Defect Oriented Testing of Analog Circuits Using Wavelet Analysis of Dynamic Current

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Abstract

In recent years, Defect Oriented Testing (DOT) has been investigated as an alternative testing method for analog circuits. In this paper, we propose a wavelet transform based dynamic current (IDD) analysis technique for detecting catastrophic and parametric faults in analog circuits. Wavelet transform has the property of resolving events in both time and frequency domain simultaneously unlike Fourier transform which decomposes a signal in frequency components only. Simulation results on benchmark circuits show that wavelet transform has higher fault detection sensitivity than Fourier or time-domain methods and hence, can be considered very promising for defect oriented testing of analog circuits.

I. Introduction

The slow and expensive nature of specification testing has motivated research into fault-based or structural test for analog circuits [1] [2]. Voltage measurement based techniques cannot access the internal nodes and has poor fault coverage for analog circuits. IDDQ testing in analog circuits have been explored because of its high fault coverage but it has problems like very high steady state currents in many analog circuits [3]. On the other hand, measurement of dynamic power supply currents has been found very useful for testing analog or mixed-signal ICs because of its potential to detect large class of manufacturing defects [4] [5] [6]. The current passing through the VDD or GND pin is measured under application of an input stimuli and the waveform is used to detect fault. While the waveform contains significant information about the circuit performance, appropriate analysis is required to extract specific knowledge about the signal. Existing analysis methods based on statistical or spectral properties of current waveform are effective for catastrophic faults but does not work well for parametric faults, which are more difficult to detect.

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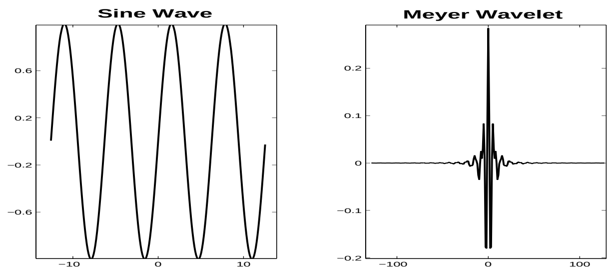

Fig. 1. **Basis functions for Fourier (sinewave) and wavelet (meyer) transforms**

In this paper, we present a wavelet based dynamic current analysis method for fault detection in analog circuit. We show that wavelet decomposition has better sensitivity to detect parametric faults than techniques which use spectral or time domain information separately. Wavelet transform of a signal is a two-dimensional decomposition technique which analyzes the signal in multiple resolutions. Coefficients corresponding to each resolution localize events in time domain. Hence, wavelet transform coefficients of a signal contains both time and frequency information making it more sensitive for fault detection. In our work, we have used a simple metric for comparing the sensitivity of the wavelet method with DFT based method and a time domain method. Simulation results on two benchmark circuits demonstrate the superiority of wavelet method for parametric faults.

The rest of the paper is organized as follows. Section II presents basic ideas about wavelet transform. Section III deals with fault detection using wavelet transform of the IDD signal. In section IV we present the simulation results. In Section V, we consider some important issues for analog fault detection using wavelet. Section VI concludes the paper.

II. An Overview of Wavelet Transform

Wavelet transform is a mathematical operation that decomposes input signal simultaneously into time and frequency components [10][11]. Fourier analysis

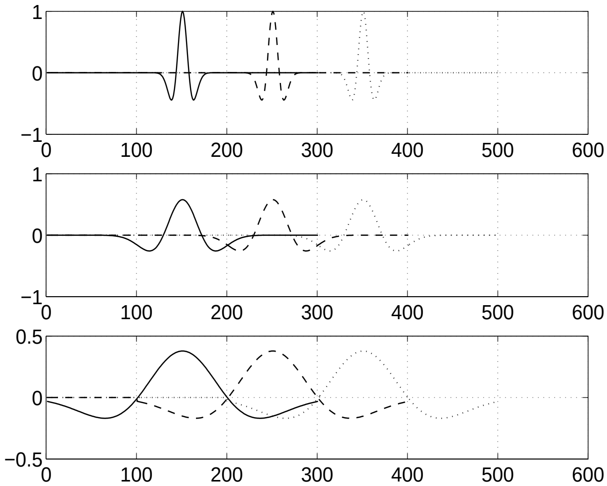

Fig. 2. **Translated and dilated mother wavelet (*mexican hat*) used in wavelet decomposition**

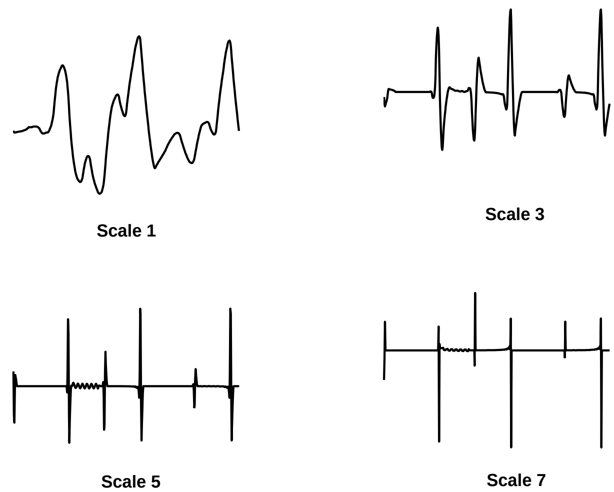

Fig. 3. **Wavelet coefficients at different *scale*s obtained from current waveform in figure 2**

has a serious drawback since it transforms signal in frequency domain losing all information on how the signal is spatially distributed. Hence, it is impossible to localize an event in time scale looking into the Fourier coefficients of a signal. Wavelet decomposition of a signal, on the other hand, can resolve events in both time and frequency domain, which turns out to be very useful in fault detection. In wavelet transform we take a real/complex valued continuous time function with two properties - a) it will integrate to zero, b) it is square integrable. This function is called the *mother wavelet* or wavelet. (This has to satisfy another property called *admissibility*, to perform the inverse transform). Property (a) is suggestive of a function which is oscillatory or has wavy appearance and thus in contrast to a sinusoidal function, it is a small wave or wavelet (figure 1). Property (b) implies that most of the energy of the wave is confined to a finite interval. The CWT or the Continuous Wavelet Transform of a function $f(t)$ with respect to a wavelet $\Psi(t)$ is defined as:

$$W(a,b) = \int_{-\infty}^{\infty} f(t)\Psi^*_{a,b}(t)dt \qquad (1)$$

$$\text{where } \Psi_{a,b}(t) = \frac{1}{\sqrt{|a|}}\Psi(\frac{t-b}{a}) \qquad (2)$$

Here a,b are real and $*$ indicates complex conjugate. $W(a,b)$ is the transform coefficient of $f(t)$ for given a, b. Thus the wavelet transform is a function of two variables. For a given a, $\Psi_{a,b}(t)$ is a shift of $\Psi_{a,0}(t)$ by an amount b along time axis. The variable b represents time shift or translation. Since a determines the amount of time-scaling or dilation, it is referred to as *scale* or dilation variable. If $a > 1$, there is stretching of $\Psi(t)$ along the time axis whereas if $0 < a < 1$ there is a contraction of $\Psi(t)$ (figure 2). Each wavelet coefficient $W(a,b)$ is the measure of approximation of the input waveform in terms of the translated and dilated versions of the *mother wavelet*. Figure 1 compares the basis signals of DFT and wavelet transform. The *mother wavelet* shown in figure 1 is called *meyer* wavelet. Figure 2 shows the translated and dilated *mother wavelet* used to approximate an IDD waveform of an analog circuit. Figure 3 shows the wavelet components of the IDD signal in figure 2 at four different *scales*. It can be noted that components have rapidly diminishing magnitudes at higher frequencies (higher *scale*s).

III. Fault Detection Using Wavelet Transform

Our fault detection method is based on current signature comparison. The two dimensional set of wavelet coefficients obtained from a test circuit (DUT) for a particular input stimuli, is compared with those from a golden circuit for the same stimuli. We compute the RMS error between the coefficients for comparing the response of the DUT with golden circuit. An RMS error which is more than a predetermined test margin indicates a faulty DUT. The precision of the testing process depends on the quality of the test margin. Manufacturing process parameter variations and measurement hardware noise need to be taken into account in identifying test margin. In addition, the success of the test largely depends on the choice of input stimulus which plays important role in determining fault coverage [7].

In this research, our goal is to show wavelet transform as a more efficient dynamic current waveform analysis than DFT and other statistical methods [8] [5] for detecting faults in analog circuits. We have chosen a simple RMS error metric for comparing the sensitivity of the wavelet based testing with DFT or time-domain method. In the following equations G_i's are the coefficients for golden circuit response and F_i's are those for DUT response. Equation 3 represents the RMS value of difference. The normalized RMS, as in equation 4 can be considered a direct measure of the sensitivity of the transforms. In equation 4, we use the fault free components (G_i) for normalization. It computes the root mean square value of the difference as a fraction of the corresponding golden circuit coefficient(G_i). In addition to DFT method, we also use a pure time domain approach based on charge computation (area under supply current curve) to compare the wavelet method.

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(F_i - G_i)^2} \qquad (3)$$

$$normRMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{F_i - G_i}{G_i}\right)^2} \qquad (4)$$

IV. Simulation Results

We used two test circuits taken from ITC'97 set of analog benchmarks. One of the circuits is a leapfrog filter (figure 4) and the other is a continuous-time state-variable filter (figure 5). Both are taken from the ITC'97 set of benchmarks. We performed simulations on the *Hspice* netlist of the circuits with AC input stimuli for both the circuits. The *mother wavelet* chosen was *db2* [10]. We used Matlab software for computing the DFT and wavelet coefficients. To model catastrophic faults we used a bridging resistance of 10 Ω for shorts. Opens were modeled using a 100M Ω resistance. Parametric faults were modeled either by +/- 6 σ variation in circuit component or by varying the transistor threshold voltage (Vth). We used the same number of frequency components for both wavelet and DFT methods. Coefficients with value less than 1 were not considered to compute the normalized error.

Table I shows the result of comparison for parametric faults in both the circuits. 'LF' stands for circuit leapfrog filter and 'CTSV' for continuous-time state-variable filter. Column 2 specifies the kind of parametric fault introduced in the circuit. Column

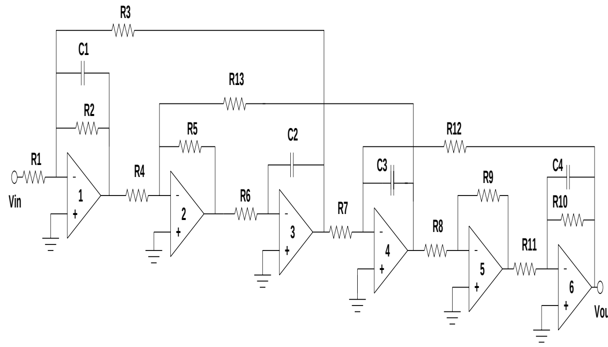

Fig. 4. **Analog benchmark circuit : leapfrog filter** *(ITC'97)*

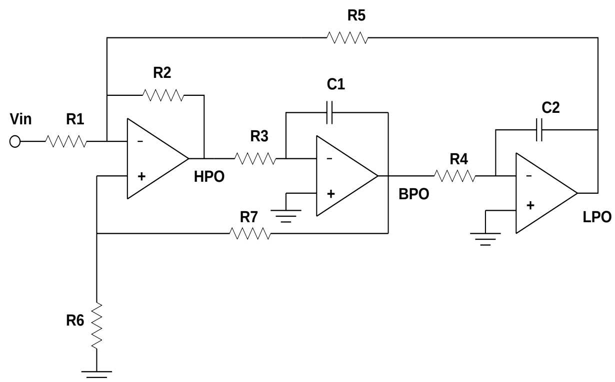

Fig. 5. **Analog benchmark circuit : continuous-time state-variable filter** *(ITC'97)*

3 and 4 are the RMS error for wavelet and DFT method respectively. Column 5 (ERRQ) is the error calculated as difference in area under current waveform while the column 6, 7 and 8 represent the normalized error value for all three cases. It can be observed that the wavelet based method has significantly better sensitivity than the other two methods. The average sensitivity for wavelet is about 25 times of DFT and about 80 times of the charge based method (NormQ) for the 10 parametric faults considered in table I.

The test margin for the catastrophic faults should fall outside the test margin required to detect the parametric faults. To verify that it is true for wavelet based testing, we experimented with a set of catastrophic faults in the leapfrog filter and computed the sensitivity. Table II shows that catastrophic faults can be detected using the test margin for parametric faults and wavelet based method has the better sensitivity measure also for the catastrophic faults.

For table I and table II the number of frequency components used is 8 starting from the lowest fre-

TABLE I
Comparison of sensitivity for parametric faults

Design	Fault	RMS(Wav)	RMS(DFT)	ERRQ	$NormRMS$(Wav)	$NormRMS$(DFT)	NormQ
LF	C4, +6s	525962.0	627369.9	575.2	1.86	0.24	0.11
	C2, -6s	1179645.0	969349.8	869.3	7.41	0.45	0.17
	R2, -6s	2190771.0	3554285.6	1845.3	2.74	0.51	0.35
CTSV	C1, -6s	2094.3	1422.6	33.1	27.57	0.40	0.10
	C2, +6s	836.9	607.4	20.3	7.30	0.17	0.06
	R7, +6s	2417.0	2937.7	40.5	4.10	1.22	0.12

TABLE II
Comparison of sensitivity for catastrophic faults

Fault	RMS(Wav)	RMS(DFT)	ERRQ	$NormRMS$(Wav)	$NormRMS$(DFT)	NormQ
R8, VCC bridge	59724930.8	83412522.5	8936.2	142.61	10.21	1.69
C2 shorted	16354037.4	26511764.3	5075.5	15.73	2.72	0.96
Drn/Src short, Opamp4, M3	14492540.8	21761478.2	4571.2	51.36	2.04	0.87
R5 Open	27378158.7	28496386.6	4910.6	1228.67	11.74	0.93
Drn/Gate short, opamp5, M7	7173998.5	10345002.0	3135.3	22.44	1.41	0.59

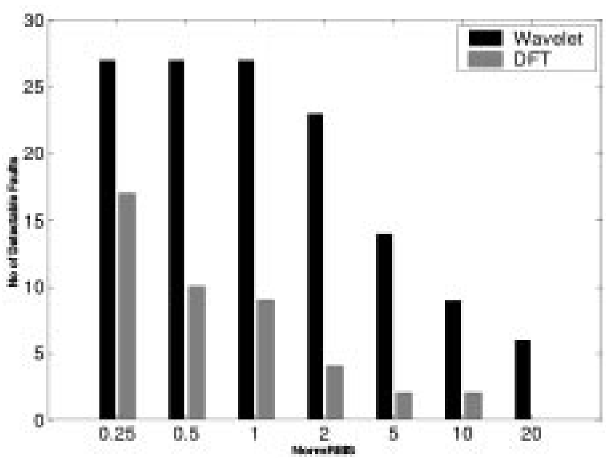

Fig. 6. **Comparison of fault coverage for wavelet and DFT method.**

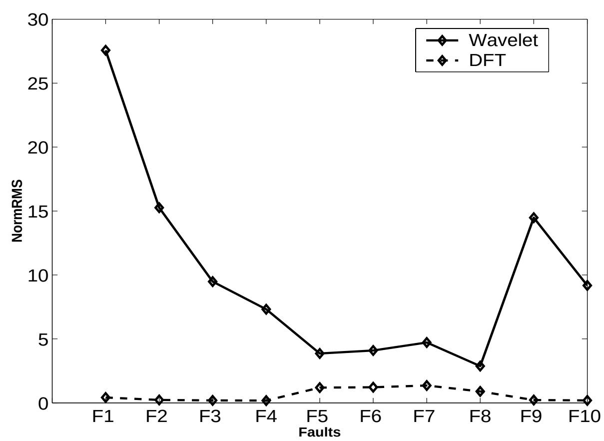

Fig. 7. **Distribution of Normalized RMS for 10 different faults.**

quency component for both wavelet and DFT methods. It is observed that the DFT coefficients converge to zero at a very slow rate and we can get equivalent sensitivity in DFT method only if we consider large number of frequency components.

Figure 6 plots the fault coverage of two methods to compare their effectiveness to detect fault for a fixed normalized error. We considered a total of 23 parametric and 5 catastrophic faults in two test circuits. The plot shows that for a Normalized RMS error of 0.25 we can detect 1.6 times more faults using wavelet while it is 5.8 times for an error bound of 5. The plot in figure 7 compares the distribution of normalized RMS for two cases. For this plot we considered 10 parametric faults as in table I. It can be noted that the error distribution for wavelet has more deviations across faults than DFT.

V. Test Design Issues

A. Choice of *mother wavelet*

Selection of basis for wavelet analysis (*mother wavelet*) has impact on the sensitivity of fault detection. For the test circuit (leapfrog filter) and the faults considered, we have observed that the basis *Meyer* wavelet has the best sensitivity while the *Mex-hat* wavelet has the least. One significant advantage of using wavelet for fault detection is that we can choose the basis wavelet according to application i.e. in this case we can choose the basis which fits to the IDD waveform of the golden circuit best.

B. Measurement noise

Effect of measurement hardware error is an important factor to consider for fault detection especially for off-chip supply current monitoring [4]. Usually the measurement hardware acts as a low pass filter smoothening out many high frequency components. Hence, the detection technique which largely depends on the high frequency components, is not suitable for off-chip testing. In our experiments, we have shown that wavelet renders a more sensitive detection method than DFT when both use only lower frequency components of IDD for fault detection. This observation makes wavelet a more promising technique than DFT for off-chip testing.

C. Process Variation

Setting the threshold between faulty and fault-free responses needs to consider the manufacturing process parameter variation. Time domain approach e.g. the charge integration is not very useful here due to problems like *aliasing*. We believe, wavelet components are better than DFT for comparison of faulty and fault-free waveforms. The impact of process parameter variation on dynamic current waveform, in most cases, can be observed more in some particular spectral ranges than others. We can easily eliminate those frequency bands of the IDD waveform and still can achieve a high sensitivity of fault detection using wavelet transform.

VI. Summary and Conclusions

Wavelet decomposition based dynamic supply current analysis has been shown to have better sensitivity than pure DFT or time-domain analysis method due to the multi-resolution analysis property of wavelet. Better sensitivity can help us get better fault coverage than pure spectral analysis for detecting parametric faults. Wavelet can be particularly useful for off-chip analysis of IDD, because high frequency components of the current are usually filtered out by the measurement hardware and wavelet can approximate the residue signal better than DFT. Another important advantage of using wavelet over DFT is that we can use the *mother wavelet* to adapt to the current waveform of the particular circuit, producing better representation of the signal in terms of transform components. This is not possible with Fourier transform which has a fixed sinusoidal basis function. Our research has also shown [9] that wavelet is very promising for fault detection in CMOS digital circuits. This makes it a suitable candidate for testing Mixed-signal circuits with a unified testing solution for both digital and analog parts.

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