Spectral Testing

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Basic Idea

• Meaningful inputs (e.g., test vectors) of a circuit are not random.
• Input signals must have spectral characteristics that are different from white noise (random vectors).
History of this Work

• Class project, Spring 1999:
  • Develop an ATPG program using vector compaction.
  • Determination of input weights had limited success for combinational circuits and no success for sequential circuits.
  • Combinational ATPG improved when input correlations were considered (space correlation).
  • Sequential ATPG required both spatial and time correlation.
References: Books


References: Papers


Statistics of Test Vectors

100% coverage
Tests:

\[
\begin{align*}
    a & = 00011 \\
    b & = 01100 \\
    c & = 10101
\end{align*}
\]

Test vectors are not random:
1. Correlation: \( a = \overline{b} \), frequently.
2. Weighting: \( c \) has more 1s than \( a \) or \( b \).
Vectors for 74181 ALU

Twelve vectors:
01010000111101
01011111111100
01010001111001
01010010110001
01011000000011
01010100100001
10100000000100
10101100001000
10100110101010
10101111111010
01010011000000
10100011101111
46% 1’s
TLC Circuit: s298

Test vector sequence:

000  repeat 3 times
001  repeat 8 times
000  repeat 39 times
010  repeat 17 times
000  repeat 24 times
001  repeat 5 times
000

100  repeat 3 times
000  repeat 17 times
Spectrum of a Bit-Stream

• Hadamard matrix of order $k$ gives bases for bit-streams of length $2^k$.

• Example: $k=2$

\[
\begin{bmatrix}
1 & 1 & 1 & 1 \\
1 & -1 & 1 & -1 \\
1 & 1 & -1 & -1 \\
1 & -1 & -1 & 1 \\
\end{bmatrix}
\begin{bmatrix}
-1 \\
1 \\
1 \\
1 \\
\end{bmatrix}
= 
\begin{bmatrix}
2 \\
-2 \\
-2 \\
-2 \\
\end{bmatrix}
\begin{bmatrix}
1 \\
0 \\
0 \\
0 \\
\end{bmatrix}
\]

$H(k) \times C = k.B$
Filtering Noise

• Determine coefficient matrices for the input bit-streams.
• Eliminate minor (small) coefficients.
• Multiply modified coefficients with Hadamard matrix to obtain the filtered bit-streams.
Spectral ATPG

1. Initial vectors (random)
2. Fault simulation and vector-compaction
3. Fault coverage?
   - If low, compute spectral coefficients and add filtered vectors to test set
   - If ok, stop
### ATPG RESULTS

<table>
<thead>
<tr>
<th>Circuit name</th>
<th>HITEC</th>
<th>Strategate</th>
<th>Proptest</th>
<th>Spectral ATPG</th>
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<td>CPU s</td>
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</table>

Ref: Giani et al., DATE ’02

**CPU:** Ultra Sparc 10  
**HITEC:** Nierman and Patel, EDAC’91  
**Strategate:** Hsiao et al., ACM/MTDAES’00  
**Proptest:** Guo et al., DAC’99
ATPG for b12

Faults detected

Number of iterations

Spectral ATPG

Proptest
Spectral Self-Test TPG

• Compute spectral coefficients for given test vectors.
• Save major coefficients.
• Generate tests by multiplying saved coefficients with Hadamard matrix.
• TPG may be implemented in software or hardware.
SOC Self-Test Application

<table>
<thead>
<tr>
<th>Circuit name</th>
<th>Total faults</th>
<th>Weighted-random patterns</th>
<th>Spectral patterns</th>
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<tbody>
<tr>
<td></td>
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<td>Ideal</td>
<td>Rounded</td>
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<td>3102</td>
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<td>636</td>
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</tbody>
</table>

Ref: Giani et al., VTS '01

Number of patterns = 70,000
Self-Test Signature

- Susskind, FTCS ’81, IEEETC ’83
- Match Walsh coefficient of input vector with output.
- Compute number of times output matches minus #mismatches for
  - $C_0$ – first Walsh coefficient (counting 1’s or syndrome)
  - $C_{all}$ – highest order Walsh coefficient, 0(1) for odd(even) number of zeros in the input vector
Susskind’s Response Compactor

- **CUT**
- **TPG**
- **Response counter**
- **Output**
- **Signature**
- **Reset-start/stop**

Diagram details:
- 1
- \( C_0 \)
- \( C_{all} \)
Matching Output to Tone

- Khan and Bushnell, ITC ’04
- Susskind’s C0 is DC, 111111 . . .
- Tones are:
  - 01010101010 . . .
  - 10101010101 . . .
  - 001100110011 . . .
  - 110011001100 . . .
  - . . . . .
- Empirical result: Zero aliasing in benchmark circuits when two tones are matched separately for each output.
Transfer Function

• Characterize digital circuit in frequency domain by a transfer function.

\[ Y(\omega) = H(\omega) \times X(\omega) \]
Circuit 1: Non-Oscillatory Behavior

Non-oscillatory steady-state output is due to a feedback free structure.
Circuit 2: Oscillatory Behavior

Characteristic input

0

01010 ... Natural frequency

Oscillatory steady-state output is due to the feedback structure.
Some Observations

- Feedback free circuit
  - Like simple filter. May pass some frequencies and block others.
  - Fixed inputs produce a transient output followed by a fixed steady state output.
  - Maximum duration of transient is determined by the sequential depth of the circuit.
  - Combinational circuit is similar.
  - Testing or verification may be possible by examining the pass and stop bands.
  - A complete characterization of transfer function may lead to new methods of synthesis.
More Observations

- **Circuit with feedback**
  - Like a complex filter may pass some frequencies and block others.
  - Fixed input can produce either a transient or oscillatory (natural frequency) output (poles in the transfer function?)
  - Fixed inputs (characteristic vectors) that produce output oscillation may have test and verification significance.
  - Natural frequencies can be determined from the lengths of feedback cycles.
Conclusion

• A vector sequence is efficiently represented by its spectral coefficients.
• Spectral analysis is useful in ATPG and BIST.
• Spectral TPG synthesis is an open problem.
• A digital circuit is a filter:
  • Output spectrum for random inputs is the impulse response.
  • Analysis of impulse response may lead to suitable input spectrum for test and verification.
  • Useful (?) characteristics are natural or resonance frequencies, characteristic vectors, transient behavior.