Voltage-Mode CFTA-C Fifth-Order Low-Pass Filter Design and Optimization

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Abstract

Based on the fifth-order voltage-mode low-pass LC ladder structure the active only grounded-C equivalent circuit solutions are presented. As active building blocks the current follower transconductance amplifiers (CFTAs) are used. Using the signal flow graph approach, the initial solution using nine active elements is further optimized to a more simple topology employing only six active elements and five capacitors. Using the readily available UCC-N1B integrated circuit, the performance of the optimized active only grounded-C voltage-mode low-pass filter has been verified both by the simulations and the experimental measurements.

1. Introduction

The analog frequency filters belong to the most frequently used function blocks in analog signal processing since they can be found useful in areas such as instrumentation, automatic control, communication systems etc. Although the mathematical description of these function blocks is very well known and there is a number of verified circuit solutions using different types of active elements, the engineers are still looking for new challenges if low supply voltage, low power consumption or low noise are to be considered. Therefore, new or modified active elements and new frequency filter solutions are presented in the literature.

Probably the best known active elements are the operational amplifier (OPA) and operational transconductance amplifier (OTA) that are assumed to be employed in voltage-mode function blocks. However, also other types of active elements such as current conveyors (CCs) [1]-[3], voltage conveyors [4]-[6] and other CC, VC and OTA based active building blocks [7]-[9] are presented and used for the design of filters.

This paper deals with the application possibilities of the current follower transconductance amplifier (CFTA), which is the OTA based active building block and has been recently introduced in [10]. The advantageous usage of this active element has been shown e.g. in [11]-[17]. However, the authors limit only on the design of simple biquads and hence the behavior of CFTA in complex structures is more or less unknown. Therefore, this paper deals with the design of a fifth-order low-pass filter working in the voltage mode. Based on a passive prototype, an initial active only solution is shown that is further optimized in terms of the number of active elements. The final solution is then simulated in PSpice and also verified by experimental the measurements.

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2. CFTA - Current Follower Transconductance Amplifier

The current follower transconductance amplifier (Fig. 1(a)) is an analog building block that has been presented in [10] and is a simplified version of the current differencing transconductance amplifier (CDTA) [7]. The simplification of CDTA consists in the reduction of one low-impedance current input (n) as it can be seen from Fig. 2. The reason of such simplification was the fact that in numerous circuit solutions using CDTAs p or n terminals of individual active elements remain unused. These unused input terminals can cause undesired noise injection into the function block and hence decrease the signal to noise of the output signal. Therefore, the basic CFTA uses only single low-impedance current input denoted as f, two high-impedance current outputs $x+$ and $x-$ and one auxiliary high-impedance voltage terminal z. The relation between the terminal currents and voltages of the CFTA can be described as follows:

$$i_z = \alpha i_f,\;\; v_f = 0,\;\; i_{x+} = g_m \cdot v_z,\;\; i_{x-} = -g_m \cdot i_z, \quad (1)$$

where $\alpha = 1 - \varepsilon$ is the current gain from the f terminal to the z terminal and g_m is the transconductance of the active element, whereas $|\varepsilon| << 1$ is the current tracking error. Generally, the both g_m and α are frequency dependent, however for sake of simplicity, in the following sections ideal values are assumed, i.e. g_m being constant and α being unity.

The basic CFTA features only one $x+$ and one $x-$ current output. However, the number of these current outputs can be arbitrary, which results in the multiple-output CFTA (MO-CFTA) as shown in Fig. 2(a), where two positive and two negative current output are assumed. Such MO-CFTA can be implemented using the UCC-N1B integrated circuit [18] as shown in

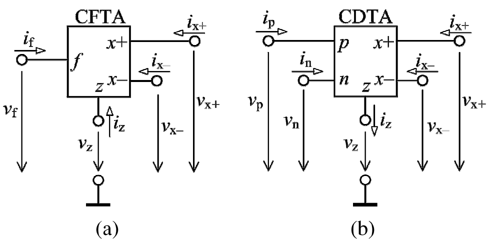


Figure 1. Circuit symbols of (a) CFTA, (b) CDTA.

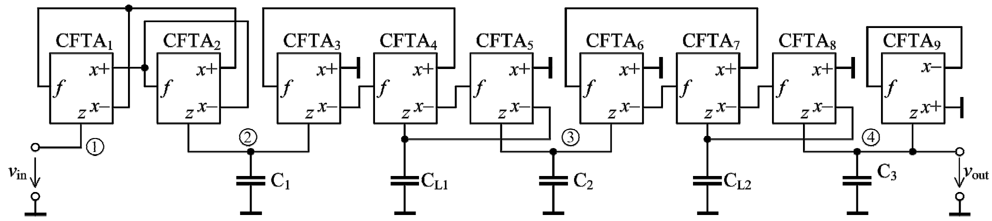


Figure 4. Initial solution of the active only CFTA-C filter

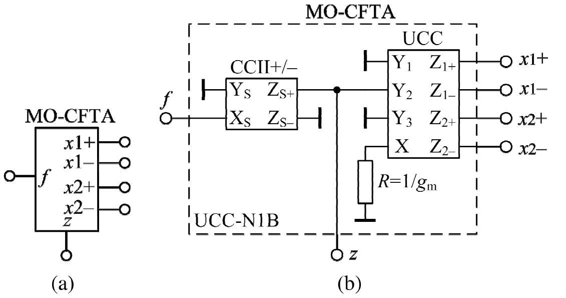


Figure 2. (a) Circuit symbol of MO-CFTA, (b) its implementation using UCC-N1B.

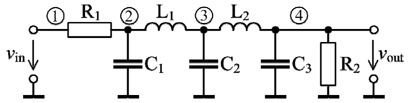


Figure 3. Fifth-order passive LC ladder prototype.

Fig. 2(b). Such configuration is also used for the experimental verifications discussed later in section 4.

3. Proposed Circuit Description

As already mentioned above, the proposed active only CFTA-C frequency filter is based on the passive LC ladder prototype shown in Fig. 3. This circuit represents a fifth-order low-pass filter with the following voltage transfer function:

$$K_{pas} = \frac{v_{out}}{v_{in}} = \frac{G_1}{a_5 s^5 + a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0}, \tag{2}$$

where $a_5 = L_1L_2C_1C_2C_3$, $a_4 = L_1L_2C_2(C_1G_2 + C_3G_1)$, $a_3 = L_1L_2C_2G_1G_2 + L_2C_3(C_1 + C_2) + C_1L_1(C_2 + C_3)$, $a_2 = L_2G_2(C_1 + C_2) + L_1G_2(C_1 + C_2 + C_3) + L_2C_3G_1$, $a_1 = G_1G_2(L_1 + L_2) + C_1 + C_2 + C_3$, $a_0 = G_1 + G_2$.

To implement the active only CFTA-C frequency filter equivalent to the passive prototype, it is basically sufficient to replace the resistors R_1, R_2 and inductors L_1, L_2 by their corresponding synthetic elements, e.g. those presented by our group in [19]. Such simple replacement of the passive elements results in the solution shown in Fig. 4. Here, the resistor R_1 is represented by $CFTA_1$ and $CFTA_2$, inductor L_1 by $CFTA_3$-$CFTA_5$ and C_{L1}, inductor L_2 by $CFTA_6$-$CFTA_8$ and C_{L2}, and resistor R_2 by $CFTA_9$, where according to [19] the relation between the passive and active filter solution is the following:

$$\begin{gathered} g_{m1} = g_{m2} = G_1, \;\; g_{m9} = G_2 \\ g_{m3} = g_{m5} = \frac{C_{L1}}{g_{m4}L_1}, \;\; g_{m6} = g_{m8} = \frac{C_{L2}}{g_{m7}L_2}. \end{gathered} \tag{3}$$

The transfer function of the active filter from Fig. 4 can be represented as:

$$K_{act} = \frac{g_{m1}g_{m3}g_{m4}g_{m6}g_{m7}}{b_5 s^5 + b_4 s^4 + b_3 s^3 + b_2 s^2 + b_1 s + b_0}, \tag{4}$$

where

$$\begin{aligned}
b_5 = \; & C_1C_2C_3C_{L1}C_{L2}, \\
b_4 = \; & C_2C_{L1}C_{C2}(C_3g_{m2} + C_1g_{m9}), \\
b_3 = \; & C_1C_{L1}g_{m7}(C_3g_{m6} + C_2g_{m8}) + \\
& + C_3C_{L2}g_{m4}(C_2g_{m3} + C_1g_{m5}) + \\
& + C_2C_{L1}C_{L2}g_{m2}g_{m9}, \\
b_2 = \; & C_{L1}g_{m2}g_{m7}(C_3g_{m6} + C_2g_{m8}) + \\
& + C_{L2}g_{m4}g_{m5}(C_3g_{m2} + C_1g_{m9}) + \\
& + g_{m9}(C_{L1}C_1g_{m6}g_{m7} + C_{L2}C_2g_{m3}g_{m4}), \\
b_1 = \; & g_{m4}g_{m7}\left[g_{m3}(C_3g_{m6} + C_2g_{m8}) + C_1g_{m5}g_{m8}\right] + \\
& + g_{m2}g_{m9}(C_{L1}g_{m6}g_{m7} + C_{L2}g_{m4}g_{m5}), \\
b_0 = \; & g_{m4}g_{m7}(g_{m2}g_{m5}g_{m8} + g_{m3}g_{m6}g_{m9}).
\end{aligned}$$

Analyzing the solution from Fig. 4 it is obvious that it is excessive in number of active elements. Also some current outputs of individual CFTAs are grounded. Therefore, it is necessary to optimize the initial solution and try to reduce the number of active elements as much as possible. To perform the optimization of the initial solution of the active filter, the M-C signal flow graph approach is advantageously used [20], [21]. The M-C signal flow graph of the initial and optimized structure is shown in Fig. 5. As a result, the optimized structure of the active CFTA-C filter uses only six active elements, five simple CFTAs and one MO-CFTA as shown in Fig. 6. The transfer function of the optimized filter is given as follows:

$$K_{opt} = \frac{g_{m1}g_{m2}g_{m3}g_{m4}g_{m5}}{c_5 s^5 + c_4 s^4 + c_3 s^3 + c_2 s^2 + c_1 s + c_0}, \tag{5}$$

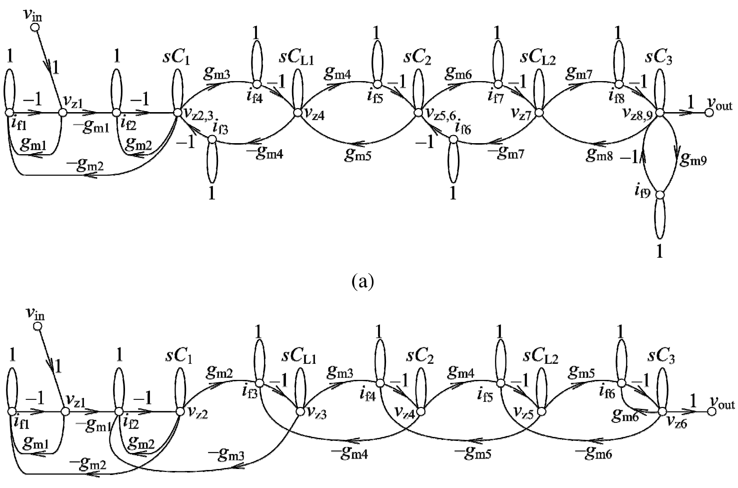
where

$$\begin{aligned}
c_5 = \; & C_1C_2C_3C_{L1}C_{L2}, \\
c_4 = \; & C_2C_{L1}C_{L2}(C_3g_{m2} + C_1g_{m6}), \\
c_3 = \; & C_1C_{L1}g_{m5}(C_3g_{m4} + C_2g_{m6}) + \\
& + C_{L3} + C_3g_{m3}(C_2g_{m2} + C_1g_{m4}) + \\
& + C_{L1}C_2C_{L2}g_{m2}g_{m6}, \\
c_2 = \; & C_{L1}g_{m5}g_{m6}(C_2g_{m2} + C_1g_{m4}) + \\
& + C_3g_{m2}g_{m4}(C_{L2}g_{m3} + C_{L1}g_{m5}) + \\
& + C_{L2}g_{m3}g_{m6}(C_2g_{m2} + C_1g_{m4}), \\
c_1 = \; & g_{m2}g_{m3}g_{m5}\,[g_{m6}(C_1 + C_2] + \\
& + g_{m2}g_{m4}g_{m6}(C_{L1}g_{m5} + C_{L2}g_{m3}), \\
c_0 = \; & 2g_{m2}g_{m3}g_{m4}g_{m5}g_{m6}.
\end{aligned}$$

After optimization the relation between the values of passive elements from the passive prototype and the active elements' transconductances is as follows:

$$\begin{gathered} g_{m1} = g_{m2} = G_1, \;\; g_{m4} = g_{m6} = g_{m1} \\ g_{m3} = \frac{C_{L1}}{g_{m2}L_1}, \;\; g_{m5} = \frac{C_{L2}}{g_{m4}L_2}. \end{gathered} \tag{6}$$

whereas it is assumed that $G_1 = G_2$.



(a)

(b)

Figure 5. M-C signal flow graph of (a) initial, (b) optimized solution of active only CFTA-C filter.

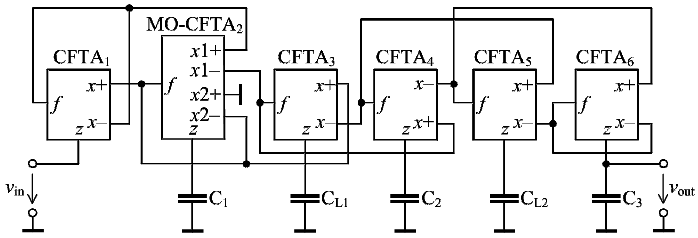


Figure 6. Optimized solution of the active only CFTA-C filter

4. Simulation and Measurement Results

The optimized active only CFTA-C frequency filter from Fig. 6 has been first simulated and compared to the behavior of the passive prototype. Considering the frequency bandwidth of the active elements [18] used to implement CFTAs, for the pole-frequency $f_0 = 100$ kHz of the filter the values of passive elements of the LC ladder structure were determined as follows: $R_1 = R_2 = 680\ \Omega$, $L_1 = L_2 = 2.2$ mH, and $C_1 = C_2 = C_3 = 3.9$ nF. Using (6), the transconductances of the active elements are given as $g_{m1} = g_{m2} = g_{m4} = g_{m6} = G_1 = 1.47$ mS, $g_{m3} = g_{m5} = 1$ mS for $C_{L1} = C_{L2} = 3.3$ nF, whereas the values of capacitors C$_1$–C$_3$ in the optimized structure remain the same as in the LC ladder structure.

Using the readily available UCC-N1B, the required CFTAs were implemented as shown in Fig. 2(b) and using the network analyzer Agilent 4392A the proposed optimized active only CFTA-C frequency filter has furthermore been verified by the experimental measurements.

The magnitude response of the optimized active only CFTA-C filter from Fig. 6 obtained both by the simulations and by the experimental measurements compared to the response of the passive LC ladder structure is shown in Fig. 7. As it can be seen the behavior of the proposed structure agrees very well with the theoretical presumptions. Both in the simulations and the experimental measurements of the active only CFTA-C filter the pole-frequency has slightly increased compared to the pole pole-frequency of the LC ladder structure, which can be seen as paradox. However, the non-ideal behavior of the active elements used to emulate CFTAs results in higher transconductances that cause lower values of equivalent inductance (see (7) in [19]) of the synthetic inductors implemented by corresponding CFTAs. Subsequently, the lower inductances result in the increase of the pole-frequency, which is observed in the simulations and the experimental measurements. From the measurements it is also obvious that the attenuation in the stop-band does not increase with the frequency as it is the case of the simulations, but rather limited to approx. 90 dB. Such limitation of reached attenuation in the stop-band is caused by the influence

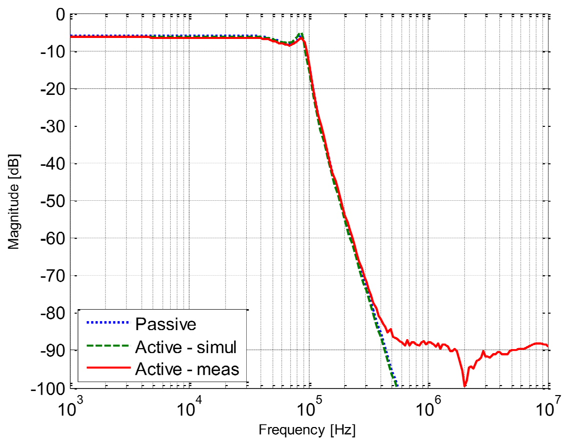


Figure 7. Simulated and measured magnitude response of the optimized filter from Fig. 6 compared to passive structure.

of the printed circuit board designed to perform the experimental measurements. However, such value in attenuation is expected to be sufficient for most of the in practice utilization of the proposed structure, such as antialiasing filters, reconstruction filters or base-band receivers.

5. Conclusion

In this paper we have presented the application possibilities of the current follower transconductance amplifiers (CFTAs) in more complex structures of frequency filters than basic biquads. Based on the fifth-order voltage-mode low-pass LC ladder structure the equivalent active only CFTA-C circuit solutions have been presented. The basic solution of active only filter, referred to as initial, has been realized by substituting the resistors and inductors by their corresponding synthetic structures that have been presented by our research group previously in [19]. This initial structure employes nine active elements and five capacitors, whereas all are grounded. Using the signal flow graph approach, the initial structure of the active only filter has been optimized in terms of the number of active elements. The final, i.e. optimized, solution of the active only CFTA-C filter employes only six active elements and can be used to design filters equivalent to passive structures, where $R_1 = R_2$.

To verify the rightness of the optimization steps, the proposed optimized structure of the active only CFTA-C voltage-mode fifth-order low-pass filter has been simulated in PSpice OrCAD and furthermore experimentally measured, where the active elements have been realized using the model of the UCC-N1B integrated circuit that was designed at our workplace and realized in cooperation with ON Semiconductor Ltd. Both simulation and experimental measurements have shown proper behavior of the proposed active filter solution and hence proved the ability of the CFTA active building block to be used to implement very complex function blocks.

6. References

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