Improving X-Tolerant Combinational Output Compaction via Input Rotation

Asad Amin Bawa and Nur A. Touba
Computer Engineering Research Center
University of Texas, Austin, TX 78712
bawa@utexas.edu, touba@utexas.edu

Abstract

Combinational linear compactors can be used to compact the output response for a large number of scan chains into a smaller number of outputs. While some compactor designs can guarantee observation of all scan chains in the presence of a small number of X's, this may not be sufficient for designs with higher X densities. This paper describes an approach for using a combinational rotator between the scan chains and compactor to allow detection of faults even in the presence of high X densities. It is shown that the number of control inputs to the rotator is comparable to the number of control inputs required by conventional X masking approaches, but by not masking, the proposed approach is able to provide higher observability which translates to fewer test patterns, better compression, and better coverage of non-modeled faults. Moreover, the control data for the rotator has many more don't cares than the control data for X masking thereby making it easier and more efficient to compress with a linear decompressor. A heuristic procedure for ordering the inputs to a combinational compactor to increase the probability of observation for a given maximum shift distance is also presented. Experimental results indicate that high observability can be achieved using the proposed method with a relatively small number of control inputs.

1. Introduction

There are many sources of unknown (X) values in output response arising from various sources such as uninitialized memories, analog blocks, tri-states, false paths, multi-cycle paths, etc. X's present a challenge for output response compaction. A number of techniques have been developed to handle X's in the output response. One approach is to modify the circuit-under-test (CUT) to eliminate the sources of X-values. This involves blocking sources of X within the circuit by inserting design-for-testability (DFT) hardware to prevent Xs from propagating into scan cells [Wang 06]. Another approach, which does not require modifying the CUT, is X-masking which masks out X's at the input to the compactor. Mask control data is used to specify which scan chain outputs should be masked during which clock cycles. Many schemes for X-masking hardware design and mask control data compression have been developed [Barnhart 01], [Wohl 01, 03, 04], [Pomeranz 02], [Chickermane 04], [Volkerink 05], [Chao 05], [Tang 06], [Rajski 06a], [Rajski 08], [Mrugalski 09]. A third approach is to use an X-tolerant compactor which can compact an output stream that contains X's without the need for X-masking. X-tolerant compactors have been developed based on linear combinational compactors [Mitra 04], [Patel 03], [Sharma 05], [Wohl 07a, 07b, 08], finite memory compactors [Wang 03], [Rajski 05], [Rajski 06b], [Gizdarski 10], and X-canceling MISRs [Yang 12], [Bawa 12], [Chung 12].

The focus of this paper is on combinational compactors which have the advantage of very simple design and low overhead. The original idea of designing a combinational linear circuit that can compact output responses with X's was first described by Mitra and Kim [Mitra 04]. The idea is that each scan chain fans out to multiple outputs where they are XORed together. The combinations of scan chains that are XORed together at each output are selected in such a way that if any single scan chain has an X value, it is still possible to observe all other scan chains. The scan chain with an X value will corrupt all the outputs that it fans out to which will then be masked on the tester, but all other outputs can still be observed as all other scan chains fan out to at least one of those outputs.

In [Wohl 07a], Wohl, et al., use the same principle, but limit the number of outputs that each scan chain fans out to only 3. The output compactor is designed using Steiner triple systems [Colbourn 99] such that each scan chain fans out to three outputs where no other scan chain fans out to more than one of those three outputs. Consequently, any two scan chains with X's can be tolerated while still allowing observation of all other scan chains.

While observation of all scan chains in combinational compactors can be guaranteed for a small number of X's using the methods in [Mitra 04] and [Wohl 07a], this may not be sufficient for designs with higher X densities. The scan cells that need to be observed to ensure detection of necessary faults for a test vector will be referred to as D values in this paper. When the number of X's in a particular scan slice is sufficiently large, it may block observation of some D's. Handling more X's can be done through either masking [Wohl 07b] or filtering [Sharma 05]. The technique in [Wohl 07b] provides the ability to selectively mask on a slice-by-slice basis a sufficient number of scan chains such that all unmasked scan chains can be directly observed through the compactor. The technique in [Sharma 05] involves adding an X-filtering circuit at the output of the compactor which can cancel out the X's. However, this comes at the cost of a large number of control inputs equal to a multiple of the number of X's to be tolerated per slice thereby making it unattractive.

The drawback of masking X's is that in order to keep the amount of data required for masking at a reasonable level, the number of different combinations of scan chains that can be masked has to be kept small. Consequently, the masking is coarse grain resulting in many non-X values also getting masked. This reduces the amount of observation and can result in more test patterns needing to be applied to achieve the same fault coverage (i.e., test pattern inflation).

The proposed idea involves tolerating high X-densities without masking. The key idea is to exploit the fact that for combinational compactors where the inputs fan out to a small number of outputs, a sizeable fraction of the inputs will remain observable even in the presence of many X's. For example, consider a compactor designed using Steiner triple systems using the procedure in [Wohl 07] that has 610 inputs and 61 outputs. Even in the presence of 40 X's in a scan slice, over

978-1-4799-8606-4/15/$31.00

35% of the inputs remain observable. Normally this is not sufficient as the probability of observing a particular D would be only 35%. However, the proposed approach adds a combinational rotator between the scan chains and the compactor which allows the connection of scan chains to compactor inputs to be shifted with the very last bit position being rotated to become the first bit position. By selectively rotating, a D can be matched to an observable input ensuring that it will be observed at the output of the compactor. A procedure for carefully ordering the inputs to the compactor to maximize the probability of having an observable input within a given maximum shift distance is described. Using this procedure, the number of control inputs required for the rotator can be minimized.

To illustrate the advantage of the proposed approach consider the example mentioned earlier of a Steiner triple system compactor with 610 inputs and 61 outputs. Whereas a conventional masking technique that can directly observe any D will only observe 61 of the 610 inputs (i.e., 10% observability), the proposed approach using the same number of control inputs would also observe any D, but would provide much higher observability. As will be seen in the experimental results in Sec. 4, for 10 X's, it would provide 95% observability, for 20X's, it would provide 76% observability, for 30X's it would provide 54% observability, and for 40X's it would provide 35% observability. Increased observability translates to less test pattern inflation and better compression as well as better coverage of non-modeled faults.

Another nice property of the proposed method is that the control inputs to the rotator are don't cares except for scan slices in which both D's and X's are simultaneously present. For an arbitrary scan slice with no D's or no X's, it doesn't matter how the inputs are connected to the compactor, the overall percentage of observable inputs will be approximately the same. This makes it very efficient to drive the control inputs to the rotator from a linear decompressor. This is a further advantage compared to masking approaches because driving the control inputs for masking circuitry with arbitrary values results in unnecessary masking and loss of observability, so typically an additional enable signal needs to be added to the design to disable the masking circuity when it is not needed if the other control signals are to be driven by a linear decompressor.

Note that the Response Shaper in [Chao 05] and X-Align in [Sinanoglu 09a, 09b] also involve adding a block between the scan chains and combinational compactor. However, these methods are fundamentally different from the proposed method. They involve using flip-flops to selectively delay subsets of scan chains so as to change the composition of X's and D's arriving at the inputs to the compactor. Whereas the proposed method is using purely combinational logic to rotate the inputs to the compactor and not changing the composition of X's an D's. Since it is only using combinational logic, the proposed method is a much simpler design with less overhead. The proposed method is actually orthogonal to the methods in [Chao 05] and [Sinanoglu 09a, 09b] and could be used in conjunction with those methods.

The paper is organized as follows: Section 2 presents the proposed scheme and the hardware required. Section 3 describes the procedure for ordering the inputs of the compactor to maximize the probability of having an observable input within a given shift distance. Section 4 shows the experiments results, and Section 5 is a conclusion.

2. Proposed Scheme

A block diagram for the proposed scheme is shown in Fig. 1. A combinational rotator is added between the scan chains and the inputs to a combinational compactor. The additional hardware required for the proposed scheme beyond what is already present for test compression is shown in red. The inputs to the combinational rotator can be driven by tester channels or can be driven by a linear decompressor. As mentioned earlier, these inputs are don't care except for scan slices when both D's and X's are simultaneously present. When both D's and X's are simultaneously present, the control signals to the combinational rotator are selected to propagate the D's.

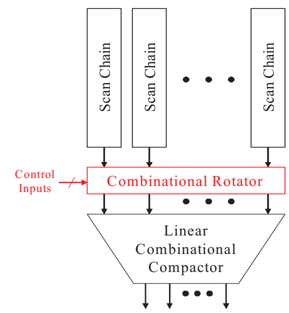

Figure 1. Block Diagram of Proposed Scheme

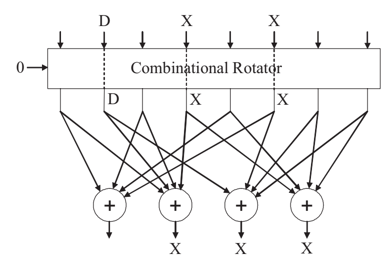

Figure 2. Example of D Blocked from Observation

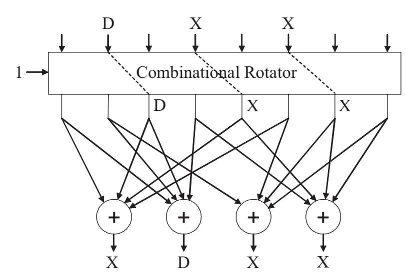

Figure 3. D Becomes Observable with Rotation

The number of control signals to the rotator determines the maximum shift distance that is possible. For c control inputs, the maximum shift distance would be 2^c-1. The shift distance should be selected to achieve a high probability (e.g., greater than 99%) of being able to observe a D's under the expected X density. The number of control inputs will depend on the number of inputs and outputs to the compactor and the expected X density.

An small example illustrating how the scheme works is shown in Figs. 2 and 3. There is one D input and two X inputs. In Fig. 2 where the rotation is 0, the two compactor outputs that the D fans out to both receive X inputs as well which block observation at the output. In Fig. 3, with the rotation set to 1, all the inputs are shift one step to the left. In this case, the D fans out to one compactor output that does not receive any X inputs, so it is able to be observed. The addition of the combinational rotator provides the ability to avoid cases where D values get blocked.

3. Procedure for Ordering Compactor Inputs

Since a combinational rotator only shifts inputs and doesn't permute them, the order of the inputs in the compactor design is important. Of course, for a completely symmetric compactor design, the order of the compactor inputs doesn't matter for the proposed scheme. However, in the general case, the compactor is not completely symmetric starting with the fact that the number of inputs times the number of fan outs per input may not necessarily be a multiple of the number of outputs. Even if that is the case, it would still not be symmetric unless the fan outs for every input are connected in the exact same pattern.

In the general case where the compactor is not symmetric, the probability of having an observable input within a given maximum shift distance depends on how the inputs to the compactor are ordered. Some input orders can be better than others. As a simple example, consider a maximum shift distance of 1. Assume X's are located at inputs i and j and a D is located at input k, and the X's block observation of the D at all outputs that the D fans out to (as in the example in Fig. 2). If the inputs are shifted by a distance of 1, then the X's will now be located at inputs i+1 and j+1, and the D will be located at input k+1. If an X at input i+1 and j+1 blocks a D at location k+1, then it will not be possible to observe the D within a maximum shift distance of 1. In order to maximize the probability that a D can be observed in the presence of two X's within a maximum shift distance of 1, the inputs should be ordered in a way that minimizes the number of i, j, k sets where *X*'s at i and j block a D at k, and X's at i+1 and j+1 block a D at k+1.

```
SHIFT_OBSERVE(p,offset) {
  For each output q reached from input position p {
    Initialize set REACH_q = ∅
    For each input position i that reaches output q {
      Add to set REACH_q all outputs reachable from i+offset
    }
  }
  If possible to cover all outputs reachable from p+offset
  by selecting one element from each set of REACH_q then {
    /* Some combination of X's that block p can block p+offset */
    Return(FALSE)
  }
  else {
    /* No combination of X's can block p+offset */
    Return(TRUE)
  }
}

HILL_CLIMB_INPUT_ORDERING() {
  Repeat {
    Initialize swap_performed = FALSE
    For each pair (p1,p2) of input positions for compactor {
      Initialize starting_value = 0
      If SHIFT_OBSERVE(p1-1,offset) then starting_value++
      If SHIFT_OBSERVE(p1,offset) then starting_value++
      If SHIFT_OBSERVE(p2-1,offset) then starting_value++
      If SHIFT_OBSERVE(p2,offset) then starting_value++
      Swap p1 and p2
      Initialize swapped_value = 0
      If ( SHIFT_OBSERVE(p1-1,offset) ) then swapped_value++
      If ( SHIFT_OBSERVE(p1,offset) ) then swapped_value++
      If ( SHIFT_OBSERVE(p2-1,offset) ) then swapped_value++
      If ( SHIFT_OBSERVE(p2,offset) ) then swapped_value++
      If ( swapped_value ≤ starting_value ) then {
        Swap p1 and p2 back to initial values
      }
      else if ( swapped_value > starting_value ) then {
        swap_performed = TRUE;
      }
    }
  } while ( swap_performed)
}
```

Figure 4. Hill Climbing Procedure for Input Ordering

Pseudo-code for a procedure that takes as an input a linear compactor design and uses a heuristic hill climbing process to reorder the inputs so as to improve the probability of observing D's through rototating inputs is shown in Figure 4. A basic subroutine used in the procedure is SHIFT_OBSERVE(p,*offset*) which determines whether a D at input position p that is blocked (where one X reaches each output that the D reaches) can be observed if it is shifted by some offset. The main procedure HILL_CLIMB_INPUT_ORDERING() is based on selecting a candidate pair of inputs (p_1,p_2) to swap. If swapping inputs p_1 and p_2 will increase the number of D positions that can be observed by a shift offset of 1, then the swap is performed. To determine this, four calls are made to SHIFT_OBSERVE, one each for p_1, p_2, p_1-1, and p_2-1. Those four positions are the only ones that can be affected for a shift offset of 1. The procedure could be expanded to also consider larger shift distances if desired. Since it is a hill climbing procedure, it can be terminated at any time, and the best solution found so far can be used. So it is very easy to tradeoff runtime versus optimality of the result.

The heuristic procedure in Fig. 4 is general can be used for any linear compactor design. Note that for specific classes of compactor designs, it may be possible to construct an optimal procedure for ordering the inputs.

4. Experimental Results

Experiments were performed for two different linear combinational compactor designs. Both were constructed using the procedure in [Wohl 07a] based on Steiner triple systems where each input to the compactor fans out to three outputs. One design compacts 425 scan chains into 51 outputs, and the other design compacts 610 scan chains into 61 outputs. Table 1 shows what percentage of D's could be observed for different percentage of X's using the conventional approach with no rotator, versus the proposed approach with a compactor. Results are shown for different numbers of control inputs going to the rotator. The maximum shift distance for the rotator is 2^c-1 where c is the number of control inputs. As can be seen from the table, for both compactors, 5 control inputs was sufficient to handle up to 10% X's while maintaining 99% observability of D's. Given the expect percentage of X's, the number of control inputs to the compactor can be selected accordingly. It can also be seen that as the number of inputs to the compactor goes up, the effectiveness of a particular number of control inputs slightly reduces. This is due to the fact that the ratio of the maximum shift distance for the rotator to the total number of inputs to the compactor is reducing.

The overhead for a combinational rotator is one MUX per control input for each scan chain. Since the number of control inputs can be expected to scale logarithmically as the number of scan chains increases, this overhead will scale well as design size grows.

Table 1. Percentage of D's Observed for Different Percentage of X's with Proposed Approach

Percent X's	425-to-51 Compactor						610-to-61 Compactor					
	No Rotator	Rotator (Control Inputs)					No Rotator	Rotator (Control Inputs)				
		1	2	3	4	5		1	2	3	4	5
0.5%	100%	100%	100%	100%	100%	100%	99.9%	100%	100%	100%	100%	100%
1%	99.6%	100%	100%	100%	100%	100%	99.0%	100%	100%	100%	100%	100%
2%	95.1%	100%	100%	100%	100%	100%	92.4%	99.4%	100%	100%	100%	100%
3%	86.2%	98.2%	100%	100%	100%	100%	80.8%	96.4%	99.9%	100%	100%	100%
4%	78.9%	94.3%	99.7%	100%	100%	100%	67.3%	89.4%	98.9%	100%	100%	100%
5%	64.8%	87.8%	98.5%	100%	100%	100%	54.0%	79.0%	95.6%	99.8%	100%	100%
6%	54.2%	79.1%	95.7%	99.9%	100%	100%	40.3%	64.4%	87.4%	98.4%	100%	100%
7%	44.4%	69.2%	90.5%	99.1%	100%	100%	30.7%	52.1%	77.1%	94.8%	99.7%	100%
8%	33.9%	56.5%	81.1%	96.4%	99.9%	100%	23.0%	40.8%	65.0%	87.8%	98.5%	100%
9%	27.0%	46.8%	71.7%	92.0%	99.4%	100%	17.1%	31.3%	52.8%	77.7%	95.1%	99.8%
10%	20.1%	36.2%	59.3%	83.5%	97.3%	99.9%	12.5%	23.6%	41.6%	65.9%	88.4%	99.0%

5. Conclusions

The use of a combinational rotator is an attractive alternative to adding masking logic for handling designs with high X-density. While the number of control inputs and overhead is comparable to what would be required for masking logic, more scan cells get observed when no masking is performed. Moreover, the control inputs for a rotator will have more don't care conditions than masking logic which makes them more compressible if a decompressor is used to generate them. Note also that a rotator can be used in conjunction with other techniques such as Response Shaper [Chao 05], X-align [Sinanoglu 09], and even with masking techniques as well.

Some areas for future research include designing linear combinational compactors that are optimized for use with a rotator, and considering hybrid approaches that combine rotating and masking.

References

[Barnhart 01] Barnhart, C., V. Brunkhorst, F. Distler, O. Farnsworth, B. Keller, and B. Koenemann, "OPMISR: the Foundation for Compressed ATPG Vectors", *Proc. of International Test Conference* , pp. 748-757, 2001.

[Bawa 12] A.A. Bawa and N.A. Touba, "Using Partial Masking in X-Chains to Increase Output Compaction for an X-Canceling MISR", Proc. of Symp. on Defect and Fault Tolerance, pp. 19-24, 2012.

[Chao 05] M. C.-T. Chao, S. Wang, S.T. Chakradhar, and K.-T. Cheng, "Response Shaper: A Novel Technique to Enhance Unknown Tolerance for Output Response Compaction", *Proc. of Int. Conf. on Computer-Aided Design (ICCAD)*, pp. 80-87, 2005.

[Chickermane 04] Chickermane, V., B. Foutz, and B. Keller, "Channel Masking Synthesis for Efficient On-Chip Test Compression", *Proc. of Int. Test Conf.*, pp. 452-461, 2004.

[Chung 12] J. Chung and N.A. Touba, "Exploiting X-Correlation in Output Compression via Superset X-Canceling", *Proc. of VLSI Test Symposium*, pp. 182-187, 2012.

[Colbourn 99] C.J. Colbourn, and A. Rosa, *Triple Systems*, Clarendon Press, Oxford, 1999.

[Gizdarski 10] Gizdarski, E., "Constructing Augmented Time Compactors," *Proc. of European Test Symposium*, pp. 151-156, 2010.

[Mitra 04] Mitra, S., and K.S. Kim, "X-Compact: An Efficient Response Compaction Scheme", *IEEE Trans. on Computer-Aided Design*, Vol. 23, No. 3, pp. 421-432, Mar. 2004.

[Mrugalski 09] Mrugalski, G., N. Mukherjee, J. Rajski, D. Czysz, and J. Tyszer, "Highly X-Tolerant Selective Compaction of Test Responses," *Proc. of VLSI Test Symposium*, pp. 245-250, 2009.

[Patel 03] Patel, J.H., S.S. Lumetta, and S.M. Reddy, "Application of Saluja-Karpovsky Compactors to Test Responses with Many Unknowns", *Proc. of VLSI Test Symposium*, pp. 107-112, 2003.

[Pomeranz 02] Pomeranz, I., S. Kundu, and S.M. Reddy, "On Output Response Compression in the Presence of Unknown Output Values", *Proc. of Design Automation Conference*, pp. 255-258, 2002.

[Rajski 06a] Rajski, J., J. Tyszer, G. Mrugalski, W.-T. Cheng, N. Mukherjee, and M. Kassab, "X-Press Compactor for 1000x Reduction of Test Data", *Proc. of International Test Conference*, Paper 18.1, 2006.

[Rajski 06b] Rajski, W., and J. Rajski, "Modular Compactor of Test Responses", *Proc. of VLSI Test Symposium*, pp. 242-251, 2006.

[Rajski 08] Rajski, J., J. Tyszer, G. Mrugalski, W.-T. Cheng, N. Mukherjee, and M. Kassab, "X-Press: Two-Stage X-Tolerant Compactor with Programmable Selector," *IEEE Trans. on Computer-Aided Design*, Vol. 27, Issue 1, pp. 147-159, Jan. 2008.

[Sharma 05] Sharma M. and W.-T. Cheng, "X-Filter: Filtering Unknowns from Compacted Test Responses", *Proc. of International Test Conference*, Paper 42.1, 2005.

[Sinanoglu 09] O. Sinanoglu and S. Almukhaizim, "X-Align: Improving the Scan Cell Observability of Response Compactors," *IEEE Trans. on VLSI*, Vol. 17, No. 10, Oct. 2009.

[Tang 06] Tang, Y., H.-J. Wunderlich, P. Engelke, I. Polian, B. Becker, J. Schölöffel, F. Hapke, and M. Wittke, "X-Masking During Logic BIST and Its Impact on Defect Coverage", *IEEE Trans. on VLSI*, Vol. 14, No. 2, Feb. 2006.

[Volkerink 05] Volkerink, E.H., and S. Mitra, "Response Compaction with Any Number of Unknowns Using a New LFSR Architecture", *Proc. of Design Automation Conference*, pp. 117-122, 2005.

[Wang 03] C. Wang, S.M. Reddy, I. Pomeranz, J. Rajski, and J. Tyszer, "On Compacting Test Response Data Containing Unknown Values," *Proc. of Int. Conf. on Computer-Aided Design (ICCAD)*, pp. 855-862, 2003.

[Wang 06] L.T. Wang, C.-W. Wu, X. Wen, *VLSI Test Principles and Architectures*, Morgan Kaufmann, 2006.

[Wohl 01] Wohl, P., J.A. Waicukauski, and T.W.Williams, "Design of Compactors for Signature-Analyzers in Built-In Self-Test", *Proc. of Int. Test Conference*, pp. 54-63, 2001.

[Wohl 07a] P. Wohl, J.A. Waicukauski, R. Kapur, S. Ramnath, E. Gizdarski, T.W. Williams, and P. Jaini, "Minimizing the Impact of Scan Compression," *Proc. of VLSI Test Symposium*, pp. 67-74, 2007.

[Wohl 07b] P. Wohl, J.A. Waicukauski, and S. Ramnath, "Fully X-Tolerant Combinational Scan Compression," *Proc. of International Test Conference*, Paper 6.1, 2007.

[Yang 12] J.-S. Yang and N.A. Touba, "X-Canceling MISR Architecture for Output Response Compaction with Unknown Values," *IEEE Trans. on Computer-Aided Design*, Vol. 31, No. 9, pp. 1417-1427, Sept. 2012.