). For that we have to do the following.

1. If a literal \(y_{k-1}\) is absent in the \(K_j\) from the SoPP* but a literal \(y_k\) is present, \(k \neq i, k-1 \neq i\) then add the literal \(y_{k-1}\) into the \(K_j\) so that signs of inversions of both these literals are the same (if \(k = 1\), then \(k - 1 = n\)). This procedure provides turning the product \(K_j\) into the 1 by both vectors \(v_1, v_2\) when the LOS technique is used.

Recall that any product \(K_j\) does not contain the variable \(y_i\). Add this variable to generate robust test pair providing the state variable value change.

2. If variables \(y_{i-1}, y_{i+1}\) are both present in the \(K_j\) add the variable \(y_i\) with the same sign of inversion that the variable \(y_{i+1}\) has.

3. If the variable \(y_{i+1}\) is present in the \(K_j\) but \(y_{i-1}\) is absent add the variable \(y_i\) with the same sign of inversion that the variable \(y_{i+1}\) has and add \(y_{i-1}\) with the opposite sign of inversion.

4. If the variable \(y_{i+1}\) is absent in the \(K_j\) but \(y_{i-1}\) is present add variables \(y_i, y_{i+1}\) with the opposite sign of inversion that the variable \(y_{i-1}\) has.

5. If variables \(y_{i-1}, y_{i+1}\) are absent in the product \(K_j\) we generate two products from the \(K_j\). One is obtained by appending \(y_i y_{i+1}\) without an inversion and the variable \(y_{i-1}\) with an inversion. Another one by appending \(y_i y_{i+1}\) with an inversion and \(y_{i-1}\) without an inversion.

If \(i = n (i = 1)\) the similar 2–5 conditions may be formulated for variables \(y_{n-1}, y_1\) \((y_n, y_2)\).

Points 2–5 provide conditions for turning the product \(K_j\) into the 1 on vectors \(v_1, v_2\) and for the value change of the state variable \(y_i\) in the test pair. After executing points 1–5 for all products of the SoPP* we obtain the SoP*. We should additionally check products of the SoP* against proposals 1, 2, because of boundary conditions may not be satisfied after appending some variables in points 1–5. After exclusion some incompatible products we obtain SoP**. Its products may not be prime products but each of them provides generation of robust test pairs which turns into the 1 corresponding product of the SoPP*.

Execute disjunction of all SoPs** corresponding to different ENF products related to the path \(\alpha\) and represent this disjunction as a ROBDD \(R_\alpha\).

It should be noted that in special case, when \(n \leq 3\) (number of state variables is less than or equal to 3) all observabilities are equal to 0 because of incompatibility with proposals 1, 2.

Theorem 1. When using the LOS technique the robust test pair exists if and only if the vector \(v_1\) is absorbed with a product contained in the ROBDD \(R_\alpha\).

Proof. Let the vector \(v_1\) be absorbed with one product \(K\) from the DSoP corresponding to the \(R_\alpha\). Show that \(v_1\) forms the robust test pair when the LOS technique...
is used. From the construction of the DSoP we conclude that the variable $y_i$ changes its value to opposite one on the vector $v_2$. As the $K$ is absorbed by at least one product from the SoPP* (proper $K_j$) then vectors $v_1$, $v_2$ keep values of variables of the product $K^*$ (theorems 1, 2, point 4) and vectors $v_1$, $v_2$ are orthogonal to the set $K$ (theorems 1, 2, point 3). It means that $v_1$ and $v_2$ form robust PDF test pair together.

Let we have the robust test pair so that the vector $v_2$ is built in the frame of the LOS technique. Show that the vector $v_1$ of this test pair is absorbed with a product from the DSoP corresponding to the $R_\alpha$. The construction of the ROBDD corresponding to the $R_\alpha$ let us forming $v_2$ from any possible $v_1$: we have in the proper SoP** all necessary minimal subsets of variables for providing the orthogonality to products of the set $K$. The ROBDD $R_\alpha$ contains functions represented by all necessary SoPs** and consequently $v_1$ is absorbed with a product of the DSoP of the $R_\alpha$. The theorem is proved.

Using $R_\alpha$ and the probability distribution of input and state variables we may calculate a probability of the robust PDF manifestation (observability estimation) along the path $\alpha$.

We can calculate observability estimation $P_{\alpha}(LOS)$ of the state variable $y_i$ for one circuit output by deriving ROBDDs for each path started at $y_i$ and terminated at this circuit output. For that we must summarize observability estimations for each path corresponding to the state variable and the circuit output as products representing test pairs for different paths terminated at one output are orthogonal.

To obtain more representative results we should calculate average observability estimation $P_{\alpha,avg}(LOS)$ of the state variable $y_i$ per all circuit outputs. In the similar way it is possible to calculate observability estimations for all state variables of the sequential circuit. We have got the following experimental results.

### 2. Experimental results

The suggested approach is based on ENF analysis and ROBDD application. ENF is very complicate formula for real circuits. It is possible to use OR-AND trees to present all paths of a circuit $C$ [5], one OR-AND tree for each output of a combinational part of a sequential circuit. These trees were used for finding estimations for benchmarks of the Table.

#### Experimental results of observability estimations for ISCAS89 benchmarks set

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Inputs</th>
<th>Outputs</th>
<th>State Variables</th>
<th>$P_{\alpha,avg}(LOS)*10000$</th>
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<td>CT2; CT0; CT1; MRVQN0; MRVQN1; MRVQN2; MRVQN3; AX0; ACVQN0; AX1; ACVQN1; AX2; ACVQN2; AX3; ACVQN3</td>
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Observability estimation of a state variable when the LOS technique is applied

<table>
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<tr>
<th>Circuit</th>
<th>Inputs</th>
<th>Outputs</th>
<th>State Variables</th>
<th>$P_{o,avg}(LOS)^*10000$</th>
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</tbody>
</table>
Flip-flops corresponding to state variables with low $P_{o,avg}(LOS)$ can be selected for including them in enhanced scan chains. The additional investigations are necessary for choosing the threshold values for $P_{o,avg}$.

**Conclusion**

The method of observability estimation based on probability calculation of robust PDF manifestation of all paths connected with a state variable in the frame of the LOS technique was developed. It allows grading state variables and including ones with low $P_{o,avg}(LOS)$ in enhanced scan chains.

**REFERENCES**