Current-Mode Biquads For Low-Frequency Operation

Serdar ÖZOĞUZ Ali TOKER H. Hakan KUNTMAN

Istanbul Technical University, Faculty of Electrical and Electronics Engineering, Department of Electronics and Communication Eng., 80626, Maslak, Istanbul, TURKEY
Tel: +90-212-285 36 19, Fax: +90-212-285 36 79
E-Mail: serdar@ehb.itu.edu.tr, alitoker@ehb.itu.edu.tr, kuntman@ehb.itu.edu.tr

Abstract

Two approaches for the realisation of current-mode active filters for low frequency operation are given. According to these, two low-frequency current-mode multifunction filters using practical integrated circuit components are obtained and their performances are discussed. SPICE simulation results verifying theoretical analysis are included.

1. Introduction

Continuous-time active filters are widely used to synthesise various types of filter functions. However, at low frequencies, these filters require passive components that are too large to be economically fabricated using integrated circuit technology. In this manner, the until now reported active-RC filters can not implemented as an integrated circuit for low frequency operation.

In the literature, integrable voltage-mode single-pole lowpass filters for low-frequency operation which employ an opamp have been presented [1,2]. Also, for realising low-frequency active filters, impedance scalers are known to be useful [3]. However, today, due to reduced power supplies in IC implementation, the operation at low voltage levels and in current-mode (CM) are of great interest. Also, the use of impedance scalers yields filters employing floating capacitors which is an important drawback from the integrated circuit implementation point of view.

Considering these facts, in this work, the realisations of second-order CM biquads capable of operating at low-frequencies are discussed. To do this, three basic blocks using dual-output current conveyors (DO-CCII) and grounded capacitors are proposed. These blocks are shown to be suitable for the realisation of large time constants with integrable passive components. In order to show the feasibility of the active filters using these blocks, an insensitive and integrable CM universal filter, which simultaneously produces three basic type of filter responses and a CM multifunction filter, which simultaneously realises bandpass (BP) and highpass (HP) filter responses are presented. The proposed filters employ all grounded capacitors and are suitable for integrated circuit implementation. The performances of the filters are discussed and their feasibilities are verified through SPICE simulations.

2. Basic circuits with large time constants

In this work, we use DO-CCII as active element, which enables flexible design and avoids the use of too much active elements. However, by implementing the basic blocks presented in this section using different active elements, such as CCIIs, OFAs, etc., filter topologies employing different type of active elements can be obtained.

A DO-CCII is defined by the following terminal relationships [4]:

$$I_Y=0, \quad I_X=V_Y, \quad I_Z=+kI_X, \quad I_{Z-}=-kI_X \qquad (1)$$

where k is equal to unity.

However, for our purpose, we use a specially designed DO-CCII which can also be defined by the relationship of Eq. 1. However, this modified DO-CCII differs from the conventional one in that the value of the parameter k can be different than unity.

Taking the non-idealities of the DO-CCII into account, the above given terminal relationships can be rewritten as,

$$I_Y=0, \quad V_X=\beta V_Y, \quad I_Z=+\alpha kI_X, \quad I_{Z-}=-\alpha kI_X \qquad (2)$$

where $\beta=1-\varepsilon_v$, $\alpha=1-\varepsilon_i$, and ε_v ($|\varepsilon_v|<<1$) and ε_i ($|\varepsilon_i|<<1$) denote the voltage and current tracking errors, respectively.

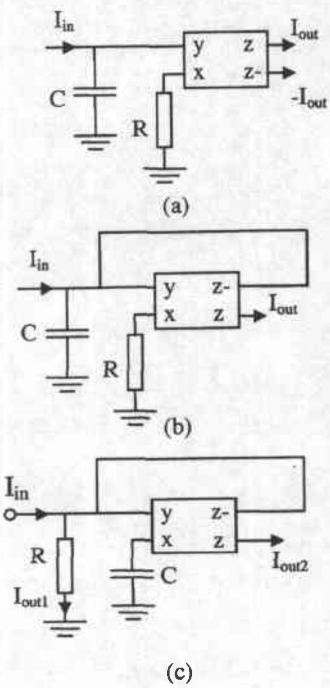

Figure 1 a) Lossless integrator, b) Lossy integrator c) Lossy integrator and dumped differentitor

It is known from the literature that lossy and lossless integrators are widely used as basic building blocks for the realisation of various active filters [5]. Therefore, a lossy and a lossless integrators are presented in Figs. 1a and 1b. Using the relationship given in Eq. 2, routine analyses for the circuits in Figs. 1a and 1b yield the following transfer functions respectively,

$$\frac{I_{out}}{I_{in}}=\frac{1}{s\tau/k} \tag{3}$$

and

$$\frac{I_{out}}{I_{in}}=\frac{1}{1+s\tau/k}. \tag{4}$$

where $\tau=RC$. It is obvious from Eqs. 3 and 4 that the time constants of the integrators are τ/k. Therefore, by keeping k much smaller than unity, one may obtain very large time constants with practical passive component values. In this way, with integrable maximum values of resistances and capacitances of R_{max}=50kohm and C_{max}=50pF, time constants in audio frequency region are permissible.

Also, a lossy integrator along with a dumped differentiator are known to be useful for the implementation of active filter configurations [6]. Routine analysis of the single-input double-output basic circuit shown in Fig. 1c yields the following transfer functions,

$$\frac{I_{out1}}{I_{in}}=\frac{1}{1+s\tau k},\qquad \frac{I_{out2}}{I_{in}}=\frac{s\tau k}{1+s\tau k} \tag{5}$$

Therefore, this circuit simultaneously realises a lossy integrator and a dumped differentiator. It is seen from Eq. 5 that the time constant of this circuit is τk. Therefore, large time constants can be obtained by keeping the value of k much larger than unity.

3. The proposed CM multifunction biquads

The first proposed CM filter shown in Fig. 2 is constructed by cascading the lossy and the lossless integrators in Figs. 1a and 1b in an unity gain feedback. Note that owing to the use of DO-CCII, the basic integrator blocks are implemented using all grounded passive components. Thus, the circuit has a simple realisation and easy implementation as an integrated circuit. Moreover, the proposed filter has very good sensitivity performance.

Using the terminal relationship given in Eq. 2, routine analysis of the circuit yields the following current transfer functions:

$$\frac{I_{LP}}{I_{in}}=\frac{\dfrac{k_1k_2}{\tau_1\tau_2}}{D(s)},\quad \frac{I_{BP}}{I_{in}}=\frac{\dfrac{sk_4}{\tau_1}\dfrac{R_1}{R_3}}{D(s)},\quad \frac{I_{HP}}{I_{in}}=\frac{s^2k_3\dfrac{C_3}{C_1}}{D(s)} \tag{6a}$$

where

$$D(s)=s^2+s\frac{k_1}{\tau_1}+\frac{k_1k_2}{\tau_1\tau_2}. \tag{6b}$$

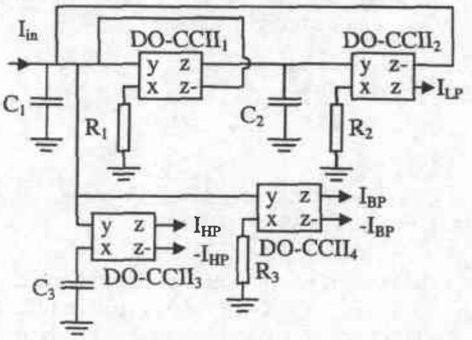

Figure 2 The first proposed CM multifunction filter

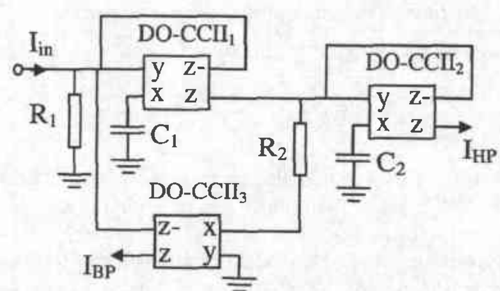

Figure 3 The second proposed CM multifunction filter

From Eq. 6a, it can be seen that lowpass (LP), BP and HP filter responses are obtained simultaneously. Also, one may verify that by adding the current outputs properly, any arbitrary transmission zeros can be realised.

From Eq. 6b, the natural angular frequency and the pole quality factor of this filter are calculated as:

$$\omega_0=\sqrt{\frac{k_1k_2}{\tau_1\tau_2}}\quad\text{and}\quad Q=\sqrt{\frac{k_2\tau_1}{k_1\tau_2}} \tag{7}$$

It can be seen easily that all passive sensitivities are all ½ in magnitude. Note that, if we choose $k_1=k_2=0.01$, then the natural frequency will be decreased by a factor of 100 and this results to integrable maximum time constant of about 0,25ms using the maximum integrable passive component values. Taking into account the DO-CCII non-idealities, the new natural angular frequency and the pole quality factor can be rewritten as:

$$\omega_0'=\sqrt{\frac{\alpha_1\beta_1\alpha_2\beta_2k_1k_2}{\tau_1\tau_2}},\; Q'=\sqrt{\frac{\alpha_2\beta_2k_2\tau_1}{\alpha_1\beta_1k_1\tau_2}} \tag{8}$$

One may verify that the active sensitivities with respect to α_i, β_i and k_i are all equal or smaller than unity.

The second proposed CM filter shown in Fig. 3 is obtained according to the method presented in [6] by using the basic circuit of Fig. 1c. Assuming k_3 as unity, routine analysis of this circuit yields the following current transfer functions:

$$\frac{I_{BP}}{I_{in}} = \frac{-\dfrac{s}{\tau_2 k_2}}{D(s)}, \quad \frac{I_{HP}}{I_{in}} = \frac{s^2}{D(s)} \tag{9a}$$

where

$$D(s) = s^2 + \frac{s}{\tau_1 k_1} + \frac{1}{\tau_1 \tau_2 k_1 k_2}. \tag{9b}$$

Hence, this circuit simultaneously realises BP and HP responses at high-impedance outputs. The fact that all the capacitors are grounded is an important advantage of the filter.

From Eq. 9b, the natural angular frequency and the pole quality factor of this filter are calculated as:

$$\omega_0 = \sqrt{\frac{1}{\tau_1 \tau_2 k_1 k_2}} \quad \text{and} \quad Q = \sqrt{\frac{k_1 \tau_1}{k_2 \tau_2}} \tag{10}$$

Therefore, by keeping the current gains k_1 and k_2 of DO-CCIIs larger than unity, one may obtain very low natural frequencies.

Considering the DO-CCII non-idealities for the second-proposed filter, the new natural angular frequency and the pole quality factor can be rewritten as:

$$\omega_0' = \sqrt{\frac{1}{\tau_1 \tau_2 k_1 k_2 \alpha_1 \alpha_2}}, Q' = \sqrt{\frac{\tau_1 k_1 \alpha_1}{\tau_2 k_2 \alpha_2} \frac{1}{(1 + \frac{\tau_1 k_1 \alpha_1}{\tau_2 k_2 \alpha_2}(1-\alpha_3))}} \tag{11}$$

From these relations, one may verify that the sensitivity of Q with respect to α_3 is equal to Q^2. Therefore, this topology has large active sensitivities with respect to the current gain of DO-$CCII_3$ and should be carefully designed for high-Q applications. However, for low and medium-order Q (Q<5), the feasibility of the filter is verified by several SPICE simulations.

As explained above, the first proposed filter of Fig. 2 has very good passive and active sensitivities while the second proposed filter of Fig. 3 has large active sensitivities for high-Q applications. However, it is

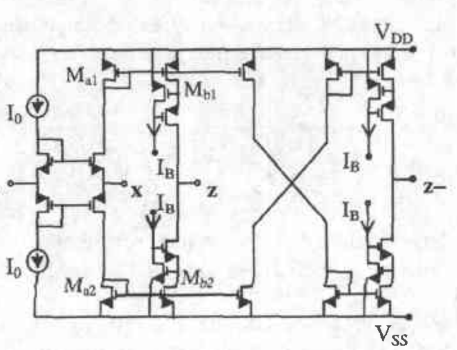

Figure 4 Simplified circuit of DO-CCII using regulated cascode output stages

noticed that, at low-frequencies, the finite parasitic output resistances at the z-terminals of the DO-CCIIs affect the performances of the basic blocks of Figs. 1a and 1b more severly than that of Fig. 1c. As a result of this, the first proposed filter is affected more due to these parasitics compared to the second filter. So, the filter in Fig. 3 can be more attractive for medium-order Q-applications. However, the filter of Fig. 2 can be succesfully realised by using DO-CCIIs which employs output stages offering very large output resistances, e.g. regulated cascode-output stages [8, 9].

4. Simulation results and discussions

In order to verify the theoretical predictions, the proposed CM multifunction filters are designed to realise two voice frequency filters and simulated in SPICE. For the first proposed filter of Fig. 2, we have used the implementation of DO-CCIIs shown in Fig. 4 with the model parameters of 1.2u MIETEC 10V process. This implementation is derived from the CCII implementation given by Bruun [7]. As explained above, for the proper operation of this filter, the output resistance of the DO-CCII should be very large. Therefore, at the outputs the DO-CCIIs, regulated cascode current mirrors have been employed [7, 8]. In order to realise the current gains k_is which should be smaller than unity for low-frequency operation, we have replaced the transistors M_{a1} and M_{a2} by $1/k_i$ parallel transistors ($1/k_i$ being an integer) having the same aspect ratio of those of M_{b1} and M_{b2} respectively. In order to realise a filter with a natural frequency of 3.6kHz and a Q of 0.707, the passive component values are chosen as $R_1=R_3=25k\Omega$, $R_2=50k\Omega$, $C_1=C_2=C_3=50pF$, and the current gains of the DO-CCIIs are taken as $k_1=k_2=k_4=1/25$ and $k_3=1$. The amplitude-frequency responses of the universal filter shown in Fig. 5 verify the theoretical analysis.

We have also simulated the filter in Fig. 3. By choosing the passive component values as $R_1=R_2=50k\Omega$, $C_1=C_2=50pF$, and $k_1=k_2=25$, we have realised a filter with a Q of unity and f_0 of 2.5kHz. For this filter, as the parasitic output resistances of the DO-CCIIs are not crucial, the regulated cascode stages have been replaced by the conventional cascode stages. In this way, a simpler implementation has been obtained. The current gain factors, i.e. $k_1=k_2=25$ are obtained as in the previous case by appropriately connecting parallel transistors. The simulation results for the BP and HP responses shown in Fig. 6 verify the feasibility of this filter.

5. Conclusion

Two approaches for the realisation of low-frequency biquads are given. In the first approach, a CM lossy and lossless integrators are proposed for low-frequency operation. In the second-approach, a lossy integrator/dumped differentiator block is presented. Two CM multifunction filter topologies have been derived according to these blocks. It is noted that the first topology has very good active and passive sensitivities, but is relatively more affected by the parasitic output resistances of the DO-CCIIs. It is shown that by using regulated cascode current mirror based output stages, this drawback can be achieved. The second proposed CM multifunction filter has a large active sensitivity for high-Q applications. However, it is not affected as in the first topology from the main parasitics resistances of the active elements.

Both of the filters operate in CM and employ grounded capacitors, hence they are suitable for integrated circuit implementation. SPICE simulation results verifying theoretical analysis are also included. Finally, it should be noted that, the proposed filters can also be used for the realisation of active filters with low-passive component spreads, as indicated in [3].

References:

[1] B. Ghosh, S. Bandyopadhyay, and D. Patranabis, 'True RC integrators with very large and very small time constants sing active control of capacitance and/or resistance', *IEEE Trans. on Instrument. and Measurement*, **37**, pp. 389-392, 1988.

[2] D. J. Comer, D.T. Comer, B.K. Casper, and J.R. Gonzales, 'An integrable single-pole lowpass filter for low-fequency operation', *Int. J. Electronics*, **83**, pp.49-54, 1997.

[3] J. S. Martinez and A. V. Gonzalez, 'Impedance scalers for IC active filters', Proc. ISCAS'98, Monterey, U.S.A., 1998.

[4] A. M. Soliman, 'New current mode filters using current conveyors', *AEÜ Int. J. Electron. Commun.*, **51,** (5), pp. 275-278, 1997.

[5] S. A. Mahmoud and A. M. Soliman, 'Novel MOS-C balanced-input balanced-output filter using the current feedback operational amplifier', *Int. J. Electron.*, **84**, pp. 479-485, 1998.

[6] C. Acar, and S. Ozoguz, 'High-order voltage transfer function synthesis using CCII+ based unity gain current amplifiers', *Electron. Letters*, **32**, pp. 2030-2031, 1996.

[7] E. Bruun, 'CMOS high speed, high precision current conveyor and current feedback amplifier structures', *Int. J. Electronics*, **74**, pp. 93-100, 1993.

[8] H.C. Yang and D. J Allstot, 'An active-feedback cascode current source', IEEE *Trans. on Circuits and Systems*, **37**, pp. 644-646, 1990.

[9] H.P. Schmid, and G.S. Moschytz, 'Tunable CCII-MOSFET-C filter biquads for video frequencies', *Proc. of ECCTD'97*, pp.82-87, Budapest, Hungary, 1997.

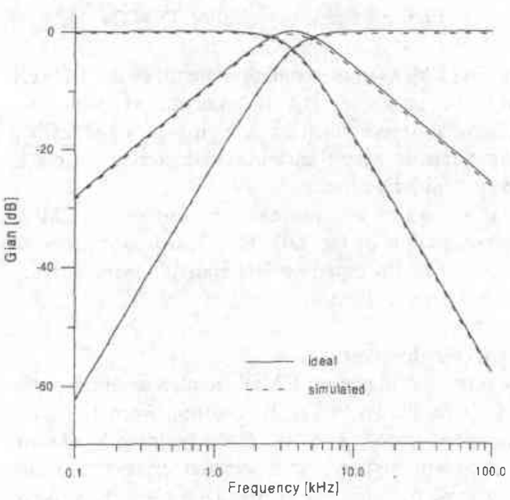

Figure 5 Frequency responses of the first CM universal filter

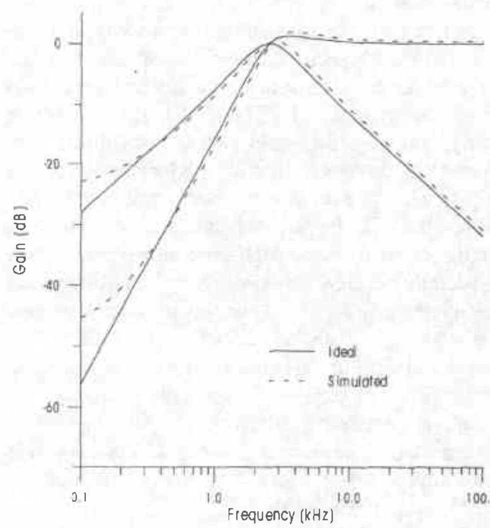

Figure 6 Frequency response of the second CM multifunction filter.