REDUCTION OF 1/f NOISE IN SC LADDER FILTERS USING CORRELATED DOUBLE SAMPLING METHOD

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ABSTRACT

Correlated double sampling (CDS) method applied to the noise generator of the operational amplifiers in SC ladder filters is described. A significant reduction of the noise in the low frequency range results. CDS action is get with a novel fully differential topology that does not increase the element count. A final stage, for the differential to single-ended conversion, that implement the CDS action, is also proposed. Numerical and experimental results confirm the behaviour of the approach.

INTRODUCTION

A fundamental limitation of the dynamic range in low frequency SC filters is the 1/f noise of CMOS operational amplifiers. Different methods can be used in order to reduce the low frequency noise contribution. One method consists in the use of large devices in the input differential stage of the operational amplifier, since the 1/f noise contribution of MOS transistors is proportional to the inverse of the gate area. A second method is the chopper stabilization technique which operates on the signal a square wave modulation and, on the noise, a square square wave modulation, hence the spectrum of the signal, after the double modulation, remains in the band base while the spectrum of the noise is carried at high frequency. In [1] it is shown that the removal of the 1/f noise term can lead to a dynamic range of 102 dB. A third technique is the correlated double sampling method (CDS) [2][3]. It operates at the system level rather than at the operational amplifier level. The principle of operation of the CDS technique is shown in Fig. 1. The noise is sampled twice, one sample is delayed, then the two samples are subtracted up in order to cancel the correlated terms.

CDS technique has been employed in CCD and is commonly used in comparators (autozero technique). However, up to date, the approach has not been used in SC ladder filters, probably because of the required additional hardware. This communication describes a novel circuit approach which allows to apply the CDS method to SC ladder filters without any increase of the active and passive component count.

Numerical simulation and experimental measurement on a breadboarded filter confirm the validity of the approach.

Fig. 2 - Switched-capacitor integrator

DESCRIPTION OF THE METHOD

In order to describe the proposed method let us first consider the simple SC integrator shown in Fig. 2. The signal generator $v_n(t)$ describes the input referred noise generator of the operational amplifier. We are interested on the output signal contributed by $v_n(t)$, it is given by:

$$V_o(t) = v_n(t) + \frac{C_1}{C_3 - 1} v_n(t)$$

(1)

$V_o$ is made of two contributions, one is the buffering of $v_n$, the second one is the SC integration of $v_n$. Recently the scheme shown in Fig. 3 [4] has been proposed, it allows to eliminate the second contribution. The circuit in Fig. 3 is a noninverting SC integrator (inverting operation is get by reversing the clocking scheme in the two input switches). On the noise generator $v_n(t)$ the circuit operates a CDS action, the right plate of $C_1$ is always connected to the virtual ground, the noise voltage is always stored on $C_1$, hence, no integration of $v_n$ occurs. However, the circuit in Fig. 3 does not eliminate the buffering contribution.
It is worth to note that action of the input switches (A, B, C and D in Fig. 4) is to connect the sampling capacitors C1 and C3 to ground during one phase and to the output of the previous operational amplifier during the other phase. But this, neglecting the noise generator effect, is just the voltage available at the output of the previous operational amplifier. Hence, the input switches may be eliminated as shown in Fig. 5.

Besides allowing to spare switches, the circuit in Fig. 5 has an important feature. It intrinsically implements a CDS action on the buffering term of the noise of the previous operational amplifier. The voltages at which C2 and C3 are connected equal the noise during one phase and the signal plus the noise during the other phase. Hence, the charge transferred into the integrating capacitor is proportional only to the signal voltages.

The use of the fully differential technique is recommended in low noise application, if this approach is used, the required inversion of the signal around the loop of two integrators is satisfied using the topology shown in Fig. 6. It is worth to note that the obtained topology looks complementary to conventional topology of loops of two integrators. Switched structures are used around the operational amplifiers and unswitched capacitor are directly connected between the output and the input of operational amplifiers.

SC LADDER IMPLEMENTATION

Loops of two integrators are basic building blocks for the design of SC ladder filters. Moreover, damped integrators and structures for the transmission zeros implementation are also required. If we consider again the basic circuit in Fig. 3 we immediately realize that a damped SC integrator can be simply obtained by adding to the circuit an unswitched capacitor between the output of the operational amplifier and the virtual ground. This additional capacitor is in parallel with C during phase 2 and it is discharged during phase 1 by the same switch that establishes the buffer path; hence, it operates as the damping structure in a conventional circuit.
In conventional SC ladder circuits, transmission zeros are implemented with capacitors directly connected between the output and the virtual ground of operational amplifiers. If we assume that the involved operational amplifiers are buffered during the same phase, it is enough, in the design of circuits with the proposed technique, to disconnect the capacitors during the buffering phase.

Using the basic building block shown in Fig. 5 and the above design considerations whatever SC ladder filter can be designed. Fig. 7 shows the schematic of a 5th order low pass elliptic filter. Fully differential operational amplifiers with four switches and feedback capacitors connected around are represented with an equivalent symbol. The capacitors used to implement the transmission zeros are in the upper part of the schematic. The values of the capacitors allow to satisfy the PCM specifications with clock frequency $f_{ck} = 256 \text{ kHz}$.

The circuit in Fig. 7 uses a simple input structure that allows to get, at the same time, the transformation from single-ended to differential.

The circuit in Fig. 7 retains the low frequency noise contribution of the last operational amplifiers (buffer term). Moreover the output is available only during phase 1. These drawbacks can be eliminated in the stage that performs the differential to single-ended transformation. A proposed final stage is shown in Fig. 8. It is made with two multiplexed amplifiers [8] insensitive to the offset and the low frequency noise. The direct connection to the output of the fully differential filter allows to implement a CDS action on the noise generator of the last operational amplifier.

**NUMERICAL AND EXPERIMENTAL RESULTS**

The fifth order elliptic filter shown in Fig. 7, cascaded with the final stage in Fig. 8, has been simulated with the software SWITCH [6]. In order to verify the CDS action of the circuit, the transfer functions from a generator in series with the noninverting terminals of the operational amplifiers and the output of the filter have been determined. These transfer functions are here referred to as noise transfer functions. The results of the numerical simulation are shown in Fig. 9. CDS action is evident: the noise transfer functions show, as expected, a derivative behaviour at low frequency.

A third order elliptic filter has been breadboarded using LF 355 as operational amplifier and CD4056 as analog switches. The unity capacitor value was 200 pF. The cutoff frequency was 1 kHz and the clock frequency 100 kHz. In Fig. 10 the response of the filter and one of the noise transfer functions are shown.
Fig. 9 - SWITCAP numerical results of the filter in Fig. 7.
  a) response, b) noise transfer functions

Fig. 10 - Experimental results of a third order elliptic filter. a) response b) noise transfer function from the second operational amplifier

REFERENCES


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