REDUCING TEST APPLICATION TIME THROUGH TEST SUB-PATTERN RE-USE

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Abstract: Test application time is a major factor of the cost associated with the scan technique. On one extreme, test application time can be drastically reduced by using built-in self-test (BIST). However, the quality of random test pattern used by BIST is low. On the other extreme, automated test equipment based testing using quality automatic test pattern generation is very time-consuming. Research in the area of economics of test application is directed towards finding a good blend of the two extremes to arrive at a workable optimal hybrid. A novel method for achieving this hybrid is presented in this paper. The approach used consists of a modification of the scan architecture and the development of a matching algorithm. The modified scan architecture involves the addition of a multiple-input signature register (MISR) to the scan chain. This way test responses are not captured in the scan chain but, rather, are compressed in the MISR. The proposed algorithm then takes advantage of repeated patterns in test vectors, by rearranging them such that those with matching patterns are adjacent to each other. An illustrating of how the algorithm works is also presented.

Key words: digital circuit testing, scan technique, test application time, multiple-input signature register, pattern matching algorithm.

1. Introduction.

The Scan Technique is a design for testability (DFT) method used to make sequential circuits easily testable. This is achieved by introducing flip-flops (latches) into the original design of the circuit. These flip-flops are designed and connected such that the circuit operates in two modes; normal and test modes [1, 2]. With such an arrangement, tests are applied to inaccessible lines in sequential circuits by shifting them into the flip-flops. The use of the scan technique requires that every bit in the test vectors is scanned-in one clock cycle. As a result, test application time increases in proportion to an increase in the number of test vectors and the number of bits per test vector.

Several solutions exist to minimise the test application time in the scan technique. One of such solutions is the use of multiple scan chains [3; 4]. Ordering of scan chains to obtain an optimal arrangement, is another method for minimising test application time. Although, Narayanan et al.[5] shows the ordering of registers in a scan chain to be a computationally complex problem, Narayanan[6] has shown that this is possible. The BIST-Aided Scan Test (BAST)[7] is also another method. Aside reducing test application time, it also reduces test data size.

Other techniques for minimising test application time include the use of reconfigurable scan chains [8, 9] and another one presented in Abramovici et al.[10]. The latter presents an approach that reduces the number of vectors for which bits are shifted into and out of scan flip-flops. It takes advantage of the possibility of grouping a large number of possible faults into sets with the following properties.

a. Each fault in a set has one or more test vectors that propagate the effects of those faults to the primary output of the circuit-under-test.

b. The state input parts of those test vectors are compatible with those of the vectors for the other faults within the set.

This paper presents a new approach to minimise test application time in scan based circuits. It is called...
the Pattern Match Approach. It consists of a modification of the scan architecture and an algorithm called the Pattern Match Algorithm (PMA). The algorithm reduces the number of bits in a test vector that are shifted into and out of the scan flip-flops.

In the next section the modified architecture is explained together with how it can be exploited to reduce the test vector scan-in time. Next, the algorithm is presented in Section 3, followed by an illustration (in Section 4) of its application. The paper ends with a conclusion.

2. Scan architecture modification

In the scan architecture, the flip-flops are arranged such that test vectors are scanned into them during the test mode. During normal mode, the scanned-in vectors, together with those from the primary inputs are applied to the circuit under test (CUT). The response is then captured in the flip-flops. In this process, the flip-flops that hold the scanned-in vectors are the same ones that capture the response. Therefore, the scanned-in vectors are cleared by the response from the CUT. This attribute of the scan architecture does not allow the re-use of patterns in a test vector that is already scanned in. As a result, the whole of the next test vector must be scanned in during the test mode.

According to Jha and Gupta[11], for a sequential circuit with \( m \) state inputs, if \( n \) vectors are needed to test for certain faults, the number of clock cycles taken to scan them in is shown in Equation (1). In addition, it takes the number of clock cycles shown in Equation (2) to scan the last response out. Putting together, the total number of clock cycles required to apply \( n \) test vectors to a circuit with \( m \) state inputs is shown in Equation (3).

\[
C_{\text{in}} = n(m + 1) \\
C_{\text{out}} = m - 1 \\
C_{\text{clk}} = C_{\text{in}} + C_{\text{out}} = n(m + 1) + m - 1
\]

(1) \hspace{1cm} (2) \hspace{1cm} (3)

It can be deduced that if test vectors are scanned in during \( \frac{m}{s} \) instead of \( m \) clock cycles, where \( m = ms - s \), then savings \( (\frac{m}{s}) \) in test application time can be achieved as shown in Equations (4) and (5).

\[
C'_{\text{in}} = n\left(\frac{m}{s} + 1\right) \\
C'_{\text{out}} = n\left(\frac{m}{s} - s\right) + 1 = C'_{\text{in}} - ns
\]

(4) \hspace{1cm} (5)

However, any reduction in the clock cycles required for the scan-in of a given test vector will leave part of the response to the previous test vector in the scan chain. This problem must be overcome in order to develop algorithms for minimising test application time based on the re-use of common patterns in test vectors. This can be dealt with by modifying the scan architecture, as shown in Figure 1.

![Scan Architecture used in the approach](image)

Figure 1: Scan Architecture used in the approach

The modified scan architecture consists of the circuit under test (CUT) with scan circuitry connected to its input. Its output is also connected with a multiple-input signature register (MISR) that has a serial output. The MISR is used to compress the response from the CUT into a signature. The signature is then scanned out at the end of the testing process through the serial output. It can be observed from the figure that only the MISR found in the traditional BIST architecture is incorporated. The pseudorandom binary sequence generator (PRBSG) is not used. Therefore, instead of pseudorandom patterns, deterministic vectors, pre-processed by an algorithm, are scanned into the CUT.

The addition of the MISR in the proposed architecture enables the separation of the response vectors from the scanned-in vectors. Whilst a response vector is captured by the MISR, the scanned-in vector stays in the scan flip-flops to be re-used. This arrangement makes it possible for algorithms, that pre-process test vectors prior to scan-in, to be developed. The pre-processing of vectors enables scan-in time to be minimised, thus, affecting the over-all test application time.

3. The pattern match algorithm.

The algorithm is made up of the Initialising Pivot Procedure, the Pivot Cycle Procedure and the Compare function. All these modules are used in the Main Procedure that implements the algorithm.
3.1. Terms and Variables used in the Algorithm

**Initializing vector** is the test vector used to set the output of a logic gate to the complement of the logic value expected when testing a fault under a fault model (such as the stuck-open fault) that requires a test pair. It also ensures that the complement logic is propagated to an observable output of the circuit under test. It is always the first vector of a test pair, however, note that there can be a situation where the second vector of a given test pair is also the first vector of the next test pair. An initializing vector is identified with an attribute \( i \).

**Dependent vector** is the second vector of a test pair. A dependent vector is identified with an attribute \( d \). If test vector \( t_i \) is the second vector of a given test pair and also the first vector of the next test pair, then \( t_p \) is both dependent and initializing.

**Independent vector** is a test vector that constitutes a complete test for a particular fault under a given fault model. An independent vector does not need any initializing vector.

**Pivot vector** is a vector that serves as the basis of comparison for other vectors.

**Starting Pivot Vector** is the first test vector to be used as a pivot vector in a cycle of the proposed algorithm.

**Pivot Cycle:** This refers to the period from the beginning of usage of a pivot vector till when a new one is selected.

\( \mathbf{A} \equiv [\mathbf{T}_i] \) is a \( m \times n \) matrix made up of binary elements, \( [d_{ik}] \) that form part of test vectors.

\( \mathbf{A}_{(p)} \) has the same size and test vectors as in matrix \( \mathbf{A} \). The starting pivot vector of \( \mathbf{A}_{(p)} \) is the vector at column \( p \) of \( \mathbf{A} \).

\( T_k = [d_{ik}] \) of \( \mathbf{A} \), for \( 0 \leq k \leq m - 1 \) and a constant \( k \), at any time. It serves as a space holder for test vectors—the value of any \( d_{ik} \) depends on the test vector held at \( T_k \) and the column operations that have been performed in the current pivot cycle.

\( k + 1 \) is the identifier of the test vector held at column \( T_k \) of \( \mathbf{A} \). At any instant of algorithm progression, \( k + 1 \) may occupy columns other than the \( k \)-th.

**NB:** In the algorithm, the name of the column a test vector currently occupies (instead of the actual identifier of that test vector) is used in a generic sense to refer to the test vector.

\( T^{(r)}_k \subset T^k \), where \( r \) signifies the number of least significant bits (elements) that have been shifted out of \( T^k \). In other words, \( T^{(r)}_k \subset T^k \) where \( T^{(r)}_k = [d_{ik}], r \leq i \leq m - 1 \). Thus \( T^{(0)}_k = T_k \), \( T^{(k-r)}_k = T_k \), where \( T_k = [d_{ik}], \) and \( 0 \leq r \leq m - r - 1 \).

**Skip, \( S \):** This signifies the length of a matched pattern in two test vectors that must be adjacent to each other (i.e., they must occupy columns \( k \) and \( k + 1 \)) according to the proposed algorithm. It specifies the number of elements in the second of the two test vectors that should be skipped by the ATE (and hence the number of celled cycles saved) during the scan-in. It is calculated as an integer attribute \( s \), where \( s = m - r \).

\( \mathbf{A}_{(p)} \) is the resultant matrix, or the optimum arrangement for minimising test application time when the test vector \( \mathbf{A}_{(p+1)} \) is used as the starting pivot vector. For each \( p \), \( \mathbf{A}_{(p)} \) is associated with an integer attribute \( Ssum_p \), the sum of skips of all test vectors in \( \mathbf{A}_{(p)} \).

\( k \) is the variable used to mark the column occupied by the current pivot vector.

\( x \) is the variable that marks the relative position of the column occupied by a test vector, with respect to the column occupied by the pivot vector.

\( y \) is the variable that represents the number of dependent vectors directly following an initialising vector.

3.2. The Compare Function

The Compare function takes two arguments, \( T^{(r)}_k \) and \( T^{(r)}_{k+1} \). If no match is found between the arguments, the function returns false otherwise it returns true. A match exists if,

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1 The two arguments are \( T^{(r)}_k \) and \( T^{(r)}_{k+1} \) when the Compare function is called in an Initialising Pivot Procedure.
∀ \( b_{ik} \) in \( T_k^{(r)} \), where \( r \leq i \leq m - 1 \), and
∀ \( b_{jk} \) in \( T_k^{(r)} \), where \( 0 \leq j \leq m - r - 1 \).
\( b_{ik} = b_{jk} = 0 \) or \( b_{jk} = 0 \) is a don't-care.

3.3. The Main Procedure

This is the main procedure of the proposed algorithm. In the algorithm all rotations are counterclockwise. The following steps describe the flow of the function.

Step 1: START
1. Set \( p = 0 \).
Step 2:
1. Is \( p < n \)?
   a. If NO,
      i. select the resultant matrix, \( A_{(p)} \), with the lowest value \( p \) having the highest value of \( S_{(p)} \). The selected \( A_{(p)} \) is an optimum matrix for reducing test application time for the test set.
      ii. Go to step 9.
   b. If YES,
      i. select \( S_{(p)} \) to null, \( r = 0 \), \( x = 0 \), and \( y = 0 \).
   c. Set \( k = p, r = 0, x = 0 \) and \( y = 0 \).
Step 3:
1. Is \( p \) a dependent vector?
   a. If YES,
      i. select \( S_{(p)} \) to null, \( r = 0 \), \( x = 0 \) and \( y = 0 \).
   b. Increment \( p \), and
      ii. Go to step 2.
Step 4:
1. Select vector \( p \).
2. Associate skip, \( y = 0 \) with the selected test vector, and
3. initialise variables as follows:
   \( k = p, r = 0, x = 0 \) and \( y = 0 \).
Step 5:
1. Is \( p \) an initialising vector?
   a. If YES,
      i. perform the Initialising Pivot Procedure.
Step 6:
1. If \( k > 0 \),
   a. rotate vectors from column 0 to \( k \) \( y \) times horizontally.
   b. Set \( k = y \).
   c. Increment \( x \), and
   d. set \( y = 0 \).
Step 7:
1. Is \( k < m - 1 \)?
   a. If YES,
      i. perform the Pivot Cycle Procedure, and
      ii. repeat Step 7.
Step 8:

1. Compute \( S_{(p)} \).
2. associate result with the resultant matrix, \( A_{(p)} \).
3. increment \( p \), and
4. go to Step 2.
Step 9: END

3.4. The Initialising Pivot Procedure

The Initialising Pivot Procedure is called when the newly found/selected pivot vector is an initialising vector. When the pivot vector is tested and found to be initialising, this procedure is executed according to the following steps.

Step 1: START
Step 2:
1. Increment \( y \), and
2. set \( r = 0 \).
Step 3:
1. Is \( r < m \)? (Are there still some elements in the initialising pivot vector yet to be shifted out?).
   a. If NO,
      i. set \( x = 0 \), and associate \( S \) with \( T_{(p)} \).
      ii. go to Step 6.
   b. If YES,
      i. increment \( r \), and
      ii. go to Step 3.
Step 4:
1. Perform the Compare function with \( T_{(p)} \) and \( T_{(m-p)} \) as the arguments.
   a. If the function returns false,
      i. increment \( r \), and
      ii. go to Step 3.
Step 5:
1. Compute skip, \( S \), and associate it with \( T_{(p)} \).
Step 6:
1. Is \( k \) an initialising vector?
   a. If YES,
      i. go to Step 2.
Step 7: END

3.5. The Pivot Cycle Procedure

The Pivot Cycle Procedure is called when the stage has been set for a fresh sequence of comparisons to be carried out after selecting a new starting pivot vector. The following steps are performed in the procedure.

Step 1: START
1. Set \( r = y = 0 \).
Step 2:
1. Is \( r < m \)?
   a. If NO,
      i. set \( x = 1 \)
ii. set \( r = m \), and 
iii. go to Step 8.

Step 3:
1. Is \( k + x > n \) ? (In other words, has the last vector been compared with the pivot vector?) 
   a. If YES, 
      i. set \( x = 1 \), 
      ii. increment \( r \), and 
      iii. go to Step 2.

Step 4:
1. Is \( t_{(k,n)} \) (the vector being compared with the pivot vector) a dependent vector? 
   a. If YES, 
      i. go to Step 7.

Step 5:
1. Perform the Compare function with \( t_{(k,n)} \) and \( t_{(k,n)} \) as the arguments.

Step 6:
1. Did the execution of the Compare function in step 5 return true? 
   a. If YES, 
      i. go to Step 8.

Step 7:
1. increment \( x \), and 
2. go to Step 3.

Step 8:
1. Compute skip, \( s = m - r \), and 
2. associate it with \( t_{(k,n)} \).

Step 9:
1. Is \( t_{(k,n)} \) an initialising vector? 
   a. If NO, 
      i. go to Step 11.

Step 10:
1. and 
2. perform Initialising Pivot Procedure.

Step 11:
1. If \( x > 1 \) 
   a. Rotate vectors from \( k + \) through \( k + \) times horizontally.

Step 12:
1. \( k = k + y + 1 \), 
2. \( x = 1 \), and 
3. \( y = 0 \).

Step 13: END

4. An illustration of application of the algorithm

In this illustration, the twelve test vectors in Table 1 are used. All bits of each vector are assumed to be applied to state inputs of the circuit under test. Labels row shows the attributes of vectors that are either initializing or dependent. The number of rows in the Vectors section of the table represents the number of elements, \( m \), in a test vector. In this test set \( m=6 \). The number of columns represents the number, \( n \), of test vectors (\( n=12 \)). The test set comprises of test vectors for faults in two fault models (one model requires test pairs and the other requires single test vectors). This mix was chosen to fully demonstrate the complete effect of the proposed algorithm.

4.1. Executing the Algorithm

The Main Procedure starts with the first vector (\( T_{p=0} \)) in the given matrix, \( A \) (Table 2) as a valid starting pivot vector, since \( T_{p} \) is not dependent. The variable \( k \) is set to \( 0 \) and so \( k = 0 \). The variables \( x \), \( y \) and \( r \) are each set to zero. Thus, \( x = y = r = 0 \). A skip, \( s = 0 \) is assigned to \( T_{p} \), as shown in Table 1. The vector \( T_{p} \) is not an initialising vector so the Initialising Pivot procedure is not executed. Since \( x > 1 \) no rotation is done. The variable \( k \) remains unchanged since \( y = 0 \). Variable \( x \) is incremented (\( x=x+1 \)). At this stage, \( k < (n-1) \), so the Pivot Cycle procedure is called.

### 3.6. The Test Application Process

When a test vector is about to be scanned in, the Automated Test Equipment (ATE) (under test program control) reads the skip value of the vector to determine the number of rows that must be skipped (i.e. the number by which to reduce the number of clock cycles per vector). A skip value of \( s \), tells the ATE to skip the first \( s \) bits of the vector and scan in the rest (thereby resulting in \( m-s \) shifts). Simultaneously the binary data within the scan register is shifted up just enough to accommodate the incoming \( m-s \) bits of binary data. The new test vector within the scan register is then applied to the CUT and the response captured by the MISR. In the case of test pairs, the MISR captures the responses produced by the second half-pairs. After all test vectors have been applied, the compressed response (signature) is scanned out of the MISR and compared with the signature of a fault-free circuit.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>( t_1 )</th>
<th>( t_2 )</th>
<th>( t_3 )</th>
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<th>( t_5 )</th>
<th>( t_6 )</th>
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<td>i</td>
<td>d/i</td>
<td>d</td>
<td>i</td>
<td>d/i</td>
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<td>d/i</td>
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<tr>
<td>( m &gt; )</td>
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<td>1</td>
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<tr>
<td>( m \leq )</td>
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<td>0</td>
<td>0</td>
<td>1</td>
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Table 2: Matrix A

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</tbody>
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Table 4: A Match Found at T, after a 2-bit shifting

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<th>T2</th>
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Table 3: Starting Pivot shifted up by 1 bit

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</table>

4.2. Executing the Pivot Cycle Procedure with \( T_9 \) as the Pivot Vector

In the Pivot Cycle procedure, each of the variables \( r \) and \( y \) is set to zero. Thus the condition \( r < m \) \((m = 6)\) is true, \( k \rightarrow x \rightarrow y \rightarrow T_{k}\rightarrow (T_k)\) is not a dependent vector and so the Compare function is executed with \( T_0 \) and \( T_2 \) as arguments. For \( r = 0 \), there is no match; thus \( x \) is incremented to 2. The execution of the Compare function, with \( T_0 \) and \( T_2 \) as arguments also returns false. The process of incrementing \( x \) and executing the Compare function continues—ignoring all dependent vectors, i.e. vectors \( T_0, T_4, T_6 \) and \( T_{12} \) are not used when encountered. At this stage \( T_0 \) is shifted up by one bit, thereby incrementing \( r \) to 1, as shown in Table 3. The variable \( x \) is re-set to 1, and the Compare function is executed with the arguments \( T_0 \) and \( T_2 \), where the latter argument takes values from \( T_0 \) to \( T_{12} \). This also does not lead to a match so \( r \) is incremented to 2 and \( x \) is reset to 1. With \( r = 2 \) and \( x = 5 \), \( T_0 \) is the second argument and the Compare function returns true (see Table 4). A skip, \( S = 6 \rightarrow 2 \rightarrow 4 \) is assigned to \( T_0 \) and since \( T_5 \) is not an initialising vector, vectors \( T_1 \) up to \( T_8 \) are rotated once horizontally. This brings the vector \( T_5 \) to column 1, as shown in Table 5. Variable \( k \) is updated to 1, and variables \( x \) and \( y \) are also reset to 1 and 0, respectively. The Pivot Cycle Procedure ends.

Table 5: The Second Pivot Vector

<table>
<thead>
<tr>
<th>Test ID</th>
<th>T0</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
<th>T7</th>
<th>T8</th>
<th>T9</th>
<th>T10</th>
<th>T11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Label</td>
<td>i</td>
<td>d/i</td>
<td>d</td>
<td>i</td>
<td>d</td>
<td>i</td>
<td>d</td>
<td>i</td>
<td>d</td>
<td>i</td>
<td>d</td>
<td></td>
</tr>
<tr>
<td>Skip</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 1 1 1 0 1 0 1 1 1 0 0</td>
</tr>
<tr>
<td>1 0 0 0 0 1 0 1 0 1 0 0</td>
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<tr>
<td>0 1 0 0 0 0 0 0 0 0 1 0</td>
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<tr>
<td>0 0 0 1 1 1 0 1 0 1 0 0</td>
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<tr>
<td>1 0 1 0 1 1 0 1 1 0 1 0</td>
</tr>
<tr>
<td>0 0 0 1 0 0 1 0 1 0 0 0</td>
</tr>
</tbody>
</table>

4.3. Executing the Pivot Cycle Procedure with \( T_1 \) as the Pivot Vector

Since \( k = (n-1) \), the Pivot Cycle procedure is executed again with \( T_1 \) as the pivot vector. With \( T_1 \) and \( T_{12} \) as arguments for the Compare function, no match is found for \( r = 0 \). \( T_{10} \) matches \( T_1 \) when \( r = 2 \) and \( x = 9 \) (see Table 6). A skip, \( S = 4 \) is assigned to \( T_0 \), and since \( T_{10} \) is an initialising vector, Initialising Pivot Procedure is invoked.

Table 6: A Match Found at T after shifting T by 2 bits up

<table>
<thead>
<tr>
<th>Test ID</th>
<th>T0</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
<th>T7</th>
<th>T8</th>
<th>T9</th>
<th>T10</th>
<th>T11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Label</td>
<td>i</td>
<td>d/i</td>
<td>d</td>
<td>i</td>
<td>d</td>
<td>i</td>
<td>d</td>
<td>i</td>
<td>d</td>
<td>i</td>
<td>d</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 1 1 1 0 1 0 1 1 1 0 0</td>
</tr>
<tr>
<td>1 0 0 0 0 0 1 1 1 0 0 0</td>
</tr>
<tr>
<td>1 0 1 0 0 0 0 0 0 0 0 1</td>
</tr>
<tr>
<td>0 1 0 0 0 1 0 1 0 1 0 1</td>
</tr>
<tr>
<td>0 1 0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>1 0 0 0 0 0 0 1 0 0 0 0</td>
</tr>
</tbody>
</table>
4.3.1. Executing the Initializing Pivot Procedure for $T_{40}$

The Initializing Pivot procedure starts by incrementing $y$ to 1 and setting $r$ to 0. Since $r < m$, the Compare function is executed with $T_{40}^{(r)}$ and $T_{40}^{(m)}$ (i.e., $T_{11}^{(m)}$ and $T_{11}^{(r)}$ where $T_{11}$ is the dependent vector of $T_{40}$) as arguments. No match is found. Variable $r$ is also incremented to 1, by shifting up the pivot vector by 1. The Compare function is executed again. This also does not produce a match. A match is, however, found when $r = 5$ (in Table 8) and the dependent vector, $T_{10}$ ($T_{11}$), is assigned a skip, $S = 6 - 5 = 1$. Since $T_{10}$ ($T_{11}$) is not an initialising vector, the Initialising Pivot procedure ends.

Still in Pivot Cycle Procedure, vectors $T_2$ to $T_{11}$ are rotated $y + 1 = 2$ times horizontally to bring $T_{11}$ to column 2, followed by $T_{10}$ in column 3, as shown in Table 8. Variable $k$ is updated to 3 whilst $x$ and $y$ are reset to 1 and 0, respectively. The Pivot Cycle procedure ends.

| Table 7: Comparing Initialising and Dependent Vectors ($T_{10}$ and $T_{11}$) |
|---------------------------------|---------------|---------------|---------------|---------------|
| $T_{10}$ $T_{11}$ $T_{12}$ $T_{13}$ $T_{14}$ $T_{15}$ $T_{16}$ $T_{17}$ $T_{18}$ $T_{19}$ $T_{20}$ $T_{21}$ |
| Test ID | $T_{10}$ | $T_{11}$ | $T_{12}$ | $T_{13}$ | $T_{14}$ | $T_{15}$ | $T_{16}$ | $T_{17}$ | $T_{18}$ | $T_{19}$ | $T_{20}$ | $T_{21}$ |
| Label | i | d | i | d | i | d | i | d | i | d | i | d |
| Skip 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 0 |
| | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 |
| | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 |
| | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 0 |
| | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 0 |
| | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 0 |

Table 8: $T_4$ as Pivot Vector

| $T_4$ $T_5$ $T_6$ $T_7$ $T_8$ $T_9$ $T_{10}$ $T_{11}$ $T_{12}$ $T_{13}$ $T_{14}$ $T_{15}$ |
|---------------------------------|---------------|---------------|---------------|---------------|
| Test ID | $T_4$ | $T_5$ | $T_6$ | $T_7$ | $T_8$ | $T_9$ | $T_{10}$ | $T_{11}$ | $T_{12}$ | $T_{13}$ | $T_{14}$ | $T_{15}$ |
| Label | i | d | i | d | i | d | i | d |

4.4. Executing the Pivot Cycle Procedure with $T_9$ as the Pivot Vector

Since $k < (m - 1)$, the Pivot Cycle procedure is executed again with $T_9$ as the pivot vector. Ignoring all dependent vectors, for example $T_6$, the Compare function with $T_9^{(r)}$ and $T_9^{(m)}$ as arguments returns true at $T_9$ when $r = 2$ and $x = 5$ (see Table 9). A skip, $S = 4$ is assigned to $T_7$ ($T_9$) and vectors $T_4$ up to $T_8$ are rotated once horizontally, bringing $T_2$ to column 4, as shown in Table 10. Variable $k$ is updated as $k = 5$ whilst $x$ and $y$ are reset to 1 and 0, respectively. The Pivot Cycle procedure ends.

4.5. Summary of the rest of Algorithm Execution

Still $k < (m - 1)$ and so the Pivot Cycle procedure is executed again with $T_6$ as the pivot vector. $T_6^{(k)}$ matches $T_{11}^{(m)}$, $T_{11}^{(r)}$ was assigned a skip $S = m - r = 6 - 5 = 1$. After rotating vectors $T_6$ through $T_{11}$ once, $T_6$ came to occupy column 5 as the pivot.

| Table 9: Comparison with $T_3$ |
|---------------------------------|---------------|---------------|---------------|---------------|
| $T_3$ $T_4$ $T_5$ $T_6$ $T_7$ $T_8$ $T_9$ $T_{10}$ $T_{11}$ $T_{12}$ $T_{13}$ $T_{14}$ $T_{15}$ |
| Test ID | $T_3$ | $T_4$ | $T_5$ | $T_6$ | $T_7$ | $T_8$ | $T_9$ | $T_{10}$ | $T_{11}$ | $T_{12}$ | $T_{13}$ | $T_{14}$ | $T_{15}$ |
| Label | i | d | i | d | i | d | i | d |
| Skip 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 0 |
| | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 |
| | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 |
| | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 0 |
| | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 |

Table 10: $T_4$ as Pivot Vector

| $T_4$ $T_5$ $T_6$ $T_7$ $T_8$ $T_9$ $T_{10}$ $T_{11}$ $T_{12}$ $T_{13}$ $T_{14}$ $T_{15}$ |
|---------------------------------|---------------|---------------|---------------|---------------|
| Test ID | $T_4$ | $T_5$ | $T_6$ | $T_7$ | $T_8$ | $T_9$ | $T_{10}$ | $T_{11}$ | $T_{12}$ | $T_{13}$ | $T_{14}$ | $T_{15}$ |
| Label | i | d | i | d | i | d | i | d | i | d | i | d |
From the table, the resultant matrices, \( A_{(9)} \) and \( A_{(10)} \), are assigned to the dependent vector, \( \mathbf{f}_2 \) (at \( T_{9} \)), and assigning \( S = m - r = 6 - 5 = 1 \) to the dependent vector, \( \mathbf{f}_2 \) (at \( T_{11} \)).

The Main Procedure continues by incrementing \( p \) to 1. In other words, \( \mathbf{f}_2 \) (at \( T_{1} \)), of matrix \( A \) is selected as next pivot without rotation because \( \chi > 1 \).

For increments of \( r \) from 1 through 6 did not result in any matches and so \( T_{8} \) becomes the next pivot vector with \( s = m - r = 6 - 6 = 0 \).

Now \( h = 11 \) and the condition, \( h < (n - 1) \), is false. The sum of all the skip values, \( \text{sum}_{s} \), is therefore computed and assigned to the resultant matrix, \( A_{(10)} \), as shown at the foot of Table 11.

Next, \( T_{2}^{(3)} \) matched \( T_{8}^{(-3)} \), a skip, \( S = 3 \), is assigned to \( \mathbf{f}_2 \) (at \( T_{6} \)), and, since \( T_{2} \) is an initialising vector, the Initialising Pivot procedure is executed. \( T_{2} \) matches its dependent vector \( T_{2}^{(3)} \) at \( r = 2 \). \( T_{2}^{(3)} \) is therefore assigned a skip, \( S = 4, T_{2}^{(3)} \), is also an initialising vector so \( y \) is incremented to 2 and \( r \) reset to 0. \( T_{2}^{(3)} \) matched its dependent vector \( T_{2}^{(-1)} \). The dependent vector, \( T_{2}^{(3)} \), is assigned a skip, \( S = 2 \). Thus, \( T_{8} \) becomes the next pivot without rotation because \( \chi > 1 \).

The sum of skips \( \text{sum}_{s} = 35 \) for matrix \( A_{(10)} \).

From the table, the resultant matrices, \( A_{(9)} \) and \( A_{(10)} \), have the highest \( \text{sum}_{s} = 35 \). Since of the two \( A_{(10)} \) has the lesser value of \( p \), it is chosen as the best arrangement of the test set for minimising test scan.
in time using the proposed method. From Equations 1 and 2, the original test set using standard scan technique (without the Vector Match method) takes 84 clock cycles to scan-in all the vectors and a total of 89 clock cycles for the complete test application process.

5. Conclusion

After reviewing the scan architecture, it was realised that it does not allow the re-use of patterns in already scanned-in test vectors. This is because the same flip-flops that hold the scanned-in vectors are the ones that capture the response during the test application process. As a result, an already scanned-in vector is cleared by the response. Consequently, every bit in all the test vectors must be scanned in. This makes test application time very long. To solve this problem, a new architecture was proposed.

The new architecture involves the addition of a MISR to the scan chain of the circuit under test (CUT). In test mode, the state outputs are disconnected from the scan chain inputs and connected to the MISR. Thus the MISR is used to capture and compress the test responses. This allows previously scanned-in vector to be held in the flip-flops—paving a way for a possible reuse of the entire vector or part thereof. Next an algorithm, called the Pattern Match Algorithm (PMA), was developed to take advantage of repetitive patterns in test vectors by re-using them. By so doing, it avoids a complete scan-in of whole vectors. Time saving is achieved as a result.

The Pattern Match Algorithm works by rearranging test vectors to achieve the optimum arrangement for reducing test application time. In a cycle of the rearrangement process, patterns in test vectors are compared with that of a vector $\textbf{P}$, called the pivot vector. Among the rest of the vectors (yet to become pivots) one with the longest matching pattern is made to follow $\textbf{P}$ directly. The vector so identified becomes the new pivot vector and the process continues to the last vector. A new cycle is then run with a new starting pivot. At the end the cycle with maximum savings in clock cycles

From Equation (4), $n_{\text{Scans}} = \frac{84 - 35}{49} = 1$. Therefore it takes $84 - 35 = 49$ clock cycles to scan-in the test vectors when the Pattern Match Algorithm is used. Adding the additional 5 clock cycles to scan-out the test signature brings the total test application time to 54 clock cycles. Evidently, the proposed approach determines the final arrangement of test vectors.

References


