An Approach to the Classification of Mixed-Signal Circuits in a Pseudorandom Testing Scheme

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BIST methods based on the application of a pseudorandom pulse sequence as input stimulus have recently been suggested for testing linear time-invariant (LTI) analog parts [1-3]. In such methods, the input-output cross-correlation function $R^{xy}(t)$ gives a good estimation of the impulse response of the DUT, h(t), provided the auto-correlation of the pseudorandom input sequence approaches a single Dirac's pulse $\delta(t)$ [4]. Much work has been devoted to the investigation of several aspects of the pseudorandom testing techniques, such as the impact of the finite length of the input pulse sequence, the duration of the single pulse, the ADC resolution, etc [1-3]. In particular, ADC's with low resolution can be employed to sample the DUT response as the averaging effect intrinsically performed by the input-output cross-correlation operation greatly reduces the effects of the quantization errors [2]. As a consequence, from a BIST point of view, the test of very fast DUT is possible, since ADC's with low accuracy and fast sampling rate are easily available on chip.

In this paper we focus on the issues related to the choice of a suitable set of samples of the cross-correlation function $R^{xy}(m_i)$, i=1,..,n, as DUT signature, and, at the same time, to the definition of an effective classification procedure [5-6].

In particular, we make the choice of the DUT signature on the basis of the sensitivities of the cross-correlation samples to the circuit specifications s_j, expressed in terms of the partial derivatives $\partial_{ij}=\partial R^{xy}(m_i)/\partial s_j$. This sensitivity study is carried out by considering a large set R_{TS} of good instances of the circuit generated in simulation by independently varying the performance parameters of an high level description of the DUT within their acceptance ranges (±5%). The same set of good circuits is used to extract the initial acceptance ranges $[R^{xy}_{min}(m_i), R^{xy}_{max}(m_i)]$ of the samples $R^{xy}(m_i)$ selected as signature components, and thus it constitutes the starting point of the subsequent classification procedure.

If a measured sample falls outside the range defined by the two envelope curves, R_{TSm} and R_{TSM} (see fig. 1), defined by the intervals $[R^{xy}_{min}(m_i), R^{xy}_{max}(m_i)]$, the DUT is immediately classified as faulty. Conversely, even if all the signature samples lie within these ranges, the DUT can not still be assumed fault-free, unless the signature samples satisfy some more stringent conditions.

The first sample $R^{xy}(m_1)$ of the DUT signature has to be chosen as the one which satisfy the following conditions:

$$\partial_{11}(\bar{S}) >> \partial_{12}(\bar{S}),....,\partial_{1n}(\bar{S}) \qquad (1)$$

where $\bar{S}$ is the vector of the nominal specifications.

As it can be shown by first order Taylor expansions of $Rxy(m_1)$, for a generic specification vector S, the conditions (1) guarantee that, if the measured sample $R^{xy}(S,m_1)$ belongs to its initial acceptance interval $[R_{TSm}(m_1),R_{TSM}(m_1)]$, also the specification s_1 is within its tolerance limits for the current DUT. The position of the m_1-th sample within its initial tolerance range $[R_{TSm}(m_1),R_{TSM}(m_1)]$ can be used to reduce the number of instances in the database, and thus the tolerance

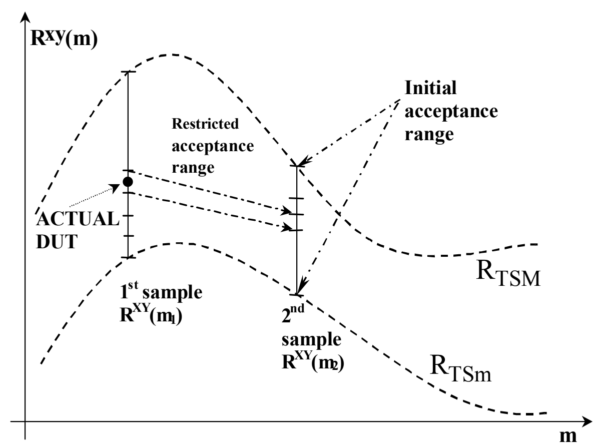

Fig. 1. Restricting the acceptance range of a sample

boundaries of the next signature samples (see fig. 1). For example, if the value of the m_1-th sample falls inside the first half of the interval $[R_{TSm}(m_1),R_{TSM}(m_1)]$, all the circuit instances for which the sample m_1 belongs to the second half of the interval can be discarded from the database, thus achieving a restricted database R'_{TS}. In this way we can determine a smaller acceptance range for the next sample $R^{xy}(S,m_2)$, which can now be chosen as the one which satisfies the less restrictive conditions:

$$\partial_{22}(\bar{S}) >> \partial_{23}(\bar{S}),....,\partial_{2n}(\bar{S}) \;. \qquad (2)$$

In other words, the second sample $R^{xy}(S,m_2)$ can be chosen regardless of the value of ∂_{21}. As for the first sample, according to the position of $R^{xy}(S,m_2)$ in its acceptance range we can further restrict the instances in

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the database R'_{TS} and consequently the acceptance range of the third signature sample $R^{xy}(S,m_3)$, which can be chosen as the one which satisfies the properties:

$$\partial_{33}(\bar{S}) >> \partial_{34}(\bar{S}),...,\partial_{3n}(\bar{S}) \ . \qquad (3)$$

By iterating this branch-and-bound search, the complete signature is identified as the minimum set of samples able to distinguish faulty instances from good ones, with a given risk of misclassification. The choice of the signature samples, together with the evaluation of all the thresholds needed to locate the position of the actual DUT samples, has to be done as a preliminary study, so it is carried out by simulations of the circuit to be tested. The implementation of the classification technique in a BIST environment requires only a small hardware excess to store the set of threshold values for each element of the signature and to perform the comparisons between the thresholds and the signature of the actual DUT. The required extra hardware depends on the number of thresholds defined on each sample and, as a consequence, on the total number L of comparisons to be done between the actual DUT samples and the stored thresholds.

We applied the proposed classification procedure to a fourth order Butterworth and to a third order Chebyshev low pass filters. In order to assess the percentage of misclassification, an extended evaluation set of both faulty and fault-free instances was generated for both circuits by independently varying the performance parameters of an high level description of the DUT within an extended range of ±10%. The acceptance tolerance was as low as ±5% for all the performance parameters.

For the Butterworth low-pass filter the following performances have been considered: the static gain A_V, the quality factor Q and the cut-off frequency f_0. The impulse response of the system was estimated by generating the input pseudorandom sequence by means of a 9 stage LFSR, with a frequency $f_{PAT}=5f_0=5khz$. A 5-bit resolution

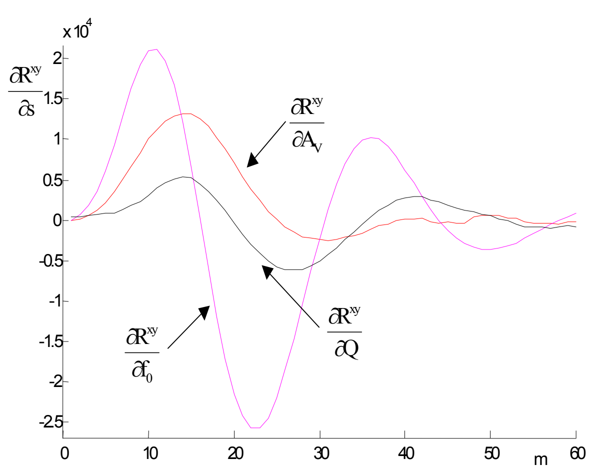

Fig. 2. Diagrams of the partial derivatives of R^{xy} for the Butterworth low pass filter.

ADC was employed with a sampling rate $f_c=5f_{PAT}=25khz$. The number of circuit instances in the evaluation set was 4096. Fig. 2 shows the diagrams of the partial derivatives of the cross-correlation function R^{xy} with respect to all the circuit performances.

For the third order Chebyshev low pass filter the following performance parameters have been selected: the cut-off frequency f_t, the maximum allowed ripple in the pass-band A_{max}, the low-frequency gain A_v. The impulse response was estimated by using a 9 stage LFSR, with a frequency $f_{PAT}=5f_t=62.2Mhz$. The sampling frequency of the ADC module was chosen as $f_c=5f_{PAT}=311Mhz$. In this case, the evaluation set was composed by 32768 circuit instances.

The classification efficiency can be expressed in terms of the total percentage of misclassification, defined on the evaluation set as:

$$F_C = \frac{n_1}{N_1} + \frac{n_2}{N_2} \qquad (4)$$

where N_1 and N_2 represent, respectively, the number of fault-free and faulty instances in the evaluation set, while n_1 and n_2 are respectively the number of fault-free instances classified as faulty and the number of faulty instances classified as fault-free.

Considering a suitable choice for the signature samples and the number of comparisons performed for each sample, the total percentage of misclassification F_C was found to be as low as 2.8% for the Butterworth filter and 3.8% for the Chebyshev filter. For both circuits, a total number of comparisons L=9 was used. The misclassification error can, of course, be further reduced if both the number of thresholds which define the acceptance intervals and the number of circuits which compose the database used to extract the thresholds are increased.

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