Oscillation-based Test Method for Continuous-time OTA-C Filters

Masood-ul-Hasan
School of ECEE
University of Hertfordshire,
Hatfield, Herts, AL10 9AB, UK
Tel: ++44 1707 285082, Fax: ++44 1707 284199,
Email: m.hasan@herts.ac.uk

Yichuang Sun
School of ECEE
University of Hertfordshire,
Hatfield, Herts, AL10 9AB, UK
Tel: ++44 1707 284196, Fax: ++44 1707 284199,
Email: y.sun@herts.ac.uk

***Abstract*— Design for testability technique using oscillation-based test topology for KHN OTA-C filters is proposed. The oscillation-based test structure is a vectorless output test strategy easily extendable to built-in self-test. During test mode, the filter under test is converted into an oscillator by establishing the oscillation condition in its transfer function. The oscillator frequency can be measured using digital circuitry and deviations from the cut-off frequency indicate the faulty behaviour of the filter. The proposed method is suitable for both catastrophic and parametric fault diagnosis as well as effective in detecting single and multiple faults. The validity of the proposed method has been verified using comparison between faulty and fault-free simulation results of KHN OTA-C filter. Simulation results in 0.25µm CMOS technology show that the proposed oscillation-based test strategy has 84% fault coverage and with a minimum number of extra components, requires a negligible area overhead.**

***Keywords*—OTA-C Filter testing, OBT for OTA-C Filters**

I. INTRODUCTION

In the last fifteen years or so, tremendous progress has been made in analogue filter research and development, however, testability of analogue integrated filters is still rather unstructured since testability is not yet a precisely defined term in the analogue world. Consumer electronic systems often require Designs-for-testability (DFT) techniques as well as built-in self-test structure for analogue and mixed-signal ICs. DFT for analogue circuits is one of the most challenging tasks in mixed-signal ASIC design due to the sensitivity of the circuit parameters with respect to component variations and process technologies. Furthermore the number of I/O pins of analogue IC is relatively small compared to that of the digital circuits, the complexity due to continuous signal values in the time domain and the inherent interaction between various circuits parameters make almost impossible to design an efficient DFT for functional verification and diagnosis. Therefore an efficient DFT procedure is required which uses a single signal as input or self-generated input signal and has access to several internal nodes and the output must contain sufficient information about the circuit under test [1][2].

Oscillation-based test (OBT) procedures for analogue circuits, based on transformation of the circuit under test to an oscillator have been recently introduced [3]. The oscillation-based DFT structure uses vectorless output frequency comparison between fault-free and faulty circuits and consequently reduces test time, test cost, test complexity and area overhead. Furthermore, the testing of high frequency filter circuits become easier because no test vector is required for the proposed test method. The proposed method shows fault coverage and diagnostic capability for both catastrophic and parametric faults in OTA-C filter. The format of the paper is as follows; Section 2 introduces the OTA-C filter to oscillator conversion scheme. Fault modelling is presented in Section 3. Test simulation results are given in Section 4, and Section 5 contains conclusions.

II. OTA-C FILTER TO OSCILLATOR CONVERSION

An ideal oscillator consists of an inverting and non-inverting lossless integrators cascaded in a loop, resulting in a characteristic equation with a pair of roots lying on the imaginary axis of the complex frequency plane. Any practical oscillator must be designed to have its poles initially located inside the right half complex frequency plane in order to assure self-starting oscillation. The existing theory for sinusoidal oscillator analysis [4] models the oscillator structure with a basic feedback loop. The feedback methodology can be used to convert the KHN OTA-C filter [5] to an oscillator and establish the oscillation condition in its transfer function.

The oscillation-based design for testability for KHN filter is discussed because the filter has some attractive features and applications. For example it can realise low-pass, band-pass and high-pass filter characteristics simultaneously. The implementation of OBT requires only two extra MOS switches in the original KHN OTA-C filter. The modified KHN OTA-C filter shown in Fig.1 performs the same filter functions with negligible pole frequency movement.

The testable OTA-C filter performances filter function when MOS switch S_p is closed and switch S_n is open. The lowpass transfer function is given by:

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$$\frac{V_{LP}}{V_{in}} = \frac{-\frac{g_{m1}g_{m2}}{C_1C_2}}{s^2 + \frac{g_{m1}g_{m3}}{g_{m5}C_1}s + \frac{g_{m1}g_{m2}g_{m4}}{g_{m5}C_1C_2}} \quad (1)$$

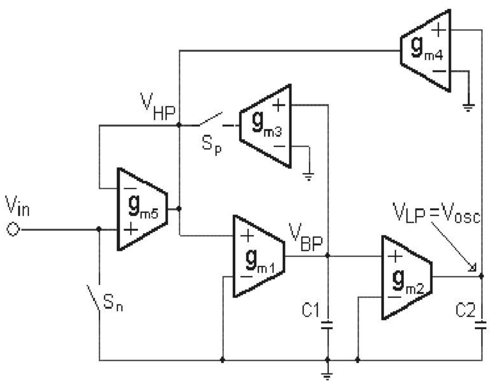

Fig.1 Testable KHN OTA-C filter based on OBT.

The cut-off frequency ω_0 and the quality factor Q can be derived as

$$\omega_0 = \sqrt{\frac{g_{m4}g_{m1}g_{m2}}{g_{m5}C_1C_2}} \quad (2)$$

$$Q = \frac{1}{g_{m3}}\sqrt{\frac{g_{m4}g_{m5}g_{m2}C_1}{g_{m1}C_2}} \quad (3)$$

Above equation shows that the quality factor Q can be tuned independently without affecting the cut-off frequency ω_0 of the filter.

To put the filter into oscillation with constant amplitude the quality factor must be sufficiently high. In the other words the network will oscillate with resonant frequency ω_0 if quality factor $Q \rightarrow \infty$. By closing the switch S_n, and opening S_p, the filter network will convert into an oscillator and the poles of the resulting oscillator are given by:

$$\Omega_{1,2} = \pm\sqrt{\frac{g_{m4}g_{m1}g_{m2}}{g_{m5}C_1C_2}} \quad (4)$$

From equation (3) we can see that the condition for oscillation will be satisfied if gm3 =0 without affecting the resonant frequency. In Fig.1 this is realized equivalently by switching off the gm3 OTA

The modified filter has two modes of operation, filter mode and test mode according to the position of the switches.

- Filter mode, in which switch S_p is closed and S_n in the open circuit and the system is connected to its normal input.
- Test mode, in which switch S_p is open and S_n in the closed position, the normal input is disconnected and a closed feedback loop encircles the filter under test (FUT).

The system is first tested in filter mode and measured the cut-off frequency of the filter. Then after test mode activated, in test mode the filter is converted into a quadrature oscillator and the frequency of oscillation evaluated. The oscillator frequency depends strongly on the transconductances of the OTAs and the filter capacitor values. The oscillation frequency of the quadrature oscillator is given by equation 2.

Deviations in the oscillation frequency with respect to the nominal frequency indicate faulty behaviour of the FUT. The amount of frequency deviation will determine the possible type of fault, either catastrophic or parametric, as well as the specific location where the fault has occurred.

III. FAULT MODELLING

In order to quantify the fault coverage of the proposed method, an accurate and realistic list of catastrophic and parametric faults is required. Catastrophic faults cause the total failure of the circuit. These types of fault are easy to detect but difficult to locate and correct. Parametric faults are caused by deviation in the process parameters and manufacturing process. The parameter deviation faults are more difficult to detect since the circuit can behave in an acceptable manner.

In this paper, we have considered two types of catastrophic fault; the stuck-short fault (SSF) and stuck-open fault (SOF). Several research results show that 90% of the observed hard faults consist of shorts and opens in transistors, diodes, and capacitors[6] . All catastrophic faults are considered to be in transistors, capacitors and interconnections and the list of the fault types is given in Table 1.

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Table 1: Catastrophic Fault Model

Fault	Cap	Transistor	Interconnect
SOF	C1-2	G,S,D	Input Transistors Output Mirrors
SSF	C1-2	G-D, G-S,S-D	Input Transistors Output Mirrors

C1-2: Capacitor terminals, G: Gate, S: Source and D: Drain

Each fault type is modelled for PSPICE simulation using either a low impedance of 10Ω for SSF or high impedance of 100MΩ for SOF. All parametric faults are considered to be in transconductance, aspect ratio, channel width, channel length and the capacitance of the capacitors.

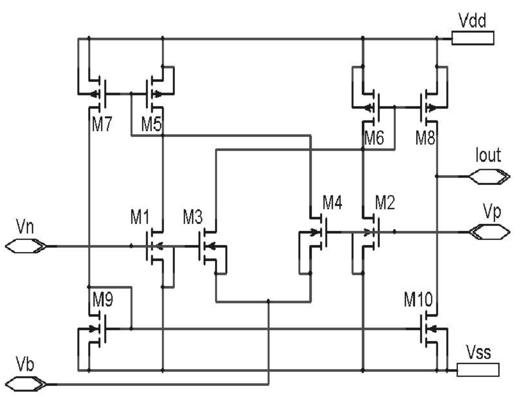

Fig.2. Schematic diagram of a simple OTA cell

IV. SIMULATION RESULTS

The testable KHN OTA-C filter in Fig.1 was simulated using PSPICE level 7 models in 0.25μm CMOS technology for verification of the proposed OBT structure. The filter was designed to have a cut-off frequency of 35MHz with a unity quality factor Q using operational transconductance amplifier given in Fig.2. An equal transconductance design was adopted with gm =830μS and circuit capacitances C1 = 5.88pF and C2 = 2.44pF. The simulation results confirmed that the self-start stable oscillation of the filter is achieved by the circuit modifications described in section 2.

The simulation results demonstrate that the circuit with MOS switches has similar performance to the original filter except the cut-off frequency of 33MHz which was slightly shifted from the designed value. The analysis of the AC responses shows that the negligible pole frequency movement and insignificant total harmonic distortion are produced due to the parasitic capacitances and nonlinearity of MOS resistance. Furthermore, the frequency of oscillation in the test mode shown in Fig.3 with built-in MOS switches is very close to the cut-off frequency of the filter. The fault-free oscillation frequency was 32MHz including the parasitic capacitance of the filter and MOS switches.

The values of MOS switch resistance are selected such that they have negligible effects on the pole frequency and the new zeros introduced by the switches are outside the filter bandwidth.

To quantify the fault coverage and the efficiency of the OBT strategy a number of different faults were injected into the filter under test according to the methodology described in section 3. To determine the undetectable tolerance band of frequency, a Monte Carlo analysis, considering 5% tolerance for all components was performed. The Fast Fourier Transforms (FFT) of the resulting output signal is illustrated in Fig.4, showing that the oscillating signal has lower and upper frequency deviation bounds of -3.25% and 4.75% respectively. The faults which produced oscillation frequency deviation outside this tolerance band were considered detectable. The comprehensive fault-modelling list and fault detection results for the KHN filter are given in Table 2.

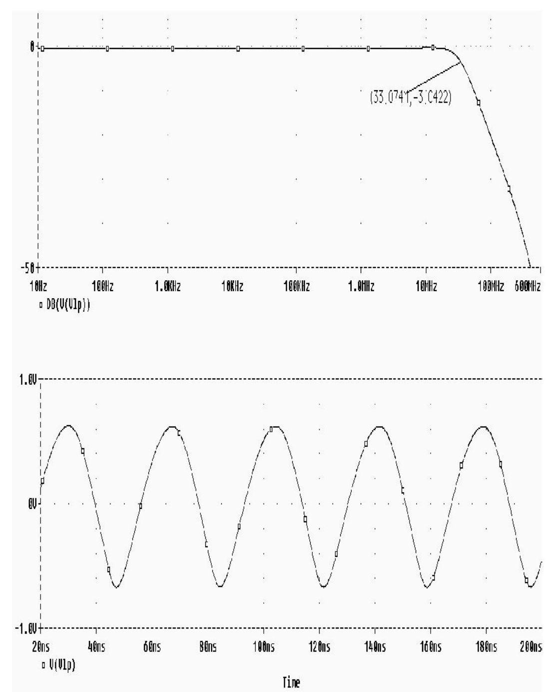

Fig.3. Cut-off frequency of the filter under test and frequency of oscillation

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The sensitivity of frequency deviation with respect to the injected faults depends upon the relationship between the components and the oscillation frequency in equation (2). All the catastrophic faults and most of the parametric faults are detectable except a small number of parametric faults in the output mirror transistors and g_{m3}. These faults can not be detected because output mirror exhibit frequency deviation below the tolerance limits and g_{m3} is not in the oscillator circuit. Overall fault coverage of more than 84% has been obtained.

Table 2 summarizes the results obtained from PSPICE simulations considering data extracted from the modified KHN filter. Altogether, 81 faults were injected into the testable filter, including parametric faults with ±10% to ±50% deviations in parameters, as described in section 3. The 58 parametric faults were detectable and most were diagnosable, except those which produced similar frequency deviations. Catastrophic faults were considered as shorts and opens in the components and between interconnections. All catastrophic faults were detected, but difficult to diagnose, especially those faults that saturated the filter under test. From above results it is clear that the very high success ratio was obtained for parametric and catastrophic faults detection.

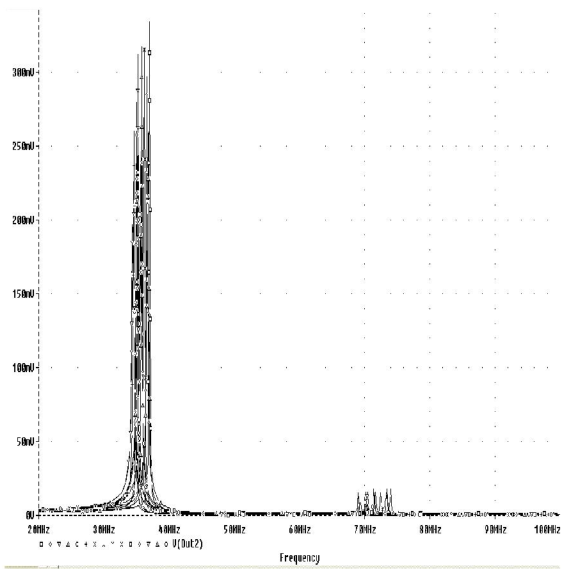

Fig.4. Monte Carlo analysis of the low pass filter based oscillator using 15 iterations

Table 2: Injected faults (IF) in the KHN OTA-C Filter

% of IF Errors	C1 or C2 $\Delta f0/f0\%$	C1 and C2 $\Delta f0/f0\%$	Input gm $\Delta f0/f0\%$
50%	24.71	62.17	-44.94
40%	17.23	43.45	-37.45
30%	11.24	28.46	-23.97
20%	5.99	16.11	-13.86
10%	2.24	7.12	-8.98
-10%	-3.75	-6.37	7.11
-20%	-6.37	-11.24	11.7
-30%	-7.49	-17.69	18.71
-40%	-10.12	-20.23	NO
-50%	-11.24	-25.09	NO
SOF	238.21	525.46	15^1,18^2
SSF	NO	NO	NO

where $\Delta f0$ / f0: oscillation frequency deviation from its fault free frequency. 1: SOF in input transistor M3, 2: SOF in input transistor M4, NO: No oscillation occurs

V. CONCLUSIONS

In this paper, we have proposed a vectorless, dynamic DFT method for KHN OTA-C filters, based on converting the filter into an oscillator using only MOS switches. The OBT technique needs only measurement of the frequency deviation to detect faults, hence requires very small test time and has good immunity to noise. The design is easily implemented with little area overhead and has negligible impact on the filter performance. The effectiveness of the proposed OBT strategy has been demonstrated through extensive simulations of the modified KHN OTA-C filter. Fault simulation results have shown that the proposed oscillation-based test technique provides high fault coverage around 84% and capable of simultaneously detecting single and multiple faults. The OBT technique is suitable for BIST filter synthesis and can be easily implemented in CAD tools for filter design.

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