Dynamic Test Signal Design for Analog ICs[†]

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Abstract

In this paper we present an approach to construct dynamic test signals for analog circuits. Using the integral measure for characterizing time-domain signals, we extend the minmax formulation of the static test problem to the dynamic case. A sub-optimal solution strategy, similar to dynamic programming methods is used to construct the test waveforms. The approach presented here may be used to construct input signals for an on-chip test scheme or for the selection of an external stimulus applied through an arbitrary waveform generator.

1: Introduction

Analog testing has been traditionally approached as verifying a subset of the specifications-the selection of the specific subset dictated by the application on hand. Although functional tests are effective in detecting faults, they are expensive in terms of test resources and typically involve collection of a large number of samples. Alternate test excitations which are designed to exploit the specific structural differences between the defective and non-defective circuits bear promise in reducing the cost of testing.

Fault based approaches to analog testing have focused on the construction of fault-dictionaries before manufacture through simulation. In [3] the authors presented an algorithm to construct the signatures and evaluate the detectability of a set of DC measurements. As far as automatic test generation for analog circuits is concerned, in [1] the author presented an approach for linear analog circuits where a quadratic error objective was maximized. In [2], a search technique in the frequency domain was presented similar to the digital ATPG approach to select the best test frequency for linear circuits. In [6] a hypothesis testing framework for test based on spectral analysis of the supply current was presented. Most of the prevailing methods are fault analysis methods, where the effect of faults are analyzed under a known excitation. In [5] a minmax framework was presented for determining a static test set. In this paper we extend the formulation for the dynamic case.

Since the number of probe points at which the signal can be measured is limited, DC tests may not result in measurable changes at the pinouts due to the structure of the circuit. For example, in a simple circuit such as an opamp the opens and shorts of the compensation transistor(M2 in Fig.1) will not affect the DC solution due to the compensation capacitor(C3 in Fig.1). Non-conducting switch structures create a similar situation. Since such structures occur often in analog circuits there is a need for some form of dynamic testing. Dynamic signal design has been dealt with extensively in optimal control literature. For the case where the measure of error is linear in terms of the control, the optimal waveform takes the form of a “bang-bang” waveform, with the input voltage swinging from the positive rail to the negative rail, the control parameters being the switching points. The application of this result to analog testing, with a heuristic for the selection of the switching points has been presented in [1]. In this paper we describe a sub-optimal procedure for dynamic test signal design for the dynamic case, based on solving a succession of static test problems in time.

2: Waveform Measure

In the dynamic case due to noise and tolerance the exact comparison of time-domain waveforms is an experimental impossibility. Hence, any detection scheme must use some measure of the waveforms as a basis for comparison. Such measures on the waveform are also referred to as signatures of the waveform.

Under a bounded excitation $x(t) \in X^t$, the non-faulty and faulty circuit equations maps the tolerance set P into two different sets of waveform, Y_g^t, Y_f^t. The test input selection problem is then to choose that $x(t) \in X^t$ which will result in sets Y_g^t, Y_f^t such that, $Y_g^t \cap Y_f^t \neq \phi$. In general, making a decision whether the intersection is empty or not, takes infinite comparisons at each time point of the waveform. Hence

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we need to transform these waveforms into a lower dimensional space where an easier comparison is possible. Increasing the dimension of the transformed space corresponds physically to a more detailed comparison.

The measure for the good waveform is defined as,

$$M_g(T,p) = \frac{1}{C}\left[\int_0^T y_g(t,p)\, w(t)\, dt\right] \qquad (1)$$

$y_g(t,p)$ represents the output waveform of the non-defective circuit, under an excitation $x(t)$.

$w(t)$ is a weighting function determining the specific characteristic of the waveform represented by the measure. A simple rectangular window over [0,T] will result in some sense, the integral measure of the waveform. This definition of measure differs from the common spectral measures in that, neither periodicity nor infinite length of data samples are necessary to evaluate the measures accurately. The measure $M_f(T,p)$ for the faulty circuit may be defined as in (1).

Using the framework presented in [5], the min-max test problem for the dynamic case now becomes,

$$\min_{\boldsymbol{p} \in P} \ \max_{x(t) \in X^t} \left|M_g(T,p) - M_f(T,p)\right| \qquad (2)$$

If we proceed along the same lines as in [5] to solve the minimax problem, then we need to discretize the set X^t. As we observed earlier, X^t is an infinite-dimensional set due to the time dependence. The set X^t may be made finite dimensional by discretizing the time axis, at a selected number of points. For example, if the time interval [0,T] is discretized at 20 points, then the dimension of set X is 20. To solve for the values of the input numerically at each of these time points, the 20-dimensional set needs to be discretized further, creating an extremely large size problem. Since an exact solution to the problem is out of reach, we seek a sub-optimal procedure for constructing the time domain waveform, while retaining the constructive nature of the synthesis.

3: Suboptimal construction

Any specification of the input has to finite dimensional, with varying degrees of freedom in the exact parameterization. In this work we assume the input waveform is specified as a piecewise linear waveform, with the signal values $x_1,\ldots\ldots x_K$ which have to be synthesized occurring at time points $t_1, t_2 \ldots t_K$. The signal values in between the specified points are evaluated through a piecewise linear interpolation. If $u(t)$ is the unit step function, the input signal under this piecewise linear interpolation is then specified as,

$$x(t) = \sum_i \left[u(t-t_i) - u(t-t_{i+1})\right]\left(\frac{x_i - x_{i+1}}{t_i - t_{i+1}}\right) \qquad (3)$$

Problem Statement: Let x_0 be the initial value at time t_0. Given the time points $t_1, t_2, \ldots. t_K = T$, find a sequence of values of $x_1,\ldots\ldots x_K$ such that in the worst case the absolute value of the difference in measures at the end of the experiment is greater than a threshold δ, sufficient for a pass/fail decision. Since solving for $x_1,\ldots\ldots x_K$ simultaneously is computationally expensive, we propose a sub-optimal solution, wherein the optimization procedure solves for each x_i sequentially in time starting at time t_1 and ending at t_K. At each t_i we generate an x_i which is optimal at that time point locally,i.e, x_i maximizes the error measure at t_i as if t_i was the final time of the experiment. The previous values of values of x_j $(j < i)$ necessary to solve for x_i are obtained from the solution of the optimization problem at the previous time points. The steps then in the optimization procedure at each time point t_i are:

Step 1. If $E(t_i,p) = M_g(t_i,p) - M_f(t_i,p)$ then solve the following minmax problem,

$$\min_{\boldsymbol{p} \in P} \left\{ \max_{\boldsymbol{x} \in X_s} \left(\left|E(t_i,p)\right|\right) \right\} \qquad (4)$$

where $X_s = [-x_{max}, x_{max}]$ represents the bounds on the waveform value at each time point. To solve this problem further as earlier the set X_s is discretized. Since this is a one dimensional set, the discretization does not create a large size problem. If j be the index of this discretization. Then (5) is solved iteratively as in [5] with the problem at iteration n represented below.

$$\min \ \gamma \qquad (5)$$

satisfying,

$$\left|E_j(t_i,\boldsymbol{p}_n) + \langle \nabla E_j(t_i,\boldsymbol{p}_n) | (\boldsymbol{p} - \boldsymbol{p}_n) \rangle\right| \le \gamma,\ j = 1 \ldots N$$

$$p_m^{L'} \le p_m \le p_m^U,\ m = 1 \ldots n_p$$

$$0 \le \gamma$$

The problem above is a linear optimization problem in n_p+1 variables with $2N+n_p+1$ constraints. An upper bound on γ is not placed since the time constant C may be adjusted later to satisfy the physical constraints. At the solution point, the value of $x_j(t_i)$ and the optimal value $\bar{\gamma}$ indicating the worst case error difference between the measures at time t_i is obtained. The value of $\bar{\gamma}$ is obtained as part of the solution to the problem whereas, the optimal test value $x_j(t_i)$ is identified using the set of lagrange multipliers produced by the LP solver at the solution point. Since the iterative procedure requires gradients, we construct quadratic response surfaces at each t_i by using a box-central sampling scheme[4]. Once the response surfaces are constructed, gradient evaluation is trivial. This is the most CPU-intensive part of the optimization, since it involves performing a series of transient simulations.

Step 2. If $\bar{\gamma} < \delta$, then construct the new waveform using equation (3) and repeat from step 1.

Step 3. Once the input waveform is determined, it is necessary to generate bounds on the measure of the good circuit so that, a pass/fail decision can be made by comparing the observed measure waveforms with these bounds. If $M(t)$ is the measure observed from the circuit under test,

the circuit is non-faulty if and only if,
$M_l(T) \le M(T) \le M_u(T)$ where $M_u(T)$ and $M_l(T)$ are given by,

$$M_u(T) = max\{M_g(T, p)\} \tag{6}$$

$$M_l(T) = min\{M_g(T, p)\} \tag{7}$$

4: Results

In this section we present two examples to illustrate the use of our dynamic test technique. The effect of the tolerance has been modelled by the set of parameters shown in Table 1. To reduce the influence of the boundary conditions on the results we have used a Hann window function as the weighting function.

The first example is a two-stage compensated opamp configured in a voltage follower mode. The second example is a switched capacitor integrator with correlated double sampling.

Figure 1 shows the schematic for the voltage follower. The interesting faults for the dynamic case in this configuration are associated with the compensation branch. They are: 1) Any opens in the compensation branch. 2) Shorts associated with the transistor M2. 3) Opens or parametric changes in the capacitor C3.We have modelled the value of the short with values of resistance ranging from 0.1-100 ohms. The effect of opens is difficult to model at the circuit level, but to test the dynamic test algorithm we have used a 100MEG resistor to represent the effect of opens. The error measure depends on the constant C, the time constant for the integral measure in equation (1). To compare different waveforms we have normalized the measures by setting C to be the interval between specification time points.

Using the dynamic test procedure with the input specification being time points spaced $1\mu s$ apart we find that the test waveforms generated by our procedure takes the form shown in Fig. 2a. The initial value at time t=0 was set at 2.5V. Waveform 1 and Waveform 2 was found to produce the same magnitude of error(Fig. 2b) for all the device level open and short faults in the opamp except, for the drain to source short in the compensation resistor M2 for which, the error is an order of magnitude lower. Now if the input specification is such that the time points are now based $0.1\mu s$ apart it is seen that the M2 device short may also be detected using the integral measure with the resulting input waveform denoted by Waveform 4, shown in Fig.2c. The resulting error profile is shown in Fig.2d. To make a pass/fail decision it is necessary to obtain bounds on the measure waveforms for the good circuit. Using the analysis presented in section 3 the bounds of the integral measure are obtained and shown in Fig. 3. If the measure of the waveform for the circuit under test does not lie within the bounds shown in Fig.3 it is considered defective. In all the cases the error voltage developed is sufficient for a pass/fail decision to be made in a few microseconds.

4.1 Switched capacitor integrator

As another example we studied the switch capacitor integrator structure shown in Fig. 4. To induce dynamic behavior at the input of the circuit, the clocking circuits are disabled so that phi1 phase switches are on while the phi2 phase ones are off. By using the dynamic test program we see that most of the faults are detected by the same inputs generated for the voltage follower. The worst case error voltages are plotted for this in Fig. 5 for a sample of catastrophic faults. A new test input which was not needed for the voltage follower was found for the integrator and is shown in Figs.6a-b. Again we observer that sufficient discrimination is developed in short test times.

5: Conclusions

In this paper we have extended the static test generation to the dynamic case by adopting a sub-optimal solution strategy similar to dynamic programming. Using the weighted integral measure for the waveforms, we find that simple ramp-type inputs are effective in detecting faults not excited by DC inputs. Although the scheme presented here is CPU intensive, we believe this is a step towards a general test generation tool for analog and mixed-signal circuits.

Table 1: Tolerance Set P

Parameter	Nominal Value	Max Value	Min Value
ΔVTOn	0 Volts	+0.1 V	-0.1 V
ΔVTOp	0 Volts	+0.1 V	-0.1 V
XWn	0 μ	1μ	-1 μ
XWp	0 μ	1μ	-1 μ
XL	0 μ	1 μ	-1 μ
TOX	3.95e-8m	3.80e-8m	4.10e-8m

6: References

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[6] G.Gielen et.al, “Fault Detection and Input Stimulus Determination for the Testing of Analog Integrated Circuits Based on Power-Supply Current Monitoring”, Proc. ICCAD, pp. 495-498, 1994.

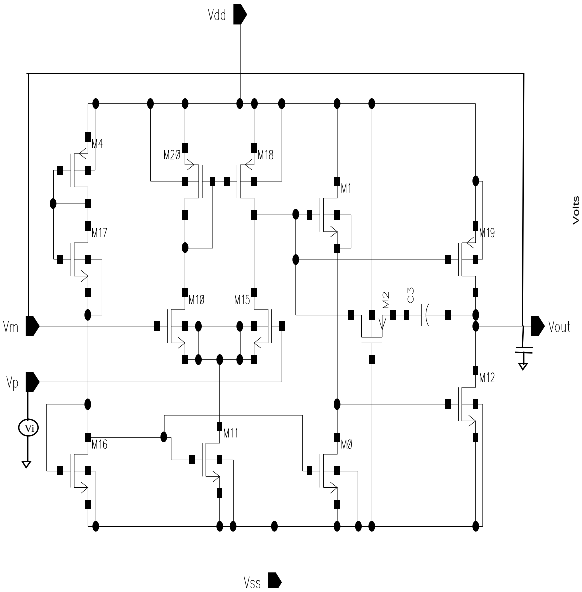

Fig. 1:Voltage follower

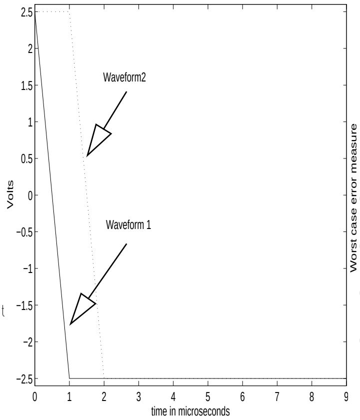

Fig.2a:Test Waveforms specified at 1us interval for circuit in FIg. 1

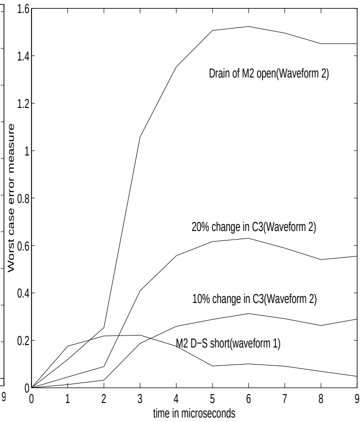

Fig.2b:Error measures for various faults indicated

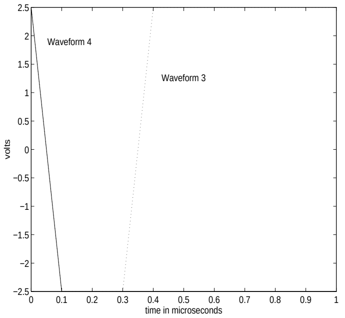

Fig.2c:Test Waveforms specified at 0.1us interval for the voltage follower

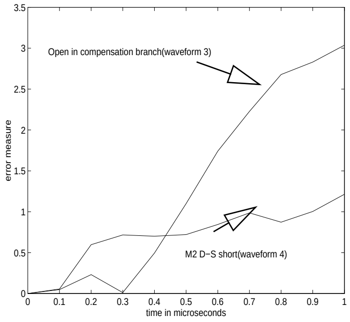

Fig.2d:Error measures for faults from voltage follower with waveforms 3 and 4 as input

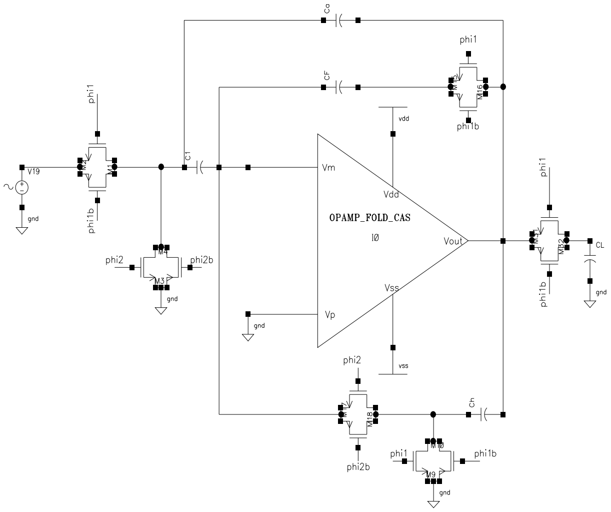

Fig.4:Switched capacitor integrator -correlated double sampling

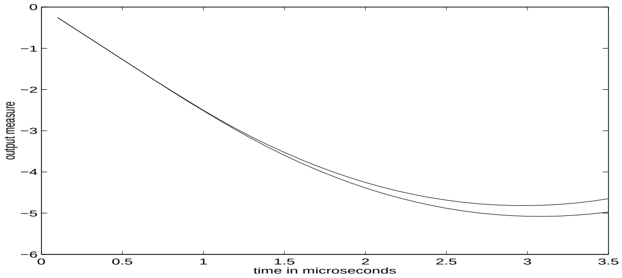

Fig.3: Envelope of the measure for the defect free voltage follower

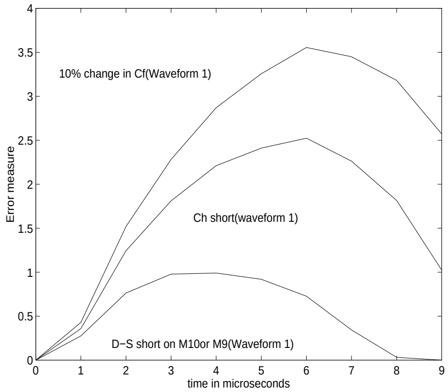

Fig.5: Error measures for integrator faults whose test input is Waveform 1

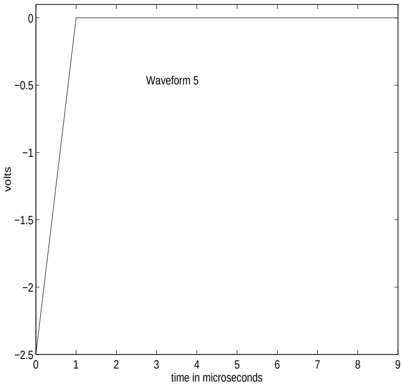

Fig.6a: New test input for integrator faults

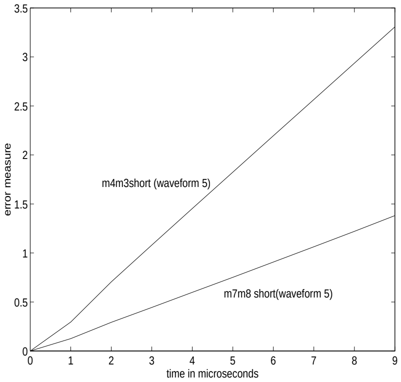

Fig.6b: Error measure for faults with waveform 5 as test input