Quasi-Oscillation Based Test for Improved Prediction of Analog Performance Parameters [*]

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Abstract

Oscillation Based Test (OBT) techniques in the past have focussed on detecting the existence of catastrophic and parametric faults. Recent work on Predictive Oscillation Based Test (POBT) has used OBT techniques to predict the performance parameters of the Circuit Under Test (CUT). However, this technique cannot be used to predict the performance parameters of the CUT for process parameter variations that cause a loss of oscillation in test mode. This paper presents a novel Predictive Quasi-Oscillation Based Technique (PQOBT) to extend the usability of POBT over a wide range of process parameter variations with minimal test generation overhead.

1. Introduction

Analog integrated circuits have been tested traditionally by measuring the performance parameters of the *Circuit Under Test* (CUT) and comparing these parameters against their specification limits, as defined by the target application. These specification based tests are time consuming and expensive. Techniques to eliminate these specification tests have focussed on detecting the existence of faults, rather than evaluating the impact of these faults on the performance parameters of the CUT. While the fault detection approach is very efficient in detecting *hard*, or catastrophic, faults such as shorts or opens, it suffers from a loss of efficiency in the case of *soft*, or parametric, faults. In some cases, the performance parameters of the CUT may still remain within their specification limits, despite the presence of parametric variations. Hence it is very important that the impact of these parametric faults on the performance parameters of the CUT be investigated to avoid misclassification. This principle is applied in *alternate tests*, where the performance parameters of the CUT are *predicted* from its response to a test stimulus [1, 2, 3]. This allows the pass/fail decision to be made in the performance parameter space by comparing the predicted values of the performance parameters of the CUT against their specification limits. However, these tests require generation of a highly optimized *Piece-Wise Linear* (PWL) stimulus using an *Arbitrary Waveform Generator* (AWG) [2, 3].

Oscillation Based Test (OBT) has been used as a low-cost test technique at the structural level for fault detection [4, 5]. In this technique, the CUT is reconfigured into an oscillator while in test mode. The oscillation parameters, such as the amplitude and the frequency of oscillation, are then compared against their nominal values to determine if the CUT is faulty or fault-free. The major advantages of this technique are its conceptual simplicity, robustness and the elimination of the test vector generation problem.

Recent work on *Predictive Oscillation Based Test* (POBT) has focussed on applying performance prediction techniques to OBT [6]. In this technique, the response of the CUT while it is configured as an oscillator is used to predict its performance parameters. This technique reduces the test generation overhead associated with alternate

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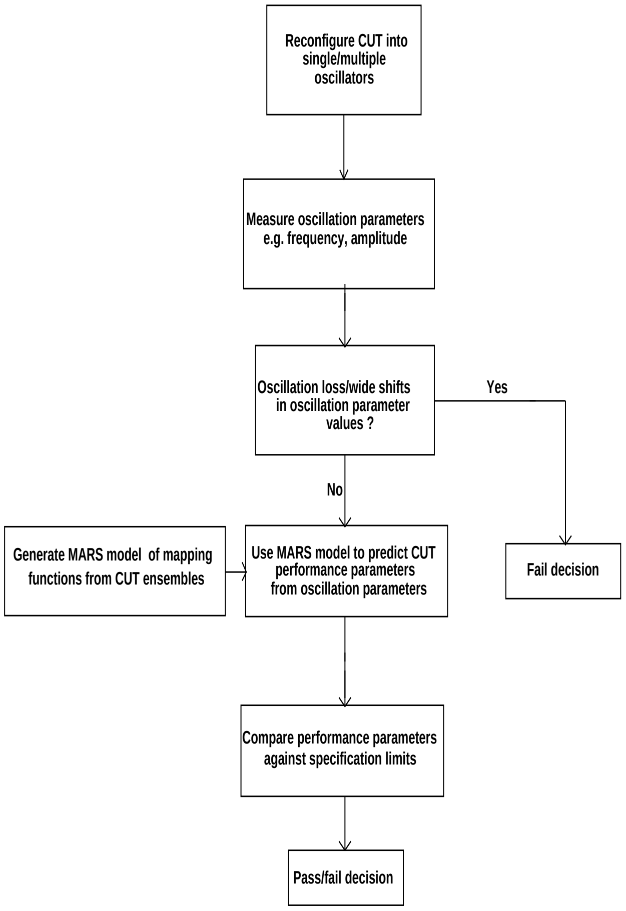

Figure 1. Predictive Oscillation Based Test methodology

tests by exploiting the vectorless nature of OBT. However, it should be noted that practical OBT implementations do require some additional circuitry to ensure safe oscillation build-up within a short transient time [7, 8]. Also, certain ranges of process parameter variations may cause a *loss of oscillation* when the CUT is configured as an oscillator in test mode. While this would typically imply the existence of a fault, the impact of this fault on the performance parameters of the CUT cannot be evaluated. In such cases, the POBT technique cannot be used to predict the performance parameters of the CUT. Fig. 1 shows the steps involved in a POBT implementation.

In this paper, a novel *Predictive Quasi-Oscillation Based Test* (PQOBT) technique is proposed to extend the predictive accuracy of OBT over a wide range of process parameter variations. In this technique, the CUT is reconfigured into a *marginally stable* test configuration whose degree of stability is strongly correlated with the performance parameters of the CUT. A short pulse is used to excite the CUT and to generate an output signature which can be used to predict the performance parameters of the CUT. The test generation overhead is limited to a short transient pulse which can be easily generated on chip.

The organization of the rest of this paper is as follows. Section 2 reviews the theory underlying performance prediction using OBT and explains the limitations of this technique in detail. The theory and implementation details of the proposed PQOBT methodology are explained in Section 3. Simulation results for two benchmark circuits are then presented in Section 4. Section 5 compares the proposed technique with the previous work. Conclusions are discussed in Section 6.

2. Review of POBT Methodology

The theory of using regression modeling to predict the performance of a CUT from its response to a transient stimulus is discussed in [1, 2]. The extension of this theory to formulate the POBT methodology is discussed in detail in [6]. This section briefly reviews the theory behind the POBT methodology and discusses its advantages and disadvantages.

2.1. Theory

A CUT ensemble is defined in the n_p dimensional circuit parameter space, P, by a set of n_p circuit parameters which affect its performance. The performance of the CUT is specified in terms of its n_s performance parameters such as DC gain, bandwidth, etc. in the n_s dimensional performance parameter space, S.

A set of n_m oscillation measurements are performed on the CUT in test mode. The POBT technique involves deriving a set of mapping functions, f_{ms} given by Equation (1) which map the n_m dimensional oscillation measurement parameter space to the n_s dimensional performance parameter space. The acceptance region, A_s, is defined by the specification limits of the CUT in the performance parameter space.

$$f_{ms}{}^{i} : \mathbf{M} \rightarrow \mathbf{S}, i = 1, \ldots, n_s \tag{1}$$

The mapping function set f_{ms} can be derived only if the corresponding mapping function sets, f_{pm}, given by Equation (2) relating the process parameter space to the measurement parameter space exist [1, 2]. In practical terms, there should be a strong correlation between the n_m oscillation measurement parameters and the n_p circuit parameters. As deriving a closed form expression for the mapping function set, f_{ms}, using analytical methods is not feasible, *Multivariate Adaptive Regression Splines* (MARS) [9] is used to model the mapping function set, f_{ms}.

$$f_{pm}{}^{i} : \mathbf{P} \rightarrow \mathbf{M}, i = 1, \ldots, n_m \tag{2}$$

In practical OBT implementations, not all of the CUT ensembles in the circuit parameter space can be mapped to corresponding points within the oscillation measurement space i.e., there exists an *unmapped region* in the circuit parameter space for which there is no corresponding region in the oscillation measurement space. This unmapped region corresponds to values of the n_p circuit parameters that cause *loss of oscillations*. Hence, the CUT performance cannot be evaluated for process parameter variations that fall within this region. Fig. 2 illustrates the relationship between the different spaces and it also shows the unmapped regions in the circuit parameter and the performance parameter spaces.

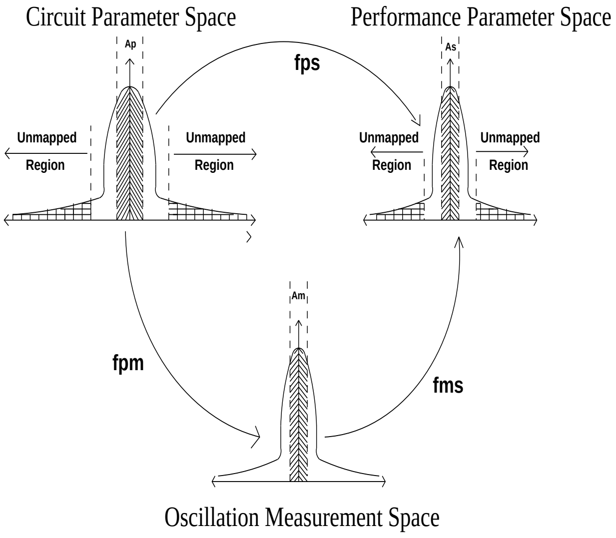

Figure 2. Unmapped regions in the circuit and the performance parameter spaces for POBT

2.2. Limitations

The major advantage of using the POBT methodology is that the OBT test results are now interpreted in the performance parameter space where the specification limits of the CUT are clearly defined. Also, the efficiency of this methodology does not depend upon the accuracy of the nominal values of the oscillation parameters used for classification, as in the case of a conventional OBT implementation. However, this technique has certain limitations which can be summarized as follows.

1. The POBT methodology uses the output of the CUT while it is reconfigured as an oscillator in test mode as a *signature* to predict the performance parameters of the CUT. For ranges of process parameter values that cause a loss of oscillation in test mode, the CUT performance parameters corresponding to these process parameter values cannot be predicted using the POBT technique.
2. Certain CUT topologies are extremely sensitive to process parameter variations while reconfigured as oscillators in test mode. In such cases, even slight variations in process parameter values could cause a loss of oscillation. This could result in misclassification of the CUT.
3. The oscillation parameters are measured only after *steady-state* is reached. Since the time needed to attain steady state has a direct influence on the test time, additional circuitry to ensure fast-oscillation buildup is required [8].
4. If the amplitude of the oscillation signal approaches the maximum output swing of the operational amplifier, *clipping* of the output response occurs. This results in a loss of accuracy if this response is used to predict the performance parameters of the CUT.

3. PQOBT Methodology

This section analyzes the influence of process parameter variations upon the behavior of the CUT while it is configured in a marginally stable test configuration. This relationship is then used to formulate the PQOBT methodology.

3.1. Theory

The application of OBT to a complex higher order system involves decomposing the system into component biquadratic sections [7]. A non-linear feedback element is then used to induce oscillations in each second-order section. Consider a second order band pass system whose transfer function is given by (3).

$$H(s) = \frac{hs}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \tag{3}$$

Here ω_0 represents the pole frequency of the system, Q represents the quality factor of the pole, and h is a constant. This system can be configured for OBT by using a non-linear element as part of the feedback path, as shown in Fig. 3. K is an additional control parameter used to control the degree of stability by adjusting the loop gain.

The non-linear element used is a saturation function whose transfer characteristic is shown in Fig. 4. The describing function, $N(A)$, given by Equation (4) approximates the transfer characteristic of the saturation function

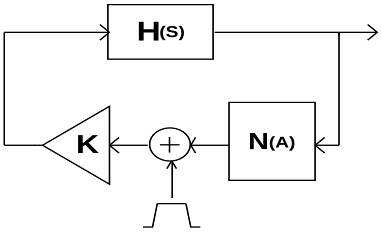

Figure 3. CUT reconfiguration for PQOBT

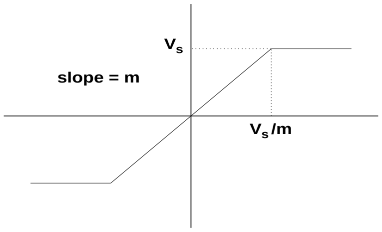

Figure 4. Saturation function transfer characteristic

as a function of the amplitude, A, of the first harmonic of its input.

$$\begin{aligned} N(A) &= mA,\ A \leq \left(\frac{V_s}{mA}\right) \\ &= \left(\frac{V_s}{mA}\right)\left[\sin^{-1}\left(\frac{V_s}{mA}\right)\right. \\ &\quad \left. + \left(\frac{V_s}{mA}\right)\sqrt{1-\left(\frac{V_s}{mA}\right)^2}\right],\ A > \left(\frac{V_s}{mA}\right) \end{aligned} \tag{4}$$

The poles of the overall system are determined by the roots of Equation (5).

$$1 - KN(A)H(s) = 0 \tag{5}$$

For oscillations to occur, the poles of the reconfigured system should lie on the imaginary axis. The degree of stability of the overall system is influenced by the distance of these poles from the imaginary axis. The minimum condition for oscillation can be derived from Equation (5) as,

$$\frac{hQ}{w_0} \geq \frac{1}{KM},\ M = max(N(A)) \tag{6}$$

In graphical terms, the above equation states that the functions $G(s)$ and $\frac{1}{KN(A)}$ should have an intersection point in a polar plot for oscillations to occur. It also implies that the degree of stability of the system is strongly correlated with the performance parameters of the CUT i.e. the response of the CUT is sensitized to process parameter variations that impact its performance, while it is reconfigured in a marginally stable test configuration. Fig. 5, Fig. 6 and Fig. 7 show the root locus plots of the marginally stable test configuration for variations in performance parameters of the CUT. A similar analysis can be performed for other types of systems.

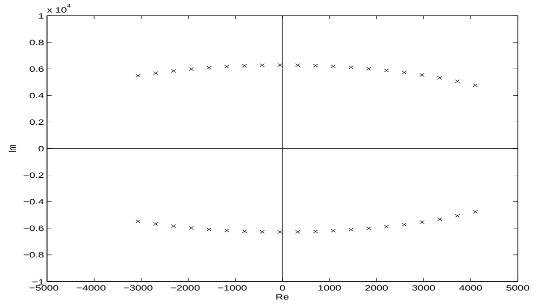

Figure 5. Root locus for varying h

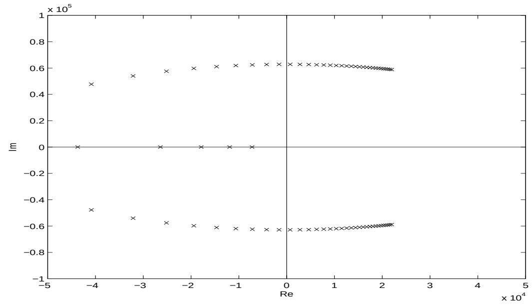

Figure 6. Root locus for varying Q

The proposed PQOBT methodology involves reconfiguring the CUT into a marginally stable configuration in test mode. This can be achieved by selecting an optimum value of K, so that the CUT remains in a marginally stable mode over the entire range of process parameter variations. A short transient pulse is used to excite the CUT when it is configured in this marginally stable configuration. This produces a damped oscillatory response at the output which is very sensitive to process parameter variations that *affect the performance parameters of the CUT*. This response is used to derive the mapping function set, f_{ms}, which can be used to predict the performance parameters of the CUT over a wide range of process parameter variations. If the CUT were configured in an oscillatory test configuration as in the case of POBT, the mapping function set, f_{ms}, cannot be derived for process parameter variations that result in the condition in Equation (6) not being satisfied.

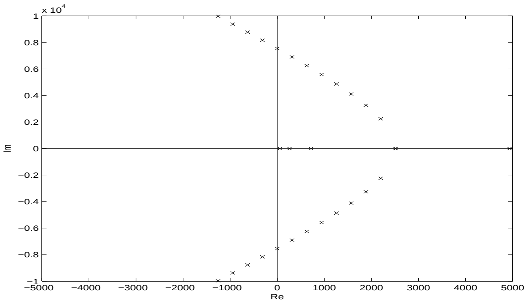

Figure 7. Root locus for varying ω_0

3.2. Implementation

This section explains the practical implementation of the PQOBT methodology. The steps involved in this methodology are shown in Fig. 8.

1. A set of CUT ensembles is obtained in the circuit parameter space by introducing statistical variations in the n_p circuit parameters that affect the n_s performance parameters.
2. The circuit ensembles are simulated in normal, or open-loop mode, and the n_s performance parameters are obtained.
3. An optimum value of K is selected such that the CUT remains in a marginally stable configuration for the entire range of process parameter variations over which it is to be evaluated.
4. The circuit ensembles are then simulated in test mode while reconfigured in marginally stable configurations, and a set of n_m measurements that have a strong correlation with the n_s performance parameters of the CUT are selected.
5. Using the data obtained from the previous two steps, the mapping function set, f_{ms}, relating the test measurements to the performance parameters of the CUT is modeled using MARS.
6. The accuracy of these mapping functions is evaluated using multiple-component fault models.
7. If additional sensitivity is required, conventional techniques at the structural level, such as reconfiguring the CUT into multiple marginally stable topologies or internal node monitoring, can be used to obtain a set of n_m measurements that have a stronger correlation with the n_s performance parameters.

The advantages of this technique are as follows,

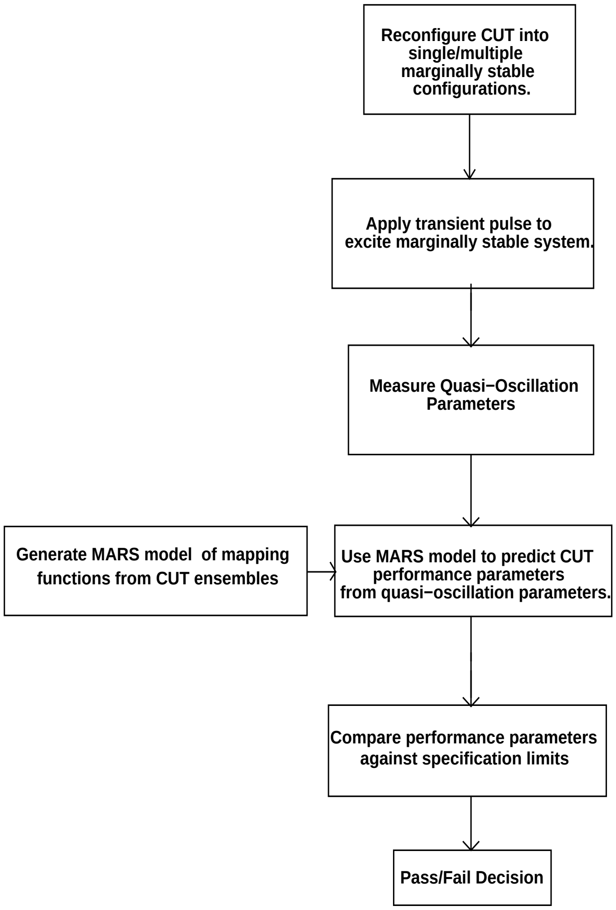

Figure 8. Predictive Quasi-Oscillation Based Test Methodology

1. The PQOBT technique allows the performance parameters of the CUT to be predicted over wider ranges of process parameter variations, i.e., the *unmapped region* problem, caused by loss of oscillations in the POBT technique, is eliminated in this technique.
2. The only stimulus required for testing is a short transient pulse that can be easily generated using on-chip digital circuitry.
3. The additional circuitry needed to ensure safe and short *oscillation buildup* is eliminated in the case of PQOBT.
4. In the POBT technique, the oscillation parameters are measured only after the CUT has attained *steady-state*. In case of the PQOBT technique, the measurements can start immediately after the application of the pulse stimulus. This translates into a significant reduction in the test time.

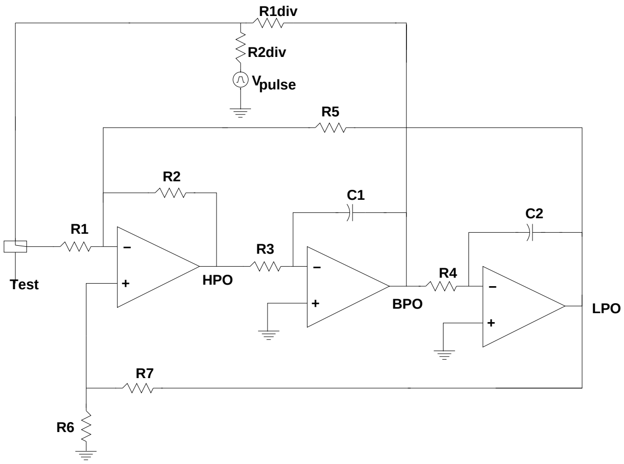

Figure 9. Continuous Time State Variable Filter (HPO: High Pass Output, BPO: Band Pass Output LPO:Low Pass Output $R_1 = R_2 = R_3 = R_4 = R_5 = 10k\Omega, R_6 = 1k\Omega, R_7 = 12k\Omega, C_1 = C_2 = 10nF$)

Table 1. POBT and PQOBT prediction errors for 10% process parameter variations in state variable filter

Performance Parameter	POBT	PQOBT
$f_{3db}(kHz)$	0.0046	0.0015
DC Gain	0.0045	0.0150
Maximum Gain	0.2341	0.0374

5. Any CUT topology that is testable using OBT, can also be tested using this technique by adjusting the feedback element so that the CUT is in a marginally stable configuration instead of an oscillatory configuration. Hence, existing OBT techniques can be easily adapted for this purpose.

4. Results

Simulation results for the PQOBT technique applied to two benchmark circuits are presented in this section. The sensitivity of this technique to various practical non-idealitites is also evaluated.

4.1. State Variable Filter

The PQOBT technique was applied to a continuous-time state variable filter benchmark circuit with low-pass, high-pass, and band-pass outputs as shown in Fig. 9. In a conventional OBT implementation, the filter is converted into an oscillator by directly connecting the band-pass output to the input as the gain of the filter is sufficiently high to induce oscillations [4]. In order to convert the filter into a marginally stable configuration in test mode, a simple resistive attenuator is added to the feedback loop to control the degree of stability as shown in Fig. 9. This makes the overall loop gain insufficient to sustain continuous oscillations, producing a damped oscillatory response at the output when a pulse stimulus is applied. Fig. 10 shows the state variable filter response to a pulse stimulus, while it is reconfigured in a marginally stable test configuration.

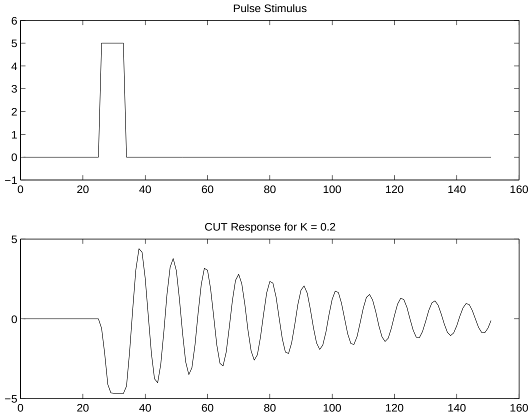

Figure 10. State variable filter response

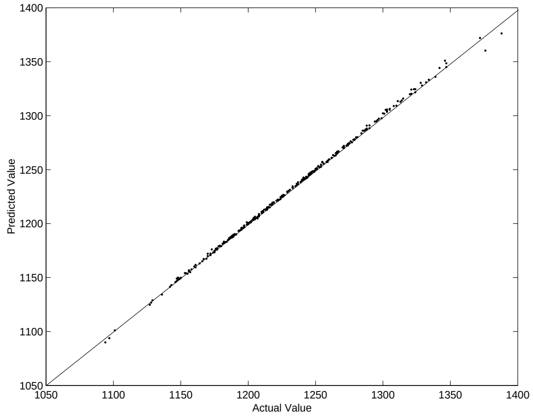

Figure 11. Comparison of actual and predicted values of f_{3dB} using PQOBT

A set of 600 CUT ensembles was generated assuming a 10% random deviation with normal distribution in the values of the passive components. These ensembles were first simulated in normal mode using HSPICE, and the performance parameters were measured. The performance parameters considered for prediction using the PQOBT method-

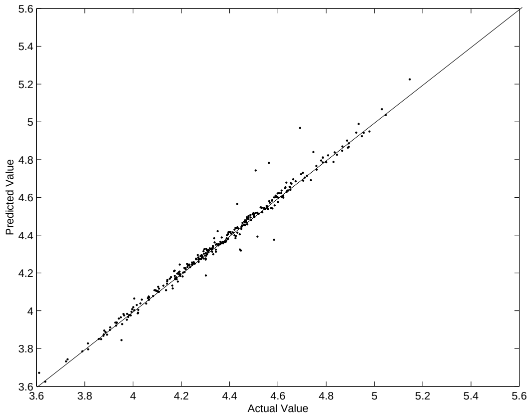

Figure 12. Comparison of actual and predicted values of maximum gain using PQOBT

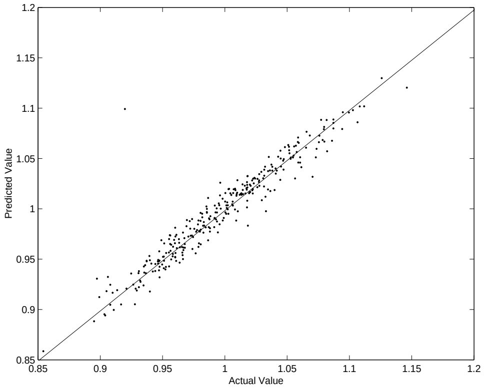

Figure 13. Comparison of actual and predicted values of DC gain using PQOBT

Table 2. PQOBT prediction errors over different process parameter ranges for state variable filter

Range	f_{3db} kHz	DC Gain	Maximum Gain
10%	0.0015	0.0150	0.0374
15%	0.0162	0.0303	0.1393
20%	0.0140	0.1393	0.2579
25%	0.0230	0.0431	0.3213

Table 3. State variable filter specifications used for classification

Performance Parameter	Specification Limits
$f_{3db}(kHz)$	1.1 - 1.4
DC Gain	0.8 - 1.2
Maximum Gain	4.2 - 4.5

ology were the 3-dB cut-off frequency, the maximum gain and the DC gain at the low-pass output of the filter. The ensembles were then simulated in test mode, and the quasi-oscillation measurements were obtained by sampling the filter response at the low-pass output at a sampling frequency of 20 kHz. The data corresponding to 300 of these ensembles were used to derive the mapping function set, f_{ms}, and the data corresponding to the remaining 300 ensembles were used to evaluate the accuracy of prediction. Fig. 11, Fig. 12, and Fig. 13 show plots of the predicted versus the measured values of the CUT performance parameters for the PQOBT technique. These parameters were also predicted using the POBT technique for the purpose of comparison. Table 1 provides the root mean squared values of the prediction errors for each performance parameter predicted using the POBT and the PQOBT techniques for a 10% deviation in process parameter values. When process parameter variations greater than 10% were considered, a significant number of CUT ensembles experienced loss of oscillations.

The PQOBT technique was evaluated for different ranges of process parameter variations and the results are shown in Table 2. The results indicate that the PQOBT technique maintains a high level of predictive accuracy over a wide range of process parameter variations.

4.1.1 Classification Accuracy

The CUT ensembles were classified by comparing predicted values of performance parameters using the PQOBT technique against the specification limits shown in Table 3. Table 4 provides the classification results obtained using the PQOBT technique for different ranges of process parameter variations. The results indicate that the PQOBT technique maintains a high degree of classification accuracy over a wide range of process parameter variations.

4.1.2 Effect of Training Set Size

The effect of the size of the training set used to derive the mapping function set, f_{ms}, on the predictive accuracy of the PQOBT technique is evaluated in this section. Training sets of different sizes were used to derive the mapping function set, f_{ms}, and these functions were then used to predict the performance parameters of a set of 200 CUT ensembles for a 25% variation in process parameter values. Table 5 provides the root mean squared values of the prediction errors

Table 4. PQOBT classification results over different process parameter ranges for state variable filter

Process Parameter Range	Pass	Fail	Misclassified
10%	127	173	0
15%	90	210	6
20%	54	246	1
25%	44	256	10

Table 5. PQOBT prediction errors for different training set sizes

Training Set Size	f_{3db} kHz	DC Gain	Maximum Gain
200	0.0736	0.0823	0.2483
400	0.0256	0.0734	0.1357
600	0.0445	0.0407	0.2082
800	0.0188	0.1237	0.1368

corresponding to mapping function sets derived using training sets of different sizes for the state variable filter. The results show that the predictive accuracy generally improves with the size of the training set. Similar results for alternate testing schemes were reported in [1].

4.1.3 Effect of Finite Sample Accuracy

The measurement samples obtained in a practical implementation are generally of finite precision. In order to evaluate the sensitivity of this technique to sample accuracy, the mapping functions were derived using test measurements of varying precision, and the performance parameters of the state variable filter were predicted using test measurements of the same precision. Table 6 provides the prediction errors corresponding to mapping functions derived using oscillation measurement samples of differing precision, for a 15% variation in process parameter values. It can be seen that the change in predictive accuracy is relatively small.

4.1.4 Effect of Sampling Jitter

The output response samples in the previous sections were obtained assuming an ideal clock without any jitter. In this section, the sensitivity of the PQOBT technique to sampling jitter is evaluated. The jitter is modeled as a uniformly distributed random variable, with a maximum deviation expressed as a percentage of the sampling frequency of 20 kHz. The mapping functions were derived using test response samples obtained with different values of jitter introduced, and the performance parameters of the state variable filter were predicted using another set of test response samples obtained in the same manner. Table 7 provides the prediction errors corresponding to mapping functions derived considering different values of sampling jitter, for a 15% deviation in process parameter values. It can be seen that the PQOBT technique is relatively insensitive to sampling jitter.

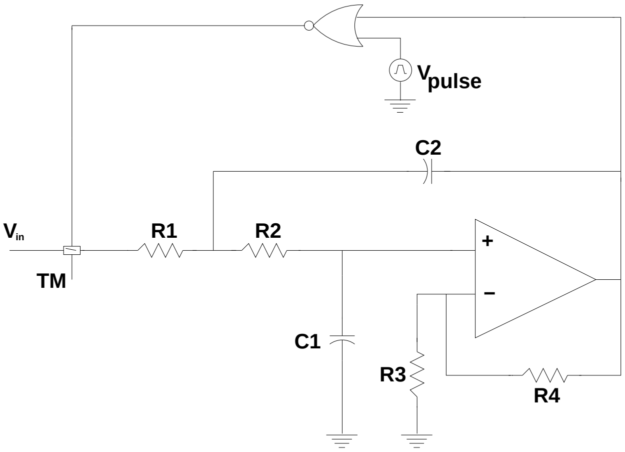

Figure 14. Sallen Key Low Pass Filter ($R_1 = R_2 = 10k\Omega, R_3 = 33k\Omega, R_4 = 27k\Omega, C_1 = C_2 = 10nF$)

Table 6. PQOBT prediction errors for different sample accuracies

Sample Accuracy	f_{3db} kHz	DC Gain	Maximum Gain
13 bits	0.0162	0.0303	0.1393
10 bits	0.0223	0.0302	0.1395
7 bits	0.0185	0.0224	0.1503

4.2. Sallen-Key Low Pass Filter

The second circuit considered was a Sallen-Key low pass filter. This topology was shown to be testable using OBT in [4]. The filter was converted into an oscillator in test mode by adding a simple digital inverter to the feedback path between the output and the input of the filter. This inverter is replaced with a NOR gate to allow application of the pulse stimulus as shown in Fig. 14.

The degree of stability can be adjusted by adding a resistive attenuator to the feedback path to reduce the overall loop gain. The performance parameters considered for this circuit were the 3-dB cutoff frequency and the DC gain of

Table 7. PQOBT prediction errors for different values of sampling jitter

Jitter % of $T_{osc}^{nominal}$	f_{3db} kHz	DC Gain	Maximum Gain
1%	0.0472	0.0261	0.0816
2%	0.0473	0.0263	0.0828
3%	0.0477	0.0163	0.0831

Table 8. PQOBT prediction errors for Sallen-Key Filter

Process Parameter Range	f_{3db} kHz	DC Gain
10%	0.0063	0.0090
20%	0.0224	0.0131
30%	0.0800	0.0705

Table 9. Sallen-Key filter specifications

Performance Parameter	Specification Limits
$f_{3db}(kHz)$	1.7 - 2.0
DC Gain	1.6 - 1.9

Table 10. PQOBT classification results for Sallen-Key filter

Range	Pass	Fail	Misclassified
10%	258	42	1
20%	138	162	1
30%	83	217	3

the filter. The PQOBT methodology was used to predict the performance parameters of the CUT for different ranges of process parameter variations. Table 8 provides the prediction errors for these performance parameters for different ranges of process parameter variations. The performance parameters predicted using the PQOBT methodology were then used to classify the CUT ensembles using the specification limits given by Table 9. Table 10 provides the classification results for this circuit.

5. Comparison with previous work

Table 11 compares the PQOBT methodology with previous performance prediction schemes. While alternate testing schemes [1, 2] have good predictive accuracy over a wide range of process parameter variations, they require generation of an optimized PWL stimulus using an Arbitrary Waveform Generator. The test generation overhead was reduced in the case of POBT [6], but this technique can be used only for a limited range of process parameter variations. Also, the test time for the POBT technique is increased by the time required for oscillation buildup. In the case of the PQOBT technique, the test generation overhead is limited to a short transient pulse. Also, the test time depends on the length of the CUT response when it is configured to a marginally stable configuration. The degree of stability can be optimized for minimum test time by adjusting the value of K. Fig. 15 shows the test response of the state variable filter for different values of K.

6. Conclusions

A novel technique for extending the predictive accuracy of POBT over a wide range of process parameter variations was presented in this paper. This technique solves the unmapped region problem associated with POBT by configuring the CUT to a marginally stable test configuration whose degree of stability is sensitized to process parameter variations. Simulation results indicate this technique can be used to predict CUT performance parameters with minimal test generation overhead.

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Table 11. Comparison with previous work

Comparison Feature	PQOBT	POBT [6]	Alternate Testing [1, 2]
Test Stimulus	Short pulse	Not required	Optimized PWL stimulus
Test Generation Overhead	Can be generated using on-chip digital logic	Circuitry needed to ensure safe and short oscillation buildup	Arbitrary Waveform Generator required
Unmapped Process Parameter Space	No	Yes	No
Test Time	Depends on length of damped response	Increased by time for oscillation buildup	Depends on length of PWL stimulus

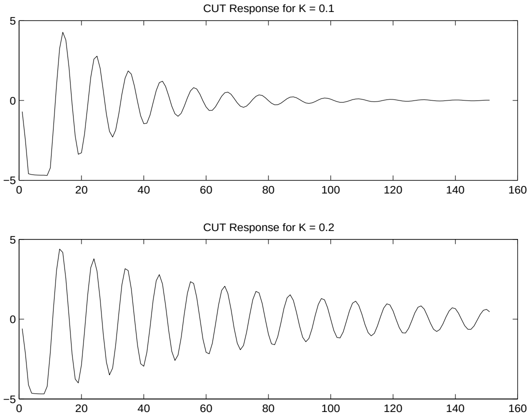

Figure 15. State variable filter response for different values of K

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