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Practical Considerations in Oscillation Based Test of SC Biquad Filters

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Abstract. Transformation of different types of switched-capacitor (SC) biquad filter stages based on Fleischer-Laker biquad SC structure in order to support oscillation based testing (OBT) have been proposed. The derived solutions are based on the generic Fleischer-Laker biquad SC structure assuming ideal characteristics of the employed components. In this paper, we explore the operation of the proposed OBT structures in the case of non ideal components. Furthermore, the efficiency of the proposed OBT schemes in terms of achieved fault coverage in comparison with other test methods is discussed.

Keywords: mixed-signal test; oscillation based test; switched-capacitor filters; test structures.

1. Introduction

Oscillation based test (OBT) [1, 2] has been applied to different kinds of circuits including filters, A/D and D/A converters, PLLs, etc. The method is based on the assumption that the tested circuit can be reconfigured into an oscillator. The frequency of oscillation is measured and compared to a reference value obtained on a known-good circuit operating in the same conditions. Faults that manifest in the discrepancy from the reference oscillation frequency can thus be detected.

So far, a number of papers on OBT of active analog filters have been published. Proposed solutions transform the target filter stage into an oscillator either by modification of the actual filter stage by introducing additional switches and passive components [3], or by employing external feedback [4]. Similar principles have been applied also in OBT of switched-capacitor (SC) biquad filter stages. In [5] and [6] Huertas et al. proposed some initial solutions for OBT of SC biquad filter stages. They also showed that it is possible to increase fault coverage of the implemented test solution by additional measurements of the amplitude of oscillation. In [7] general conditions for achieving oscillation of a SC biquad filter stage by internal transformation of the filter stage are explored. Reconfiguration scheme based on the transformation of the biquad filter stage to a quadratic oscillator is studied. In our recent publication [8], OBT reconfiguration schemes of SC biquads by employing external feedback are derived.

Most of the papers on oscillation-based test have focused on the design for testability structures and circuit-reconfiguration schemes of individual classes of analog and mixed-signal circuits. Little attention has been paid to the measurement accuracy of the developed solutions. In this paper, we address the issue of measurement inaccuracy of oscillation based test of a generic Fleischer-Laker biquad SC filter stage. Theoretical framework for the analysis of the impact of the non ideal characteristics of circuit components on the resulting oscillation frequency is presented in the first part of the paper. Next, the efficiency of the proposed OBT schemes of SC biquad filters in terms of achieved fault coverage and comparison with other test methods is presented on a selected case study.

2. The impact of non ideal components on the operation of Fleischer-Laker biquad SC filter stage

Generic Fleischer-Laker biquad SC filter stage is known to be relatively robust with regard to parasitic capacitances [9]. This, however, holds only if the filter stage is realized with ideal operational amplifiers, which consequently assures that switched capacitors are always placed between an ideal voltage source (i.e., op amp output) and real or virtual ground (i.e., op amp input).

Proposed OBT reconfiguration schemes of Fleischer-Laker biquad SC filter stage by internal transformation [7] include additional MOS switches in order to transform the filter stage into oscillator. In this way, additional parasitic capacitance and noise source (i.e., clock crosstalk) are introduced. Now, the question arises about their impact on the filter stage in its normal operation mode. Fig. 1 shows an inverting SC integrator with parasitic capacitances at different nodes modeled by C_{p1}, C_{p2}, C_{p3}, C_{p4} and the impact of the DC offset of op amp and noise modeled by a voltage source v_{off}.

The required characteristics of op amps used in SC filter stages are basicaly the same as those required for active RC filters. Due to their sampled-data nature, the open-loop DC gain and the settling time are the most important criteria [9] and the op amp output can be regarded as a good approximation of an ideal voltage source. Besides, the circuit components are designed such that time constants of charging capacitors are significantly shorter than the sampling time. Under these assumptions the impact of parasitic capacitances in given nodes can be neglected as shown in Figures 1-b and 1-c. We can see that the characteristics of the SC filter stage depend on the greater extend on the parasitic capacitances and noise sources associated with the op amp inverting input. The resulting Fleischer-Laker biquad SC filter stage with modeled non idealities is shown in Fig. 2.

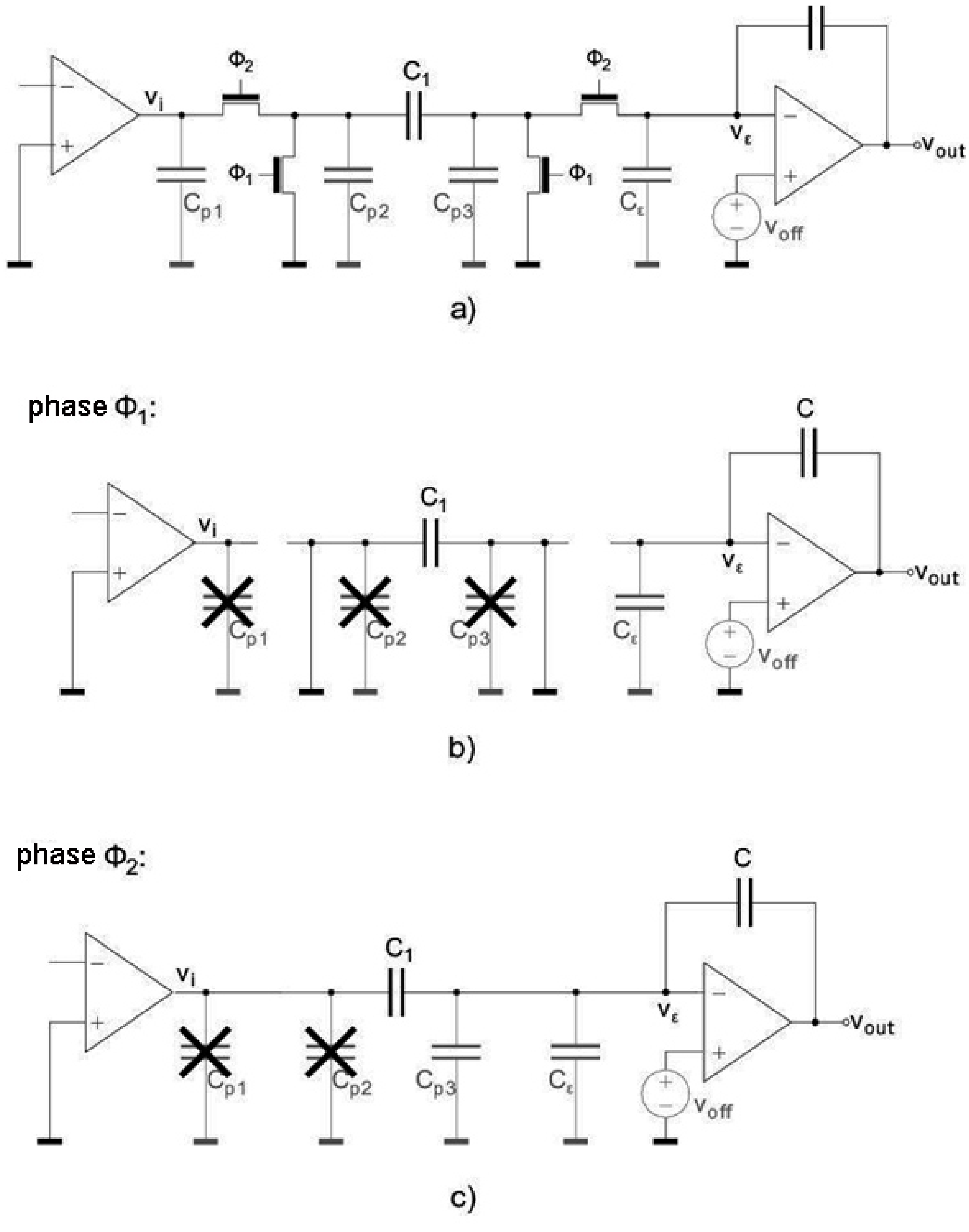

Figure 1. The impact of parasitic capacitances and noise on SC filter stage

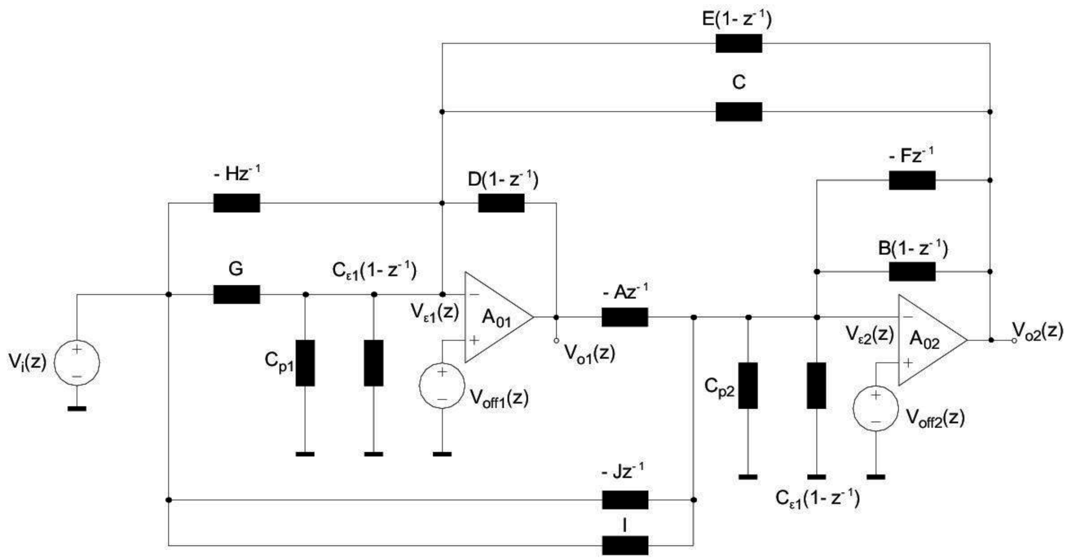

Figure 2. *z*-model of the Fleischer-Laker biquad SC filter stage with non ideal components

In order to simplify the illustration of the impact of non ideal components, let us assume that the built in OBT switches impact only the input of the second op amp. In this case the parasitic capacitance of the node is increased by ΔC_p and ΔC_{ε}, and due to the introduced switches the noise is increased by ΔV_{off}. The total impact of non ideal components on the transfer function can be described as follows

$$V_{o2} = -V_i \frac{DI - (DI + DJ - AG)z^{-1} + (DJ - AH)z^{-2}}{D(F+B) + \frac{1}{A_{02}}C_2 - (2DB + DF - AC - AE + \frac{1}{A_{02}}C_1)z^{-1} + (DB - AE + \frac{1}{A_{02}}C_0)z^{-2}} + \Delta V_{off} H_o(z) \tag{1}$$

where

$$H_0(z) = \frac{C_2 - C_1 z^{-1} + C_0 z^{-2}}{D(F+B) + \frac{1}{A_{02}}C_2 - (2DB + DF - AC - AE + \frac{1}{A_{02}}C_1)z^{-1} + (DB - AE + \frac{1}{A_{02}}C_0)z^{-2}} \tag{2}$$

and

$$C_2 = D(B + F + I - \Delta C_p - \Delta C_\varepsilon) \tag{3}$$

$$C_1 = D(A + 2B + F + I + J - \Delta C_p - 2\Delta C_\varepsilon) \tag{4}$$

$$C_0 = D(A + B + J - \Delta C_\varepsilon) \tag{5}$$

From expression (1) we can see that the impact of parasitic capacitances is reduced by the factor of DC gain of op amps. For practical values of A_0 within the range 1000 - 5000 and parasitic capacitances of an order of magnitude smaller than the values of the circuit components, we can neglect the impact of ΔC_p and ΔC_e. For larger values of A_0 the expression (2) can be further simplified:

$$H_0(z) \approx \frac{C_2 - C_1 z^{-1} + C_0 z^{-2}}{D(F+B) - (2DB + DF - AC - AE)z^{-1} + (DB - AE)z^{-2}}. \tag{6}$$

Obviously, in contrast to parasitic capacitances, Fleischer-Laker biquad SC filter stage structure itself does not reduce the impact of noise and DC offset at the inputs of operational amplifiers. In cases where we plan the test procedures for SC filters with high gain and wide dynamic range, it is necessary to pay special attention to the introduction of additional interferences during circuit normal operation via the built-in test infrastructure.

3. The impact of nonlinear feedback on the frequency of oscillation

OBT of a SC biquad filter stage with an external feedback loop is based on the use of nonlinear element with noninverting or inverting characteristic. In integrated circuits, such an element can be realized in a relatively simple way by using a voltage comparator. It can be based on Miller operational amplifier from which the compensation RC circuit is removed and a power stage with reference supply voltage added at the output. (Fig. 3a). If the open-loop amplifier configuration is connected to the SC circuit, a square wave which is in phase with the sinusoidal signal at the output of the SC stage is obtained at the output of the comparator,

In practice, the realization of external feedback loop with the comparator introduces a delay in the signal path. On the other hand, a minimum hysteresis in the characteristic of the comparator (Fig. 3b) is even desirable as it prevents accidental switching of the output due to the noise at the comparator input. Since the operating point of the oscillator structure is determined by the Barkhausen's criterion, by adding a Δt delay or phase shift ΦH, the hysteresis will affect the oscillation frequency of the tested SC circuit.

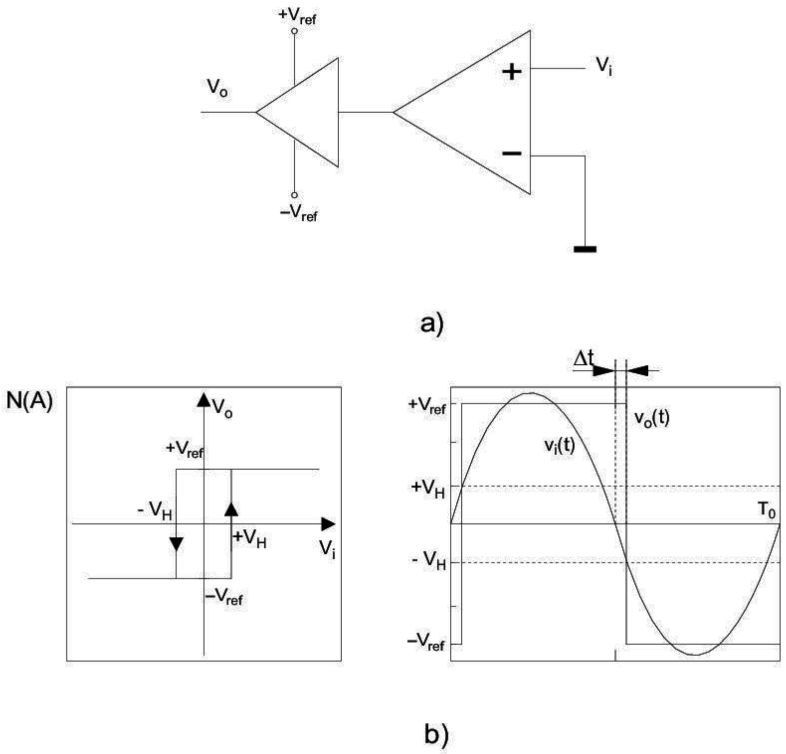

Figure 3. Realization of nonlinear feedback

For the input signal of the comparator, described as

$$v_i = A\sin(\omega_0 t) = A\sin\Phi \qquad (7)$$

the delay due to the hysteresis of the comparator is equal to

$$\Delta t = \frac{\Phi_H T_0}{2\pi}, \qquad (8)$$

where

$$\Phi_H = \arcsin\left(\frac{V_H}{A}\right). \qquad (9)$$

The limit condition for system stability is

$$\angle H(z) + \angle N(A) = 0. \qquad (10)$$

Employing the expression describing the phase of the transfer function *H(z)*

$$\Phi_H = \arctan\left(\frac{\mathrm{Im}[H(z)]}{\mathrm{Re}[H(z)]}\right) \qquad (11)$$

and employing the expression describing the amplitude of signal *A*

$$A = \frac{4V_{ref}}{\pi}\left|H(z)\right| \qquad (12)$$

where

$$\left|H(z)\right| = \sqrt{(\mathrm{Re}\{H(z)\})^2 + (\mathrm{Im}\{H(z)\})^2} \qquad (13)$$

and considering the relation

$$\arctan(x) = \arcsin\left(\frac{x}{\sqrt{1+x^2}}\right) \qquad (14)$$

we can derive the expression which enables us to determine the frequency of oscillation ω_{osc}

$$\mathrm{Im}\left\{H(e^{j\omega_{osc}T})\right\} = \frac{\pi V_H}{4V_{ref}}. \qquad (15)$$

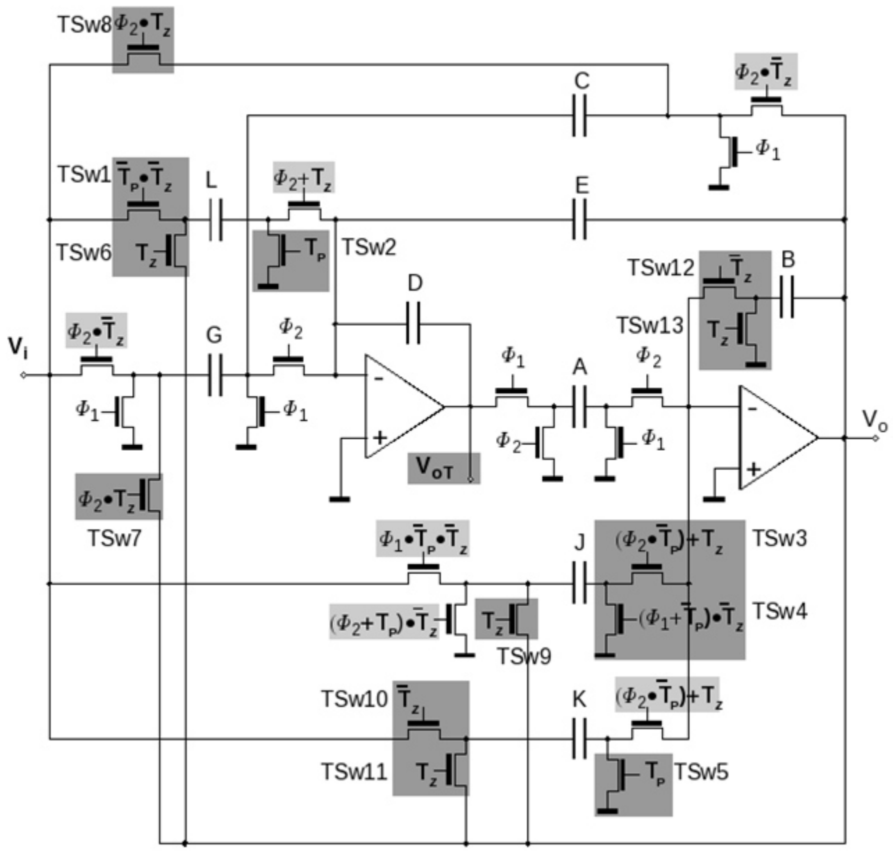

Figure 4. OBT scheme of all-pass Fleischer-Laker biquad SC filter stage configuration

From the last equation it follows that the impact of comparator hysteresis on the frequency of oscillations reduces with amplitude of the output signal of the SC stage. By choosing such V_{ref}, which takes utmost advantage of the full dynamic range of the filter circuit, it is possible to reduce the errors of the measurement methods. Simulations of realistic case studies with V_H values of the order of a few milivolts have shown that the measurement error can reach up to a few tenths of a percent. This fact should necessarily be considered when evaluating the test results.

4. Effectiveness of the proposed OBT methodology, a case study

The impact of non ideal components on filter characteristics should be carefully analysed early in the design phase in order to assure that the developed test method is feasible and can produce reliable test outcomes. Another important issue is the efficiency of the proposed solutions in terms of achieved fault coverage. In this section we shall focus on one of the proposed OBT schemes of SC biquad filter stages [8] and determine its fault coverage for a set of selected catastrophic and parametric faults.

Fig. 4 illustrates the OBT scheme of an all-pass Fleischer-Laker biquad SC filter stage configuration with the required test resources necessary to put the filter stage into oscillation. Dark grey fields denote the switches added to the original configuration while light grey fields represent the existing switches with clocking signals that require additional control logic. The biquad design parameters are collected in Table 1.

Table 1. All-pass SC biquad design parameters

Capacitor	*Value*	*Parameter*	*Value*
A	*5,491 pF*	f_{0p}	*2797,0 Hz*
B	*19,600 pF*	Q_p	*8,003*
C	*1,097pF*	f_{0n}	*2796,7 Hz*
D	*16,470 pF*	Q_n	*8,008*
E	*1,000 pF*	H_{DC}	*0,999 (0 dB)*
G	*1,097 pF*	H_{0p}	*0,995 (0 dB)*
L	*2,000 pF*	H_{DC}'	*0,182 (-14,8 dB)*
J	*1,000 pF*	H_{0p}'	*0,999 (0 dB)*
K	*19,270 pF*		

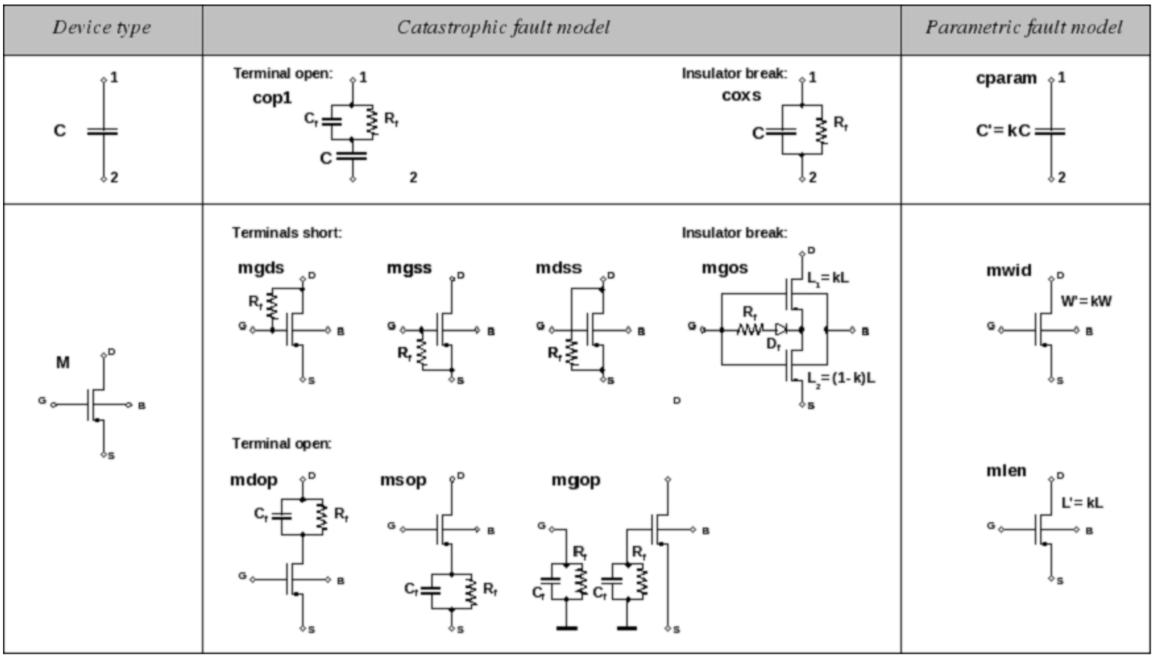

Figure 5. SC circuit devices fault models

Table 2. Simulation results in "poles" OBT mode

Device fault	*Freq. [Hz]*	*Deviation [%]*	*Device fault*	*Freq. [Hz]*	*Deviation [%]*
Fault-free (calc.)	2809.0				
Fault-free (simul.)	**2803.5**	**-0.2**			
Ca_cop1	0.0	-100.0	*Ca_cparam*	1965.1	-29.9
Ca_coxs	0.0	-100.0	*Ca_cparam_2*	3440.9	22.7
Cb_cop1	72296.7	2478.8	*Cb_cparam*	4005.0	42.9
Cb_coxs	0.00	-100.0	*Cb_cparam_2*	2288.3	-18.4
Cc_cop1	0.00	-100.0	*Cc_cparam*	1955.9	-30.2
Cc_coxs	32041.2	1042.9	*Cc_cparam_2*	3439.0	22.7
Cd_cop1	63788.0	2175.3	*Cd_cparam*	4005.0	42.9
Cd_coxs	0.0	-100.0	*Cd_cparam_2*	2284.9	-18.5
Ce_cop1	2861.2	2.1	*Ce_cparam*	2759.7	-1.6
Ce_coxs	64076.8	2185.6	*Ce_cparam_2*	2797.0	-0.2
Cg_cop1	0.0	-100.0	*Cg_cparam*	2797.5	-0.2
Cg_coxs	0.0	-100.0	*Cg_cparam_2*	2786.1	-0.6
Cj_cop1	2803.5	0.0	*Cj_cparam*	2803.6	0.0
Cj_coxs	2803.4	0.0	*Cj_cparam_2*	2803.6	0.0
Ck_cop1	2803.5	0.0	*Ck_cparam*	2803.1	0.0
Ck_coxs	2803.5	0.0	*Ck_cparam_2*	2803.3	0.0
Cl_cop1	2803.3	0.0	*Cl_cparam*	2803.6	0.0
Cl_coxs	2803.5	0.0	*Cl_cparam_2*	2805.3	0.1

Table 3. Simulation results in "zeros" OBT mode

Device fault	*Freq. [Hz]*	*Deviation [%]*	*Device fault*	*Freq. [Hz]*	*Deviation [%]*
Fault-free (calc.)	2808.8				
Fault-free (simul.)	**2802.9**	**-0.2**			
Ca_cop1	403.6	-85.6	*Ca_cparam*	1975.8	-29.5
Ca_coxs	0.0	-100.0	*Ca_cparam_2*	3431.6	22.4
Cb_cop1	2802.9	0.0	*Cb_cparam*	2805.7	0.1
Cb_coxs	2802.9	0.0	*Cb_cparam_2*	2805.7	0.1
Cc_cop1	0.00	-100.0	*Cc_cparam*	2788.9	-0.5
Cc_coxs	0.00	-100.0	*Cc_cparam_2*	2802.6	0.0
Cd_cop1	0.00	-100.0	*Cd_cparam*	3980.1	42.0
Cd_coxs	0.00	-100.0	*Cd_cparam_2*	0.00	-100.0
Ce_cop1	2778.9	-0.8	*Ce_cparam*	2805.7	0.1
Ce_coxs	66653.0	2278.0	*Ce_cparam_2*	2805.7	0.1
Cg_cop1	938.0	-66.5	*Cg_cparam*	1959.8	-30.1
Cg_coxs	32093.2	1045.0	*Cg_cparam_2*	3431.6	22.4
Cj_cop1	0.00	-100.0	*Cj_cparam*	2834.8	1.1
Cj_coxs	0.00	-100.0	*Cj_cparam_2*	2766.3	-1.3
Ck_cop1	0.00	-100.0	*Ck_cparam*	3835.5	36.8
Ck_coxs	0.00	-100.0	*Ck_cparam_2*	2303.9	-17.8
Cl_cop1	2962.7	5.7	*Cl_cparam*	2802.5	0.0

Fault free "poles" and "zeros" OBT circuit configurations were first simulated to obtain the reference results. Then, single catastrophic (shorts and opens) and parametric faults were injected into Spice device models as illustrated in Fig. 5 and simulations were ran for each "faulty" circuit.

The circuit-under-test (CUT) output signal was compared to the fault free circuit response. Table 2 and Table 3 present the resulting frequency deviations in percentage for the injected capacitor faults in both test modes. Fault *cparam* denotes a 50% decrease of the relevant device parameter (capacity), while *cparam_2* denotes a 50% increase.

One must take into account the error introduced by the measurement method. The nonlinear feedback circuit, which is used to bring the CUT into oscillation, usually consists of a comparator with a small hysteresis. This introduces a delay into the signal loop resulting in a slight deviation of the oscillation frequency. The comparator delay can be further increased due to the SC circuit signal sampling. When sampling frequency is not an integer multiple of the CUT oscillation frequency, a fixed-time measurement window can yield variable results depending on the phase between the sampling signal and CUT output signal at the time of measurement. This measurement error can also be observed by comparing the fault-free circuit simulation result with the calculated value. Therefore sufficient tolerance should be used when evaluating the results. Using a 5% fault detection margin the "poles" OBT and "zeros" OBT achieve a fault coverage of 52.8% and 63.9% respectively. However, when we combine both tests results, the fault coverage reaches 80.6%. This could be further improved by also considering amplitude deviations [10].

To better assess the effectiveness of the proposed OBT methodology, we performed a detailed analysis of the all-pass circuit. All together we inserted 239 single catastrophic faults and 231 single parametric faults affecting capacitors and MOS devices and simulated faulted circuits in both OBT configurations. Additionally, we performed CUT simulations and evaluated the resulting signals using test methods proposed elsewhere [11-13]. The first two methods are based on CUT current measurements while the last uses analog signature analysis. Table 4 summarizes the results of the OBT method compared to the other three methods.

Table 4. OBT compared to other test methods

	OBT	I_{ddq}	I_{OTA}	***ABILBO***
Coverage (catastrophic) [%]	72.4	46.2	78.1	66.2
Coverage (parametric) [%]	34.2	4.3	52.2	26.4
Test input signal	/	DC	DC	AC
Test output evaluation	digital	analog/digital	analog/digital	digital

The simulations showed that OBT was outperformed only by the method measuring the currents flowing through the biquad amplifiers output stages (IOTA). Considering that the method requires the OTA amplifiers structure to be modified and that fault detection consists in measuring small analog value (current) deviations, OBT may still prove as a better choice for the implementation of analog built-in self-test structures due to its relative simplicity.

Let us, at this point, review the fault coverage results obtained in the case study of OBT of a low-pass SC biquad, where the filter stage was transformed into a quadrature oscillator by internal SC stage reconfiguration [7]. As demonstrated in the paper, the operating conditions suitable for OBT are achieved at low gain feedback. In order to evaluate the efficiency of the approach, similar faults as in the case of all-pass SC biquad (described above) were simulated. In the case of hard faults, 64% fault coverage was achieved solely by observing deviation of oscillation frequency. However, by analyzing also the amplitude of the output signal, the fault coverage increased to 72%. As regards parametric faults, the overall fault coverage was relatively low (25%). Furthermore, the result varied substantially between 15% and 75% for different types of parametric faults. If we compare the achieved fault coverage with the results of the case study described in this paper, we can see that similar level was obtained in the case of hard faults. On the other hand, fault coverage of OBT of the all-pass biquad SC filter stage based on external feedback is better than in the case of the low-pass SC biquad, but still relatively low. Since the OBT of a SC biquad stage based on external feedback is a low cost solution it is applicable for a go/no-go production test of hard faults. As for the detection of parametric faults, some other techniques complementary to OBT should also be included.

5. Conclusion

Most of the published solutions in oscillation based test focus on the design of the test structure that changes the circuit-under-test into an oscillator. Little attention has so far been paid to the measuring accuracy of the oscillation test. D. Vazquez et al. [14] state the estimated measurement accuracy a the general case, where the measurements of the oscillation frequency are performed with a digital counter. The problem of in-circuit measuring and estimation of the controlled frequency of oscillation is further elaborated in [15]. In this paper we explored the operation of the OBT structures of a general Fleischer-Laker biquad SC filter stage in the case of non ideal components. Derived framework allows us to assess the impact of parasitic capacitances and noise introduced by the additional switches which are used to modify the circuit-under-test into an oscillator. Practical issues related to the implementation of non linear feedback and the impact of comparator hysteresis on the frequency of oscillations have also been elaborated. The efficiency of the the OBT structures of a general Fleischer-Laker biquad SC filter stage is demonstrated in terms of achieved fault coverage on a selected case study of an all-pass filter stage. Achieved results confirm the applicability of the OBT scheme in practice.

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