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COMMUNICATIONS

GAIN– AND OFFSET–COMPENSATED TECHNIQUE FOR SC LEAPFROG LADDER FILTER

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A combined approach for reducing the effects of opamps finite gain and offset voltage in SC leapfrog ladder filters is proposed. First, the conventional integrators in the filters are replaced with gain- and offset- compensated integrators. Next, the finite gain effect is further reduced by modifying the values of some appropriately chosen capacitances.

K e y w o r d s: SC filters, gain-compensation, offset-compensation

1 INTRODUCTION

Doubly-terminated passive LC ladder networks that are designed to provide the maximum power transfer from the source to the load over the filter passband feature very low sensitivities to variations in their component values. This fact has over the years spurred considerable interest in finding switched-capacitors (SC) filter structures which simulate the internal working of LC ladder prototype networks.

Among various design approaches the leapfrog ladder and coupled biquad methods are the most popular [1, 2]. The leapfrog ladder filters comprise inverting and non-inverting SC integrators connected in feedback loops. The source and the load terminations are realized with damped SC integrators.

One of the key parameters in the design of SC networks concerns the speed requirements of the operational amplifiers (opamps). The frequency of operation is usually limited by the settling time which restricts the sampling frequency f_s to about 20 % of the gain-bandwidth product GBW of the opamps [3]. But, in SC filters the distortion introduced by the finite gain A is more pronounced than that of the finite bandwidth BW [4]. Generally, the price to be paid for the high speed is a low dc gain A, because these are contradictory requirements. The amplifier gain of 60 dB is normally considered as minimum for an SC circuit, whereas 40 db is a more common figure for GaAs and BiCMOS designs [5, 6]. Application of such opamps ($A = 100$) causes significant deterioration of the performance of classical SC circuits. The input-referred opamp offset voltage Vos introduces an output offset voltage which may become a significant limitation to the permissible signal swing.

The two known general approaches for reducing the effects of opamp imperfections (finite gain A and offset voltage Vos) in SC circuits are:

a) The finite-gain-insensitive (FGI) approach;
b) The precise opamp gain (POG) approach.

The FGI approach consists in the replacement of the conventional SC building blocks with gain- and offset-compensated (GOC) structures [7, 8]. The performances of SC integrators are degraded by the effects of finite opamp dc gain A, which result in gain and phase errors, $m(\omega)$ and $\Theta(\omega)$. In GOC integrators the phase error is proportional to $1/A^2$ (in a conventional integrator this is a simple inverse dependence $1/A$). In most of the GOC integrators proposed the reduction in phase error was obtained at the expense of increased gain error.

The POG approach [6, 9] is based on the use of simple and fast amplifiers with a low but precisely known and stable gain. The precise nominal gain value A_0 is then taken into account in the capacitor sizing of SC circuits. The result is a conventional SC structure with modified capacitance values, which implements exactly the required transfer function.

In [10], a method of eliminating the influence of the finite opamp gain in a loop comprising two conventional integrators with opposite signs is presented. The price for the considerable improvement in circuit performance is a unity-gain buffer, four switches plus one additional capacitor per second-order stage. The method was applied to SC biquad and ladder structures comprising conventional integrators as the basic building blocks.

In this paper a combined approach for reducing the effects of opamps finite gain A and offset voltage Vos in SC leapfrog ladder filters is proposed. It is based on the use of simple and fast amplifiers with low but precisely known and stable dc gain [6].

In the first step, the conventional integrators (including the integrators in the source and load terminations) are replaced with Ki-89 GOC SC integrators.

In the second step, the POG approach is used to minimize the gain and phase errors of the source and load terminations. The gain errors of the remaining GOC SC integrators are reduced by modifying the values of the integrating capacitances. The effectiveness of the proposed

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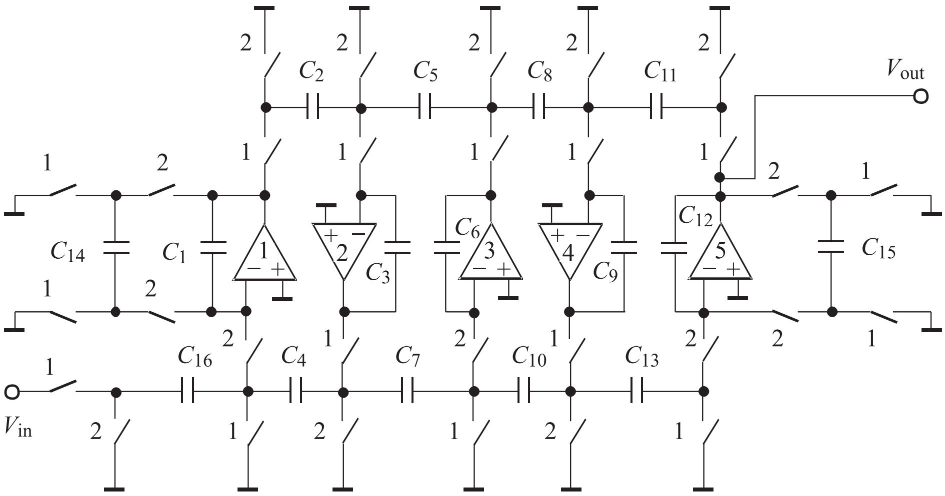

Fig. 1. Conventional lowpass SC filter

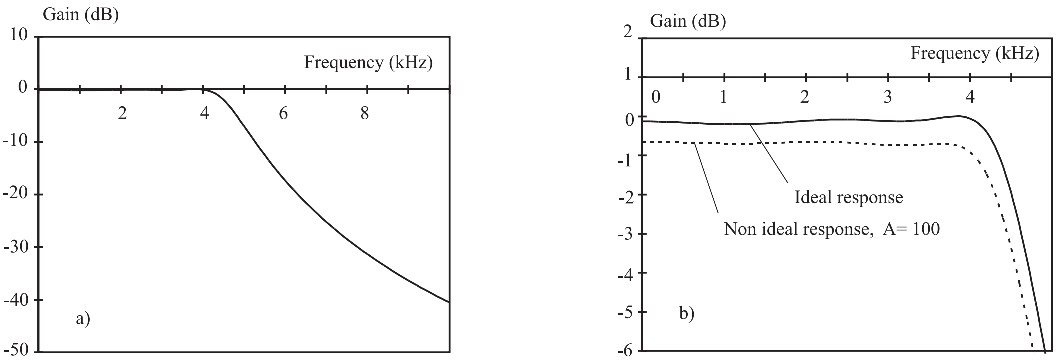

Fig. 2. Frequency responses of the SC filter: a) - Overall response, b) - Passband response

combined approach is demonstrated by designing a fifth-order lowpass leapfrog filter. The variation of the opamp dc gain A from its nominal value A_0 is taken into account.

2 CONVENTIONAL LOWPASS SC LEAPFROG LADDER FILTER

The circuit schema of the fifth-order lowpass SC leapfrog ladder filter being considered is shown in Fig. 1 [11]. For the sampling frequency $f_s = 40$ kHz the ideal filter passband characteristics are 4.1 kHz bandwidth and a lower than 0.21 dB passband ripple. The component values for the circuit are listed in Table 1.

Let us suppose that the capacitors and switches are ideal. The opamps are assumed to have a finite dc gain A and infinite bandwidth. This supposition is adequate for the analysis of SC circuits containing fast and relatively low-gain amplifiers. The performances of the filter are investigated by computer simulation.

Figure 2a shows the ideal overall filter response. Figure 2b gives a comparison in the passband between ideal performance and non-ideal response for finite opamps dc gain $A = 100$. It is observed that the passband response is deteriorated by the opamps finite gain.

The influence of the input-referred opamps dc offset voltages Vos_q $(q = 1 \div 5)$, modelled as voltage sources at the non-inverting input terminals, is evaluated by the corresponding output voltage $Vout(n)$ in steady state, for $Vin = 0$.

For the capacitance values from Table 1 and $A = 100$ the output offset voltage of the SC filter in Fig. 1 is

Table 1. Component values for the SC filter of Fig. 1

Capacitance values			
$C_1 = 1$	$C_2 = 1$	$C_3 = 3.410$	$C_4 = 1.658$
$C_5 = 1.352$	$C_6 = 3.125$	$C_7 = 1.194$	$C_8 = 1.846$
$C_9 = 4.029$	$C_{10} = 1$	$C_{11} = 1$	$C_{12} = 1.925$
$C_{13} = 1.769$	$C_{14} = 1.072$	$C_{15} = 1$	$C_{16} = 1.547$
number of capacitors			– 16
number of switches			– 30
number of opamps			– 5
total capacitance			– 27.927
capacitance spread			– 4.029

$$\lim_{n\to\infty} Vout(n) = 2.567\,Vos_1 - 1.574\,Vos_2 - 1.857\,Vos_3 + 1.423\,Vos_4 + 1.347\,Vos_5 \,. \quad (1)$$

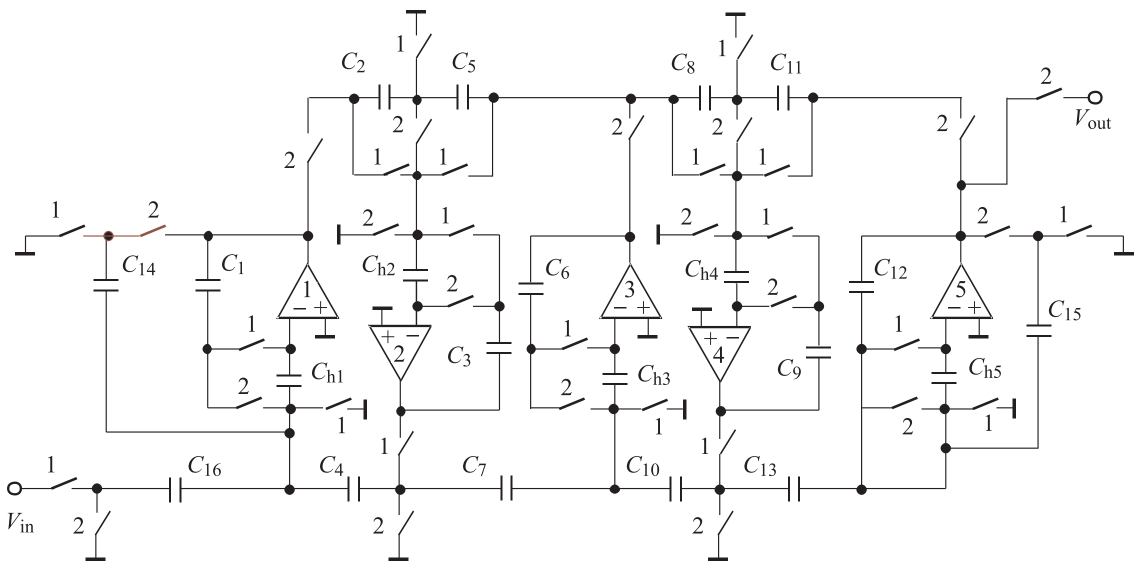

Fig. 3. GOC lowpass SC filter

Table 2. Component values for the GOC SC filter of Fig. 3

Capacitance values			
$C_1 = 1$	$C_2 = 1$	$C_3 = 3.353$	$C_4 = 1.749$
$C_5 = 1.352$	$C_6 = 3.072$	$C_7 = 1.194$	$C_8 = 1.846$
$C_9 = 3.961$	$C_{10} = 1$	$C_{11} = 1$	$C_{12} = 1.879$
$C_{13} = 1.769$	$C_{14} = 1.130$	$C_{15} = 1$	
$C_{16} = 1.632$	$C_{h1} = 1$	$C_{h2} = 3.353$	
$C_{h3} = 3.072$	$C_{h4} = 3.961$	$C_{h5} = 1.879$	
number of capacitors		– 21	
number of switches		– 37	
number of opamps		– 5	
total capacitance		– 41.202	
capacitance spread		– 3.961	

3 GAIN– AND OFFSET– COMPENSATED LOWPASS SC LEAPFROG LADDER FILTER

At first, according to the proposed approach all the integrators in the conventional SC filter from Fig. 1 are replaced with GOC Ki-89 integrators [12]. The resulting GOC filter is shown in Fig. 3, where

$$C_{h1}=C_1,\ C_{h2} = C_3,\ C_{h3}=C_6,\ C_{h4}=C_9 \text{ and } C_{h5}=C_{12}\,.$$

The compensated output voltages of opamps 1, 3 and 5 are sampled in phase 2 and stored in the capacitors C_2, C_5, C_8 and C_{11}. During phase 1, capacitors C_4, C_7, C_{10} and C_{13} sample the compensated output voltages of the opamps 2 and 4. Subsequently, the POG approach is used to minimize the gain and phase errors of the source and the load terminations (around the opamps 1 and 5) during phase 2. This is achieved by equating the expressions for the actual output voltages and for the standard ideal output voltages of opamps 1 and 5. Hence, for the modified capacitance values C_{1p}, C_{14p}, C_{12p} and C_{15p} and for the nominal opamp gain A_0 the gain and phase errors of the two terminations are simultaneously equal to zero.

Prewarped damping capacitances C_{14p}, C_{15p} and prewarped feedback capacitances C_{1p}, C_{12p} are given by the expressions [13]

$$\begin{aligned}
C_{14p}&=\Big[C_{14}\Big(1+\frac{2}{A_0}\Big)-\frac{1}{A_0^2}(C_4+C_{16})\Big]\Big(1+\frac{1}{A_0}\Big)^{-2},\\
C_{1p}&=C_1\Big(1+\frac{1}{A_0}\Big)^{-1}-\frac{1}{A_0}(C_4+C_{16}+C_{14})\Big(1+\frac{1}{A_0}\Big)^{-2},\\
C_{15p}&=\Big[C_{15}\Big(1+\frac{2}{A_0}\Big)-\frac{C_{13}}{A_0^2}\Big]\Big(1+\frac{1}{A_0}\Big)^{-2},\\
C_{12p}&=C_{12}\Big(1+\frac{1}{A_0}\Big)^{-1}-\frac{1}{A_0}(C_{13}+C_{15})\Big(1+\frac{1}{A_0}\Big)^{-2}.
\end{aligned}\tag{2}$$

Finally, the gain errors of the second and the fourth GOC integrators during phase 1 and the gain errors of the third GOC integrators during phase 2 are reduced by modifying the integrating capacitances C_3, C_9 and C_6 on the basis of the relationships [14]

$$\begin{aligned}
C_{3p}&=\Big(C_3-\frac{C_2+C_5}{A_0}\Big)\Big(1+\frac{1}{A_0}\Big)^{-1},\\
C_{6p}&=\Big(C_6-\frac{C_7+C_{10}}{A_0}\Big)\Big(1+\frac{1}{A_0}\Big)^{-1},\\
C_{9p}&=\Big(C_9-\frac{C_8+C_{11}}{A_0}\Big)\Big(1+\frac{1}{A_0}\Big)^{-1}.
\end{aligned}\tag{3}$$

From the data in Table 1 and expressions (2) and (3), for $A_0 = 100$, one finds

$$C_{14p} = 1.715807\,,\qquad C_{1p} = 0.9817175\,,$$
$$C_{15p} = 0.9997285 \approx 1\,,\qquad C_{12p} = 1.8787962\,,$$
$$C_{3p} = 3.3529505\,,\qquad C_{6p} = 3.0723366\,,$$
$$C_{9p} = 3.9609307\,.$$

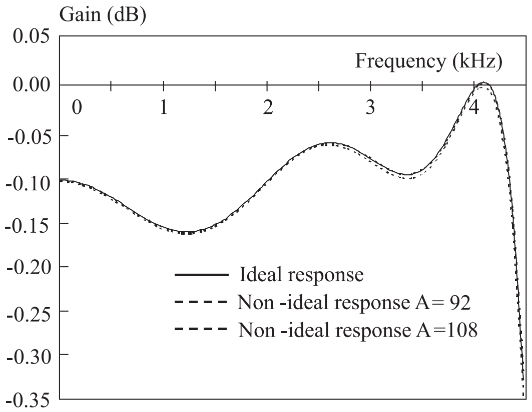

Fig. 4. Passband frequency responses of the GOC SC filter

Capacitance C_{1p} can be made equal to the unit capacitance. The final, rounded-off to the third digit after the decimal point, capacitance values for the GOC SC filter of Fig. 3 are listed in Table 2.

The passband responses of the GOC filter from Fig. 3 for the modified capacitance values (Table 2) and opamps gain variation $A = 100 \pm 8$ [6] are shown in Fig. 4. The corresponding curves converge on the scale chosen to the ideal response.

For the capacitance values from Table 2 and $A = 100$ the output offset voltage of the GOC SC filter in Fig. 3 is

$$\lim_{n\to\infty} Vout(n) = 0.027\,Vos_1 - 0.016\,Vos_2 - 0.019\,Vos_3 + 0.014\,Vos_4 + 0.014\,Vos_5\,. \quad (4)$$

The price for this considerable improvement in circuit performance, compared to the conventional filter of Fig. 1, is a by 47.53 % larger total capacitance, 5 additional capacitors and 7 additional switches.

4 CONCLUSION

A combined approach for reducing the effects of opamps finite gain and offset voltage in switched-capacitor leapfrog ladder filters has been presented. It permits the substitution of narrow-bandwidth high-gain multiple-stage amplifiers by simple wide-bandwidth single-stage amplifiers with moderate gain. The effectiveness of the approach proposed has been demonstrated by a fifth-order lowpass filter. The passband response of the gain- and offset- compensated filter with modified capacitances follows much more closely the ideal response than those of the conventional filter. The given approach can be applied to other types of switched-capacitor leapfrog filters as well.

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