

Fully-Balanced Structures of Continuous-Time MLF OTA-C Filters

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Abstract

This paper presents general fully balanced structures of continuous-time OTA-C filters based on multiple loop feedback (MLF) configurations. Both simple all pole and complex arbitrary zero fully balanced implementations are described. The general explicit iterative design formulae for the filters based on the important LF structure are presented. The design of fifth-order fully balanced LF filters is considered.

1. Introduction

Multiple loop feedback (MLF) active filters [1] have the advantage of both low sensitivity and arbitrary transmission zeros, compared with cascade structures that have high sensitivity and ladder topologies which can implement only imaginary axis zeros. Note that non-imaginary-axis zeros are required, for example, in equalizer design. OTA-C filters with multiple loop feedback configurations have received considerable attention in high frequency integrated continuous-time filter design [2-11]. Both integrators [2-8] and biquads [9-11] are used in the design. Integrator-based techniques may be most general, as biquads themselves are constructed based on integrators. This is especially true in integrated OTA-C filter design, because single-OTA biquads are no longer attractive as single-Opamp biquads in discrete Opamp-RC filter design. References [2, 3] have proposed integrator-based universal architectures using the IFLF structure with output summation and input distribution respectively. References [4, 5] have systematically explored the generation and design of integrator-based multiple loop feedback OTA-C filters with a new general unified design method having been developed and many new structures obtained including the LF configuration.

Note that fully balanced structures are most widely utilized in continuous-time integrated filter design, because balanced structures can achieve a very high common-mode rejection ratio and reduce both the even-order harmonic distortion components and the effects of power supply noise. Also, in practice, the LF feedback configuration

is one of the most important multiple loop feedback structures, since it has very low sensitivity. In this paper, we hence propose a general method for generation of fully balanced multiple loop feedback OTA-C filters and give explicit design formulae for the filter design based on the LF feedback structure.

2. General Fully-Balanced OTA-C Structures

The general form of all-pole transfer functions can be expressed as

$$H_d(s) = A_0 / (B_n s^n + B_{n-1} s^{n-1} + \dots + B_1 s + 1) \quad (1)$$

The general single-ended all-pole multiple integrator loop feedback OTA-C model [4, 5] can be converted into the balanced equivalent by using differential four input and two output OTAs (for example, the one in [6]) in integrators and mirroring the feedback network in the upper part to the lower part, as shown in figure 1. With $\tau_j = C_j / g_{mj}$ denoting the voltage integration constant of the j th integrator and f_{ij} the voltage feedback coefficient from the output of the j th integrator to the negative input terminal of the i th integrator, the transfer function can be derived as

$$H(s) = \frac{V_{out+}}{V_{in+}} = 1 / |A(s)| \quad (2)$$

where $|A(s)|$ is the determinant of system coefficient matrix $A(s)$ of

$$\begin{bmatrix} s\tau_1 + f_{11} & f_{12} & f_{13} & f_{1n} \\ -1 & s\tau_2 + f_{22} & f_{23} & f_{2n} \\ & -1 & s\tau_3 + f_{33} & f_{3n} \\ & & & \dots \\ & & & & s\tau_n + f_{nn} \end{bmatrix} \quad (3)$$

The feedback coefficient matrix $F = [f_{ij}]$ has the property that $f_{ij} \neq 0$ if there is feedback between the negative input terminal of integrator i and the output of integrator j ; and otherwise, it is zero. The nonzero feedback coefficient can always be realized using an OTA voltage

amplifier and the zero feedback coefficient can be obtained simply by an open circuit. The unity feedback coefficient can also be achieved by direct wire connection. If all the nonzero feedback coefficients are unity and are realized with pure wire connection, the whole system then has the minimum number of components.

Similarly, we consider fully balanced OTA-C structures for the synthesis of the universal transfer function

$$H_d(s) = \frac{A_n s^n + A_{n-1} s^{n-1} + \dots + A_1 s + A_0}{B_n s^n + B_{n-1} s^{n-1} + \dots + B_1 s + 1} \quad (4)$$

The first general fully balanced OTA-C model for implementing arbitrary filter characteristics is shown in figure 2. As depicted, this model is composed of a multiple loop feedback OTA-C network and an output summation OTA network. Denoting $k_j = g_{aj}/g_r$, we derive the circuit transfer function

$$H(s) = \frac{V_{out+}}{V_{in+}} = k_0 + \frac{1}{|A(s)|} \sum_{j=1}^n k_j A_{1j}(s) \quad (5)$$

where $A_{ij}(s)$ represent the cofactors of matrix $A(s)$. The system poles are determined by τ_j and f_{ij} and the transmission zeros may be controlled arbitrarily by transconductances g_{aj} through weights k_j .

The second fully balanced structures for implementation of finite transmission zeros is shown in figure 3. In this configuration the voltage signal is applied to circuit nodes by an input distribution OTA network. With $\beta_j = g_{aj}/g_{mj}$ and $\gamma = g_{m0}/g_r$, we can formulate

$$H(s) = \frac{V_{out+}}{V_{in+}} = \gamma[\beta_0 + \frac{1}{|A(s)|} \sum_{j=1}^n \beta_j A_{jn}(s)] \quad (6)$$

Again, any filter transmission characteristics may be realized through adjusting distribution weights β_j , that is, the associated g_{aj} .

Note that if the maximum order in the numerator is required to be $n-1$, then we can remove the g_{a0} OTA, and the g_{m0} and g_r OTAs for $\gamma = 1$ and simply output the voltage V_{on} directly in the distribution case (this leads to an advantage that the resistive summing node that will have effects of the parasitics at very high frequencies is avoided), while for the summation the g_{a0} OTA should be deleted. It is also of interest to note that when the transadmittance functions are required, we can eliminate the g_r OTA in both the input distribution and output summation configurations.

3. Fully-Balanced LF Structures and Design Formulae

The design methods and formulae discussed systematically in [4, 5] are completely suitable for the design of

fully balanced structures presented in the above. We now further give the design formulae for the important LF feedback structure that corresponds to $f_{ij} = 1$ for $j = i+1, i = 1, 2, \dots, n-1$ and $f_{nn} = 1$, and for the other $i, j, f_{ij} = 0$.

For the distribution form, A_{jn} can be formulated in an iterative way as

$$A_{1n}(s) = 1, \quad A_{2n}(s) = \tau_1 s, \\ A_{jn}(s) = s\tau_{j-1}A_{(j-1)n}(s) + A_{(j-2)n}(s) \quad (7)$$

where $j = 3, 4, 5, \dots, n$.

For the summation type we determine $A_{1j}(s)$ using

$$A_{1n}(s) = 1, \quad A_{1(n-1)}(s) = s\tau_n + 1, \\ A_{1j}(s) = s\tau_{j+1}A_{1(j+1)}(s) + A_{1(j+2)} \quad (8)$$

where $j = n-2, n-3, n-4, \dots, 1$.

$|A(s)|$ can be obtained by

$$|A(s)| = (s\tau_n + 1)A_{nn}(s) + A_{(n-1)n}(s) = s\tau_1 A_{11}(s) + A_{12}(s) \quad (9)$$

For any order, using the above iterative formulae and equations (2), (5) and (6) we can derive the corresponding transfer function $H(s) = V_{out+}/V_{in+} = N(s)/D(s)$. Take the fifth-order as an example. In the all-pole case, using (2) and (9) we have $N(s) = 1$ and

$$D(s) = \tau_1 \tau_2 \tau_3 \tau_4 \tau_5 s^5 + \tau_1 \tau_2 \tau_3 \tau_4 s^4 + (\tau_1 \tau_2 \tau_3 + \tau_1 \tau_2 \tau_5 + \tau_1 \tau_4 \tau_5 \\ + \tau_3 \tau_4 \tau_5) s^3 + (\tau_1 \tau_2 + \tau_1 \tau_4 + \tau_3 \tau_4) s^2 + (\tau_1 + \tau_3 + \tau_5) s + 1 \quad (10)$$

For the input distribution structure, using (6) and (7) we have the numerator of the transfer function as ($\gamma = 1$)

$$N(s) = \beta_0 \tau_1 \tau_2 \tau_3 \tau_4 \tau_5 s^5 + (\beta_0 + \beta_5) \tau_1 \tau_2 \tau_3 \tau_4 s^4 \\ + [\beta_0 (\tau_1 \tau_2 \tau_3 + \tau_1 \tau_2 \tau_5 + \tau_1 \tau_4 \tau_5 + \tau_3 \tau_4 \tau_5) + \beta_4 \tau_1 \tau_2 \tau_3] s^3 \\ + [(\beta_0 + \beta_5) (\tau_1 \tau_2 + \tau_1 \tau_4 + \tau_3 \tau_4) + \beta_3 \tau_1 \tau_2] s^2 + [\beta_0 (\tau_1 + \tau_3 + \tau_5) \\ + \beta_4 (\tau_1 + \tau_3) + \beta_2 \tau_1] s + (\beta_0 + \beta_5 + \beta_3 + \beta_1) \quad (11)$$

For the output summation type, the numerator of the transfer function is formulated using (5) and (8) as

$$N(s) = k_0 \tau_1 \tau_2 \tau_3 \tau_4 \tau_5 s^5 + (k_0 \tau_1 \tau_2 \tau_3 \tau_4 + k_1 \tau_2 \tau_3 \tau_4 \tau_5) s^4 + \\ [k_0 (\tau_1 \tau_2 \tau_3 + \tau_1 \tau_2 \tau_5 + \tau_1 \tau_4 \tau_5 + \tau_3 \tau_4 \tau_5) + k_1 \tau_2 \tau_3 \tau_4 + k_2 \tau_3 \tau_4 \tau_5] s^3 \\ + [k_0 (\tau_1 \tau_2 + \tau_1 \tau_4 + \tau_3 \tau_4) + k_1 (\tau_2 \tau_3 + \tau_2 \tau_5 + \tau_4 \tau_5) + k_2 \tau_3 \tau_4 \\ + k_3 \tau_4 \tau_5] s^2 + [k_0 (\tau_1 + \tau_3 + \tau_5) + k_1 (\tau_2 + \tau_4) + k_2 (\tau_3 + \tau_5) \\ + k_3 \tau_4 + k_4 \tau_5] s + (k_0 + k_1 + k_2 + k_3 + k_4 + k_5) \quad (12)$$

To realize the fifth-order transfer function in (4), the pole parameters, τ_j in the denominator of the transfer function in (10) are determined as

$$\tau_5 = \frac{B_5}{B_4}, \tau_4 = \frac{B_4}{B_3 - B_2 \tau_5}, \tau_3 = \frac{B_3 - B_2 \tau_5}{B_2 - (B_1 - \tau_5) \tau_4},$$

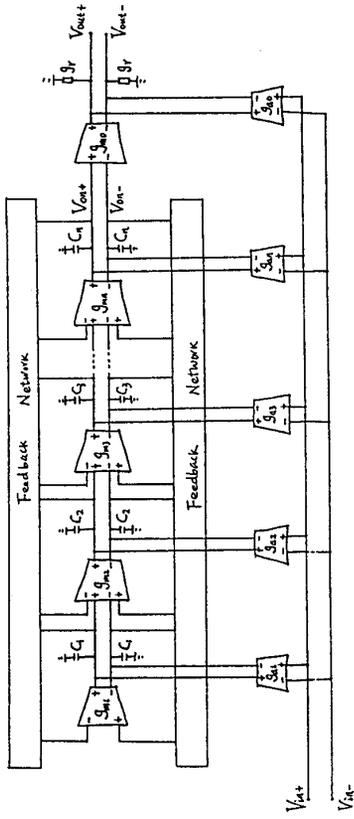


Figure 3: Fully balanced multiple loop feedback and input distribution OTA-C structure for arbitrary zero implementation

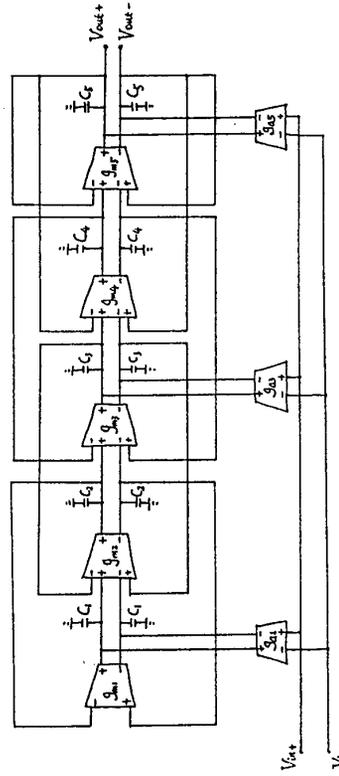


Figure 4: Fifth-order LF feedback structure with input distribution

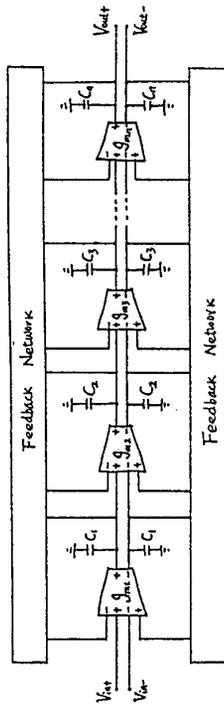


Figure 1: Fully balanced differential multiple loop feedback all-pole OTA-C structures

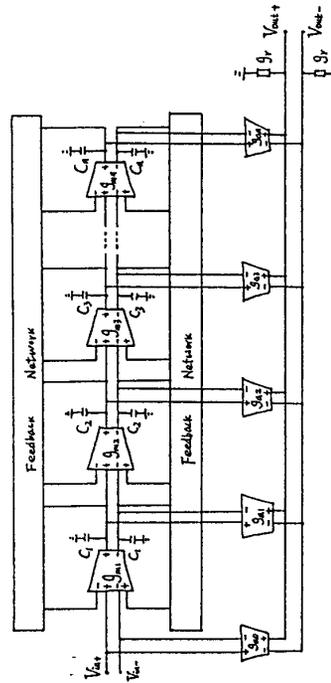


Figure 2: Fully balanced multiple loop feedback and output summation OTA-C structure for arbitrary zero implementation

$$\tau_2 = \frac{B_2 - (B_1 - \tau_5)\tau_4}{B_1 - \tau_3 - \tau_5}, \tau_1 = B_1 - \tau_3 - \tau_5 \quad (13)$$

The numerator parameters, β_j for the distribution type and k_j for the summation can be easily determined from (11) and (12) with comparison with (4) in an iterative way respectively, since τ_j are determined by (13). Figure 4 shows a fifth-order low-pass filter realizing the numerator coefficients of $A_j = 0$, $j = 1, 3, 5$, which is obtainable from figure 3 by removing the g_{a0} OTA ($\beta_0 = 0$), replacing the g_{m0} and g_r OTA's by a direct connection, and removing the g_{a2} and g_{a4} OTAs ($\beta_2 = \beta_4 = 0$). The numerator parameters can be determined as $\beta_5 = A_4/B_4$, $\beta_3 = (A_2 - \beta_5 B_2)/\tau_1 \tau_2$, $\beta_1 = A_0 - (\beta_3 + \beta_5)$.

It can be shown that for any order n in any case of all-pole and arbitrary zero realizations, the parameters, τ_j , k_j or β_j all can be determined explicitly. This will be discussed separately.

4. Conclusions

General fully balanced multiple loop feedback OTA-C filter structures have been constructed based on the single-ended counterparts previously proposed by the authors. The design formulae for the low sensitivity LF feedback structure have also been derived. The results in the paper can also be extended for the design of current-mode multiple loop feedback OTA-C filters [7, 8].

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