Left-LUD SC ladder filter with compensation for finite amplifier gain and offset voltage

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Abstract: - An approach for reducing the effects of operational amplifiers finite dc gain A and offset voltage V_{os} in left-LUD SC ladder filters is proposed. The effectiveness of the proposed approach is demonstrated by designing a sixth-order bandpass elliptic SC filter. The variation of the finite gain A from its nominal value A_0 is taken into account.

Key-Words: - Filters, gain- and offset- compensation, operational amplifiers, switched-capacitor integrators

1 Introduction

Switched-capacitor (SC) filter structures, which simulate passive RLC ladders are often employed where low sensitivity to element value deviation is important. Among various design approaches the leapfrog ladder and coupled biquad methods are the most popular [1, 2]. However, there is a major drawback for the elliptic leapfrog SC filters that there always exist delay-free loops formed by capacitors and operational amplifiers (op amps). This increases the op amps settling times.

One another alternative is the LUD ladder simulation method, which is based upon LU matrix decomposition technique and has the notable feature of being free from capacitor-coupled op amp loops [3, 4]. In [5] a large family of circuit structures is revealed depending on the choice of matrix decomposition, including the existing leapfrog, coupled biquad and LUD ones as specific cases. All circuits are insensitive to parasitic capacitances in SC implementation. A detailed comparison of various SC circuit structures has been undertaken and some notable conclusions are: the left-LUD method is the best choice for filters with very narrow and very wide passbands; the right-LUD method (related to the leapfrog structure) is the best choice for sharp transition lowpass filter design; the cascade biquads are the best choice for moderately selective lowpass and bandpass filter design.

SC circuits with low sensitivity to op amp characteristics such as finite dc gain A and input-referred offset voltage V_{os} are sometimes required, e. g. when op amps gain has to be sacrificed for bandwidth. For this reason several gain- and offset-compensated (GOC) SC building blocks (integrators, gain stages, sample-and-hold circuits) have been reported in the literature.

In [6] a method of eliminating the influence of the finite op amps gain in a loop comprising two conventional integrators with opposite sign is presented. The price for the considerable improvement in circuit performance is a unity-gain buffer, 4 switches plus one additional capacitor per second-order stage. The method was applied to SC biquad and ladder structures comprising conventional integrators as basic building blocks.

In [7] a fifth-order elliptic lowpass SC filter with very low sensitivity to capacitance ratio errors and to finite op amps gains have been presented. The proposed structure comprises 9 op amps and 10 sample-and-hold circuits. The simulated frequency response of the filter, when op amps having gain equal to 1000 and infinite bandwidth are used, is very close to the ideal response (obtained with infinite op amps gains).

In this paper an approach for reducing the effects of op amps finite gain A and offset voltage V_{os} in left-LUD SC ladder filters is proposed. It is based on the use of simple and fast amplifiers with low but precisely known and stable dc gain [8].

In a first step, the conventional integrators in the filter are replaced with GOC SC integrators and some appropriately chosen unswitched capacitors are split into two capacitors. The offset contribution to the output voltage of the filter is compensated by adding GOC sample-and-hold circuits.

In a second step, the nominal op amps gain value A_0 is taking into account in the capacitance sizing of the capacitors, connected to the uncompensated outputs of the integrators.

In a third step, the gain errors of the integrators are reduced by modifying the values of the integrating capacitances.

The effectiveness of the proposed approach is demonstrated by designing a sixth-order bandpass elliptic left-LUD filter. The variation of the op amps dc gain A from its nominal value A_0 is taken into account. The GOC structure with changed topology and modified capacitances values yields significant improvement in the passband response.

2 Conventional sixth-order bandpass elliptic left-LUD SC filter

The circuit schema of the sixth-order bandpass elliptic left-LUD SC filter being considered is shown in Fig. 1 [4].

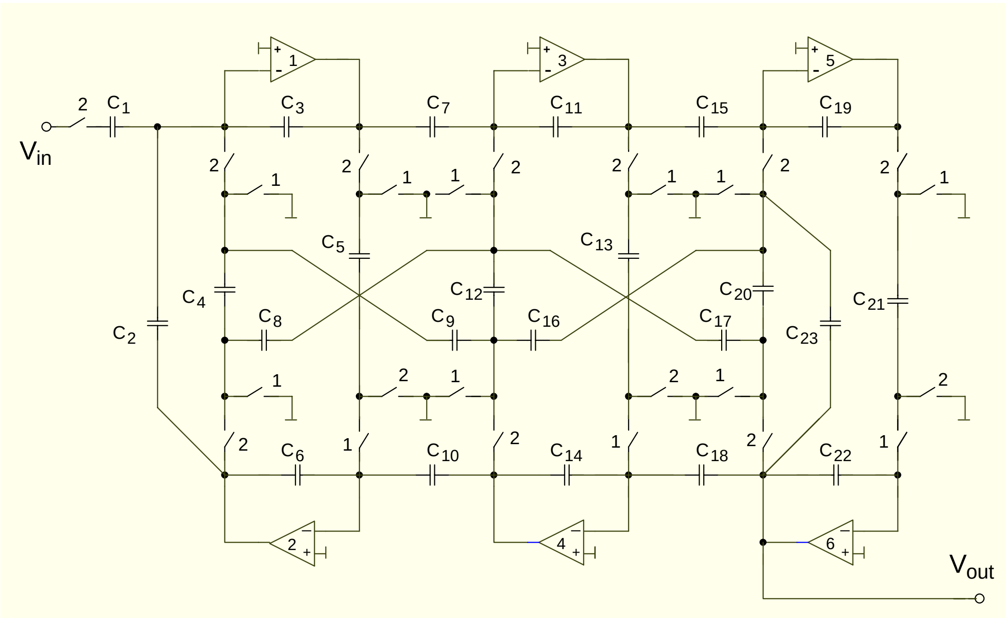

Fig. 1. Conventional sixth-order bandpass left-LUD SC filter

For the sampling frequency f_s = 128 kHz the ideal filter requirements are: lower passband edge 3600 Hz; upper passband edge 4000 Hz; maximum passband ripple 0.1 dB; minimum stopband attenuation 22 dB. The component values for the circuit are listed in Table 1.

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

C_1=1.2831	C_2 = 1.0	C_3 = 15.620	C_4= 2.3015
C_5=1.0	C_6= 4.6369	C_7 = 9.8960	C_8= 1.2620
C_9=1.0623	C_{10}= 2.4729	C_{11}=21.067	C_{12}=4.1209
C_{13}=1.0	C_{14}= 4.4922	C_{15}=10.378	C_{16}=2.0283
C_{17}=1.0	C_{18}=1.0910	C_{19}=10.604	C_{20}=2.4337
C_{21}=1.0	C_{22}=5.1269	C_{23}=1.0	

Let us suppose that the capacitors and the switches are ideal. The op amps are assumed to have 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 filter is simulated and analyzed with MATLAB 7.1. Fig. 2 gives a comparison in the passband between ideal performance and nonideal response for finite op amps dc gain A = 100. It is observed that the filter with A = 100 has a response that is clearly inadequate.

The influence of the input-referred op amps dc offset voltages V_{os_q} (q = $1 \div 6$), modeled as voltage sources at the noninverting input terminals, is evaluated by the corresponding output voltage $V_{out}(n)$ in steady state, for $V_{in} = 0$.

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

$$\lim_{n\to\infty} V_{out}(n) = 0.5679\,V_{os_1} + 0.0057\,V_{os_2} - 1.9656\,V_{os_3} - 0.0197\,V_{os_4} + 2.3976\,V_{os_5} + 0.024\,V_{os_6}\,. \tag{1}$$

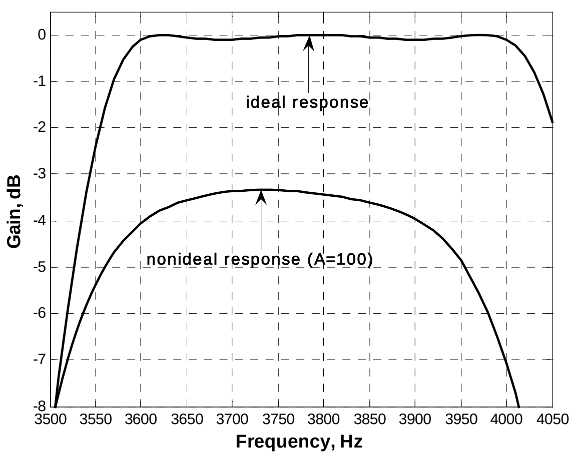

Fig. 2: Passband responses of the filter from Fig. 1

3 Gain- and offset- compensated sixth-order bandpass elliptic left-LUD SC filter

At first, according to the proposed approach all the integrators in the conventional SC filter from Fig. 1 are replaced with GOC integrators. The second integrator (around the op amp 2) is replaced with Nagaraj-86 integrator [9]. All the other integrators are replaced with Ki-89 integrators [10]. The two GOC integrators have one and the same topology, but the values of the holding capacitances C_{hq} differ. For the Nagaraj-86 integrator the capacitance C_h is equal to the smallest filter capacitance. For Ki-89 integrator the capacitance C_h is equal to the integrating capacitance.

The unswitched capacitors C_7 , C_{10} , C_{15} and C_{18} from Fig. 1 are split into two capacitors. Two GOC sample-and-hold-circuits (with the op amps 7 and 8) are added to the outputs of the first and the third integrators to reduce the influence of the offset voltages V_{os1} and V_{os3} [11]. The resulting GOC filter is shown in Fig. 3, where $C_{h1} = C_3$, $C_{h2} = 1$, $C_{h3} = C_{11}$, $C_{h4} = C_{14}$, $C_{h5} = C_{19}$ and $C_{h6} = C_{22}$.

The relation between the output voltages of the fourth Ki-89 integrator (around the op amp 4) during the uncompensated phase 2 and during the compensated phase 1 is frequency independent and given by the expression

$$V_{o_4}^2(n) = \frac{1+1/A_0}{1+2/A_0} V_{o_4}^1(n-\frac{1}{2}), \qquad (2)$$

where A_0 is the nominal value of the op amp dc gain.

The uncompensated output voltage $V_{o_4}^2(n)$ is stored in the capacitors C_9 , C'_{10} , C_{12} and C_{16} . By capacitance sizing of these capacitors the corresponding charges transferred during the two phases of the clock period can be equated. From (2) one obtains

$$C_{9p} = C_9 \frac{1+2/A_0}{1+1/A_0}, \quad C'_{10} = C_{10} \frac{1+2/A_0}{1+1/A_0},$$
$$C_{12p} = C_{12} \frac{1+2/A_0}{1+1/A_0}, \; C_{16p} = C_{16} \frac{1+2/A_0}{1+1/A_0}. \qquad (3)$$

For reducing the influence of the offset voltage V_{0S_6} the output voltage of the filter is sampled in the uncompensated phase 2 of the sixth Ki-89 integrator.

The relation between the values of the output voltage V_{out} during the phases 1 and 2 of the clock period is

$$V_{out}^2(n) = \frac{1+1/A_0}{1+2/A_0} V_{out}^1(n-\frac{1}{2}). \qquad (4)$$

The effect due to the finite gain of op amp 6 is minimized by modifying the values of the capacitances C_{21} and C'_{18}, according to the expressions

$$C_{21p} = C_{21} \frac{1+2/A_0}{1+1/A_0}, \quad C'_{18} = C_{18} \frac{1+1/A_0}{1+2/A_0}. \qquad (5)$$

Finally, the gain errors of the first, the second, the third and the fifth integrators during the phase 2, and the gain errors of the fourth and the sixth integrators during the phase 1 are reduced by modifying the integrating capacitances C_3 , C_6, C_{11}, C_{19}, C_{14} and C_{22} on the basis of the relationships [12]

$$C_{3p} = \left(C_3 - \frac{C_1 + C_2 + C_4 + C_{9p}}{A_0} \right) \left(1 + \frac{1}{A_0} \right)^{-1},$$
$$C_{6p} = \left(C_6 - \frac{C_{h2} + C_5 + C_{10} + C'_{10}}{A_0} \right) \left(1 + \frac{1}{A_0} \right)^{-1},$$
$$C_{11p} = \left(C_{11} - \frac{2C_7 + C_8 + C_{12p} + C_{17}}{A_0} \right) \left(1 + \frac{1}{A_0} \right)^{-1}, \qquad (6)$$
$$C_{19p} = \left(C_{19} - \frac{2C_{15} + C_{16p} + C_{20} + C_{23}}{A_0} \right) \left(1 + \frac{1}{A_0} \right)^{-1},$$
$$C_{14p} = \left(C_{14} - \frac{C_{13} + C_{18} + C'_{18}}{A_0} \right) \left(1 + \frac{1}{A_0} \right)^{-1},$$
$$C_{22p} = \left(C_{22} - \frac{C_{21p}}{A_0} \right) \left(1 + \frac{1}{A_0} \right)^{-1}.$$

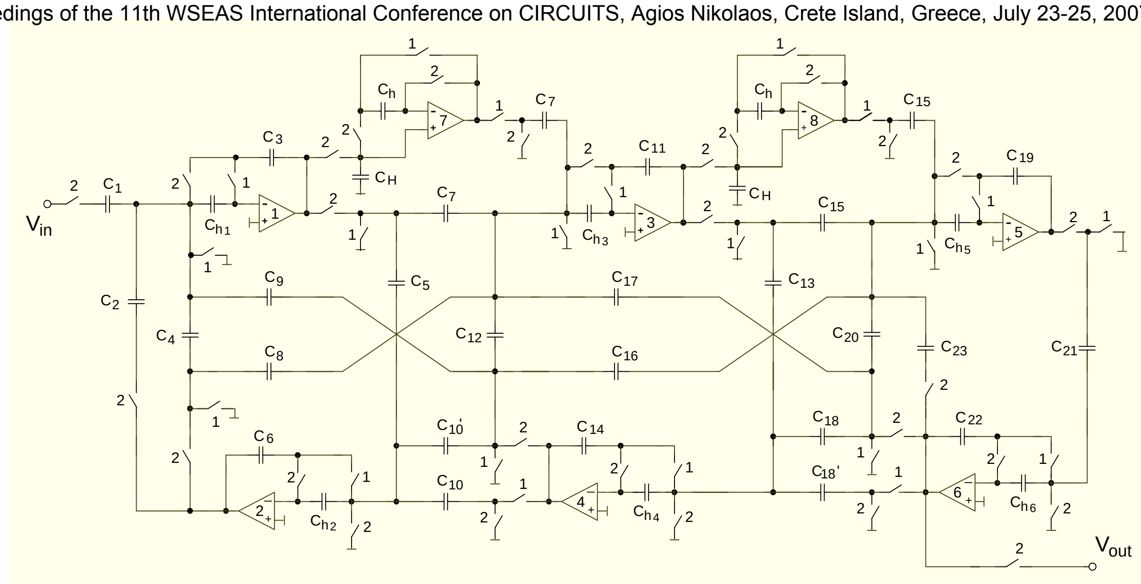

Fig. 3. GOC sixth-order bandpass left-LUD SC filter

From the data in Table 1 and expressions (3), (5) and (6), for A_0 = 100, one finds

C_{9p} = 1.0728, $C'_{10} = 2.4974$, C_{12p} = 4.1617,

C_{16p} = 2.0484, C_{21p} = 1.0099, $C'_{18} = 1.0803$,

C_{3p} = 15.409, C_{6p} = 4.5220, C_{11p} = 20.599,

C_{19p} = 10.239, C_{14p} = 4.4163, C_{22p} = 5.0653.

Then, the final capacitance values for the GOC 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 op amps gain variation A = 100 ± 8 [8] are shown in Fig. 4. It is obvious that these responses follow much more closely the ideal response than those of the conventional filter from Fig. 1.

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

C_1 =1.2831	C_2 =1.0	C_3 =15.409
C_4 =2.3015	C_5 = 1.0	C_6 = 4.5220
C_7 = 9.8960	C_8 = 1.2620	C_9 = 1.0728
C_{10} = 2.4729	C'_{10} = 2.4974	C_{11} = 20.599
C_{12} = 4.1617	C_{13} = 1.0	C_{14} = 4.4163
C_{15} = 10.378	C_{16} = 2.0484	C_{17} = 1.0
C_{18} = 1.0910	C'_{18} = 1.0803	C_{19} = 10.239
C_{20} = 2.4337	C_{21} = 1.0099	C_{22} = 5.0653
C_{23} = 1	C_{h1} = 15.409	C_{h2} = 1
C_{h3} = 20.599	C_{h4} = 4.4163	C_{h5} = 10.239
C_{h6} = 5.0653	C_h = 1	C_H = 1

The curves of Fig. 4 can be shifted near to the horizontal axis by modifying the input capacitance C_1 in accordance with the relationship

$$C_{1p} = C_1(1-\Delta_m), \tag{7}$$

where

$$\Delta_m = \frac{H_{A_0}(f_m) - H_{id}(f_m)}{H_{id}(f_m)}$$

is the relative error in the GOC filter response at the passband midpoint f_m = 3800 Hz for A_0 = 100.

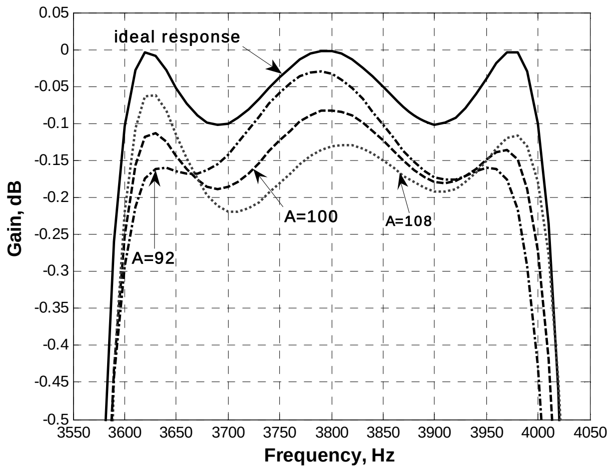

Fig. 4. Passband responses of the GOC bandpass filter for C_1 =1.2831

For $H_{A0}(f_m)$ = 0.9906181 and $H_{id}(f_m)$ = 0.9997336 one finds C_{1p} = 1.2948. The corresponding passband responses are shown in Fig. 5.

The output offset voltage of the GOC SC filter in Fig.3 for C_1 = 1.2948 and A = 100 is

$$\begin{aligned}\lim_{n\to\infty} V_{out}(n) = {} & 0.0056V_{os_1} - 1.436\,10^{-5}\,V_{os_2} - 0.0792V_{os_3} \\ & - 6.027\,10^{-4}\,V_{os_4} + 0.133V_{os_5} - 2.489\,10^{-4}V_{os_6} \\ & - 0.0299V_{os_7} + 0.0547V_{os_8}.\end{aligned} \tag{8}$$

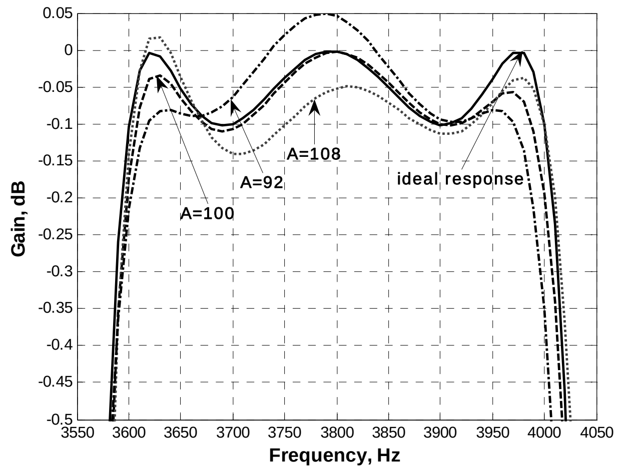

Fig. 5. Passband responses of the GOC bandpass filter for C_1 =1.2948

4 Conclusion

A combined approach for reducing the effects of op amps finite gain and offset voltage in left-LUD switched-capacitor ladder filters has been presented. The effectiveness of the approach proposed has been demonstrated by an sixth-order bandpass filter. The passband response of the gain- and offset-compensated filter with changed topology and modified capacitance values follows much more closely the ideal response than that of the conventional filter.

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