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Design of Current-Mode Gm-C Filters from the Transformation of Opamp-RC Filters

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Abstract: It is presented a method to design Current-Mode (CM) filters from the transformation of the well-known Voltage-Mode (VM) opamp-RC filters. First, it is shown the simulation of a low-frequency opamp-RC filter with stable high Q, by applying the Y-Δ transformation. Second, it is described the transformation of the VM opamp-RC filter to a VM Gm-C filter and the symbolic transfer functions of the VM Gm-C filter are derived. Third, it is shown the transformation of the VM Gm-C filter to a CM Gm-C filter and the symbolic transfer functions of the CM filter are derived to show that both, the VM and the CM Gm-C filters perform the same behavior. Finally, some guidelines are introduced to design CM filters with CMOS OTAs and current conveyors.

Key words: Analog signal processing, active filters, opamp, OTA, current conveyor, current-mode, CMOS integrated circuits

INTRODUCTION

In the literature, it has been presented the design of many active filters, known as opamp-RC (Huelsman and Allen, 1980), which have been widely used in many low-frequency applications, telecommunication networks, signal processing and conditioning circuits, communication systems, control and instrumentation. In some applications, filters with low-noise level and with stable high Q are strictly desirable to process weak signals. For instance, a low-frequency opamp-RC filter can be required to detect, measure and quantify biomedical signals, object vibrations, among others. However, as already shown in (Nobuyuki and Nakamura, 2005), to design a low-frequency filter the use of large capacitances is required to implement large RC time constants, whose realization with Integrated-Circuit (IC) technology requires of a large silicon area. This is considered a problem within the design of analog ICs, e.g., active filters. A solution to this problem within the design of active filters, is the use of the Operational Transconductance Amplifier (OTA) (Geiger and Sánchez-Sinencio, 1985), because its implementation using CMOS IC technology performs low sensitivity, low power consumption, low noise, low parasitic effects and low cost of fabrication (Sánchez-Sinencio and Silva-Martínez, 2000).

In this research is introduced a method to transform a Voltage-Mode (VM) opamp-RC filter to a Gm-C filter working in Current-Mode (CM). The case of study begins with the simulation of an already designed low-frequency opamp-RC filter with stable high Q (Nobuyuki and Nakamura, 2005), by eliminating one node by applying the transformation Y-Δ (Chua *et al*., 1987). The elimination of one node leads us to the formulation of three nodal equations, which are synthesized with OTA-C blocks having grounded capacitors, as demonstrated in (Ahmed *et al*., 2006). This process generates a VM Gm-C filter, which is transformed to a CM Gm-C filter by applying adjoint transformations (Torres and Tlelo, 2004). The symbolic expressions of the transfer functions for both, the VM and the CM Gm-C topologies are derived to demonstrate that both filters perform the same behavior.

OPAMP-RC FILTER WITH STABLE HIGH Q

In Fig. 1 is shown a low-frequency second-order opamp-RC filter with stable high Q, which has been already designed in (Nobuyuki and Nakamura, 2005). As one sees, the resistances Rya, Ryb and Ryc form a

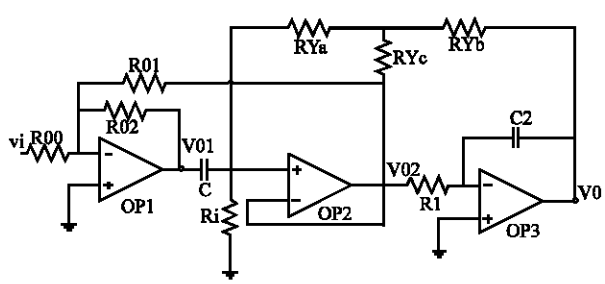

Fig. 1: Low-frequency opamp-RC filter with stable high Q

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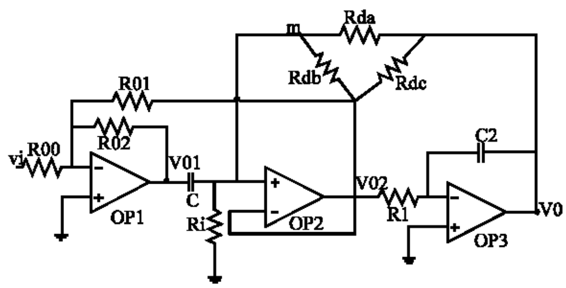

Fig. 2: Low-frequency opamp-RC filter with stable high Q, from the transformation Y-Δ

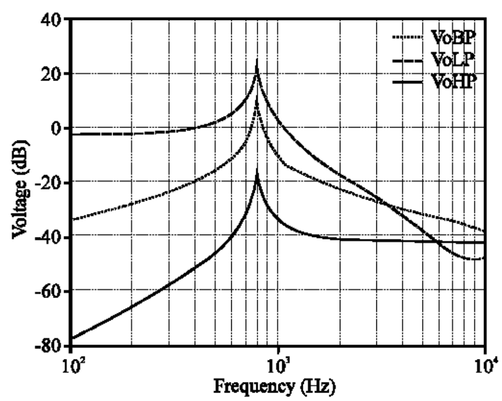

Fig. 3: Frequency response of the opamp-RC filter shown in Fig. 2

Y-type network, which include an extra node which can be eliminated by applying the transformation Y to Δ (Chua *et al.*, 1987). Indeed, this kind of transformations are quite useful to simplify passive networks, because it reduces the system of nodal equations. The transformed opamp-RC filter is shown in Fig. 2, where if Rya = Ryb = $19\times10^3\Omega$ and Ryc = $1\times10^3\Omega$, then one gets the network Δ with: Rda = $3.99\times10^5\Omega$ and Rdb = Rdc = $2.1\times10^4\Omega$.

The design of this filter for a central frequency of f_0 = 795 Hz, a quality factor of Q = 20 and by using ideal opamps, generates the following values for the elements (Nobuyuki and Nakamura, 2005): $C = C_2 = 100$ pF, R_1 = 100 KΩ, $R_{da} = 3.99\times10^5$ Ω, $R_{db} = R_{dc} = 2.1\times10^4$ Ω, R_{01} = 1 KΩ, R_{02} = 99 KΩ, R_{00} = 132 KΩ. The SPICE simulation is shown in Fig. 3, where V0 is the desired band-pass response (VoBP) and V01 and V02 are nodes simply referred to VoLP and VoHP, respectively. The results are in good agreement with Nobuyuki and Nakamura (2005) using the Δ network instead of the Y one.

TRANSFORMATION OF A VM OPAMP-RC FILTER TO A VM Gm-C FILTER

By beginning with the opamp-RC filter shown in Fig. 2 and by applying the method shown in (Ahmed *et al.*, 2006), the VM opamp-RC filter can be transformed to a VM Gm-C filter by performing two steps: formulation of nodal equations and synthesis of equations with OTA-C blocks.

Formulation of nodal equations: The goal is the formulation of the general first-order equation given by (1) in each node. This equation can be synthesized using OTA-C blocks only if (2) is used to replace C_i into (1). That way, if C_i is equivalent to C_0, G_{ci} should be fixed to G_0, so that (1) is transformed to (3). The especial cases of (1) can be expressed by (4) and (5).

$$sC_0V_0 = s\sum_n C_iV_i + \sum_m G_jV_j \tag{1}$$

$$G_{ci} = C_i\frac{G_0}{C_0} \tag{2}$$

$$sC_0V_0 = s\sum_n \frac{C_0}{G_0}G_{ci}V_i + \sum_m G_jV_j \tag{3}$$

$$sC_0V_0 = \sum_n G_iV_i \tag{4}$$

$$G_0V_0 = \sum_n G_iV_i \tag{5}$$

The formulation of a nodal equation of the type (3)-(5) from Fig. 2, begins by the selection of a node which is considered to be the output-voltage, where the outputs of the opamps have priority, while the remaining nodes are considered to be the inputs to synthesize the nodal equations. In this manner, since in Fig. 2 the node m = V_{02}, because the opamp OP2 is performing a buffer operation, then one can formulate three nodal equations, which are described by (6)-(8).

Equation 6 is formulated at the input of OP1, from which V_{02} can be evaluated. Equation 7a is formulated at the input of OP2, in this case one should to use (2) according to (7b) to get the form of (3) which is described by (7c) and from which V_{01} can be evaluated. Finally, (8) is formulated at the input of OP3, from which V_0 can be evaluated. It is important to note that by the properties of the ideal opamp and from the nodal formulation, Ri and Rdb are cancelled and Rdc does not affect the system of equations.

$$V_{02}G_{01} = -G_{00}Vi - V_{01}G_{02} \quad (6)$$

$$sCV_{01} = sCV_{02} + (V_{02} - V_0)Ga \quad (7a)$$

$$C = \frac{C_{01}}{G_{01}}G_{C1} \quad (7b)$$

$$sCV_{01} = s\frac{C_{01}}{G_{01}}G_{C1}V_{02} + (V_{02} - V_0)Ga \quad (7c)$$

$$sC_2V_0 = -G_1V_{02} \quad (8)$$

Synthesis of nodal equations: In Fig. 4 is shown the synthesis of (6), (7c) and (8) using OTA-C blocks. As one sees, the synthesis is performed by accomplishing Kirchhoff's Current Law (Chua *et al.*, 1987). This process generates circuits with grounded capacitors, which can be implemented into an IC with a smaller area than a floating capacitor, additionally a grounded capacitor can absorb the deviation caused by the shunt parasitic capacitances. The transconductances in each OTA-C block are: $G_{01} = 1\times10^{-3}$, $G_{00} = 7.5757\times10^{-6}$ and $G_{02} = 1.0101\times10^{-5}$, for Fig. 4a; $Ga = G_{01} = G_{c1} = 2.5\times10^{-6}$, for Fig. 4b and $G_1 = 1\times10^{-5}$, for Fig. 4c. By joining the synthesized blocks, the VM Gm-C filter shown in Fig. 5, is obtained.

The symbolic transfer functions of each output-voltage in the VM Gm-C filter, using the method given in (Tlelo-Cuautle *et al.*, 2004), are described by (9a), (9b) and (9c), where V_0 performs the desired band-pass behavior and V_{02} and V_{01} are simply associated to VoHP and a VoLP.

$$V_0/Vin = (sCGm_{b01}Gm_{00}Gm_1)/D(s) \quad (9a)$$

$$V_{02}/Vin = (-s^2CGm_{00}Gm_{b01}C_2)/D(s) \quad (9b)$$

$$V_{01}/Vin = -Gm_{00}\left.\begin{matrix} CC_2Gm_{c1}s^2 + Gm_{b01}C_2Gm_as \\ +Gm_{b01}Gm_aGm_1 \end{matrix}\right/ D(s) \quad (9c)$$

Where $D(s) = (CGm_{02}C_2Gm_{c1} + CC_2Gm_{a01}Gm_{b01})s^2 + Gm_{b01}Gm_{02}C_2Gm_as + Gm_{b01}Gm_1Gm_{02}Gm_a$

The SPICE simulation results of the VM Gm-C filter are shown in Fig. 6, where the behavior of the VM Gm-C filter is the same as of the VM opamp-RC filter shown in Fig. 3.

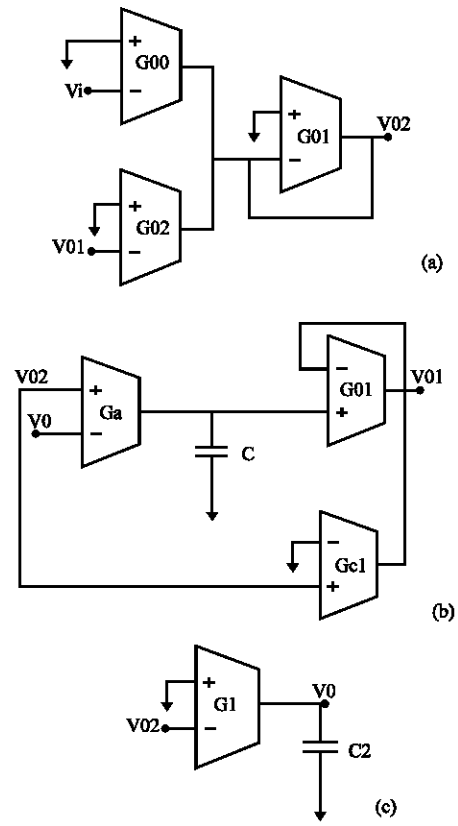

Fig. 4: (a) Synthesis of (6), (b) Synthesis of (7c) and (c) Synthesis of (8)

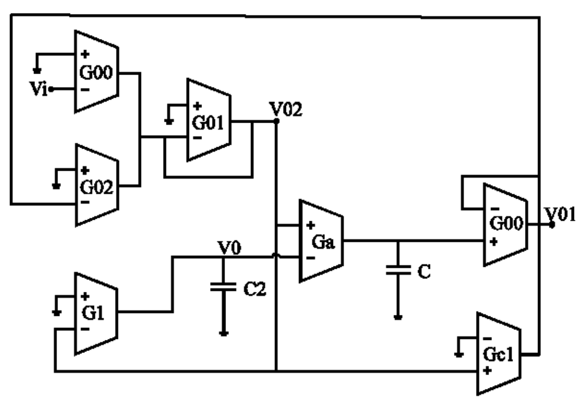

Fig. 5: VM Gm-C filter designed from the transformation of the opamp-RC filter shown in Fig. 2

TRANSFORMATION OF THE VM Gm-C FILTER TO A CM Gm-C FILTER

In (Koziel and Szezepanski, 2003) one can found several OTA-C circuits working in both VM and CM. On the other hand, Torres and Tlelo (2004) demonstrated the implementation of adjoint OTA-C filters using CMOS IC

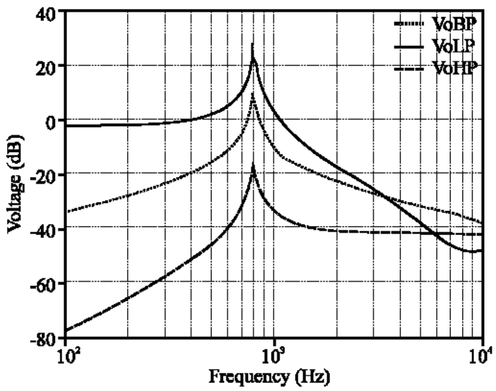

Fig. 6: Frequency response of the VM Gm-C filter, where V_0 is related to VoBP, V_{02} to VoHP and V_{01} to VoLP

technology. For instance, the rules to transform a VM OTA-C filter to a CM OTA-C filter and viceversa, are the following (Torres and Tlelo, 2004):

- Model the behavior of all OTAs using Voltage-controlled Current Sources (VCCS).
- Interchange the ports of each VCCS, but letting intact the positions of the rest of the circuit elements.
- If a voltage/current source is connected in the input port, this port is short/open circuited. Now, this becomes to be the output port used to measure current/voltage.
- If a current/voltage signal is measured at the output port, one should to connect a voltage/current source. Now, this becomes to be the input port of the adjoint circuit.

By executing this steps, one gets the adjoint circuit of the original one. It is worthy to mention that the symbolic transfer functions of both, the VM and the CM circuits, should be the same to said that they are adjoints. In this manner, by beginning with the VM OTA-C circuit shown in Fig. 5 and by applying the transformation rules, the adjoint CM OTA-C circuit is shown in Fig. 7. The VM filter has one input and three outputs, while the CM filter has one output and three inputs. The symbolic transfer functions are described by (10).

$$I_0/Iin_0 = (sCGm_{b01}Gm_{00}Gm_1)/D(s), \quad \text{with } Iin_1 = 0 \text{ and } Iin_2 = 0 \tag{10a}$$

$$I_0/Iin_2 = (-s^2CGm_{00}Gm_{b01}C_2)/D(s) \quad \text{with } Iin_0 = 0 \text{ and } Iin_1 = 0 \tag{10b}$$

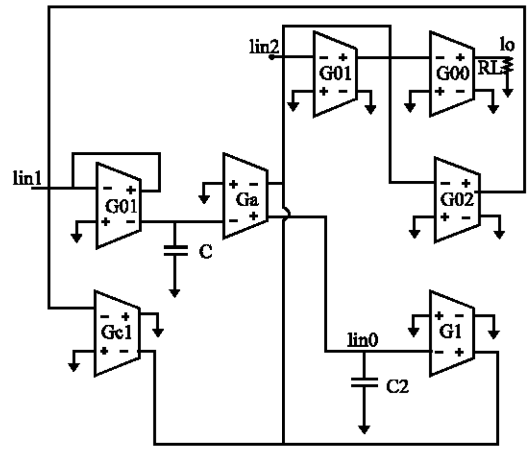

Fig. 7: CM Gm-C filter designed from the adjoint transformation of Fig. 5

$$I_0/Iin_1 = -Gm_{00}\,\frac{CC_2Gm_{c1}s^2 + Gm_{b01}C_2Gm_a s + Gm_{b01}Gm_aGm_1}{D(s)} \quad \text{with } Iin_0 = 0 \text{ and } Iin_2 = 0 \tag{10c}$$

$$D(s) = (CGm_{02}C_2Gm_{c1} + CC_2Gm_{b01}Gm_{a01})s^2 + Gm_{b01}Gm_{02}Gm_aC_2s + Gm_{b01}Gm_1Gm_{02}Gm_a$$

For the CM OTA-C filter, it is possible to add the three responses described by (10) to derive (11). Besides, the derived symbolic transfer functions shown by (10) are identical to that shown by (9), as a result, we can said the both filters are adjoints. The SPICE simulation results of the CM Gm-C filter are shown in Fig. 8, whose behavior is the same like that shown in Fig. 6.

$$I_{OUT} = \frac{(sCGm_{00}Gm_{b01}Gm_1)Iin_0 - (s^2CGm_{00}Gm_{b01}C_2)Iin_2 - \left(Gm_{00}\left(Gm_{c1}CC_2s^2 + Gm_{b01}C_2Gm_as + Gm_{b01}Gm_1Gm_a\right)\right)Iin_1}{(CGm_{02}C_2Gm_{c1} + CC_2Gm_{b01}Gm_{a01})s^2 + Gm_{b01}Gm_{02}Gm_aC_2s + Gm_{b01}Gm_1Gm_{02}Gm_a} \tag{11}$$

SYNTHESIS OF VM AND CM Gm-C FILTERS USING CMOS OTAs AND CURRENT CONVEYORS

The filters shown in Fig. 5 and 7 are adjoints. Although their symbolic transfer functions are identical, their frequency response can vary depending on the design of the transconductor to accomplish the desired value of Gm of each OTA. In this manner, the goal of an analog IC designer is to guarantee that the CMOS OTA or current conveyor perform the behavior of the Gm needed to the physical implementation of the adjoint filters. For instance, in Sánchez-Sinencio and Silva-Martínez (2000) is shown how to design CMOS OTAs and its noise characterization is described in Sánchez-López and Tlelo-Cuautle (2006). However, nowadays there is a greatest interest to use novel active devices to synthesize transconductors, such devices are known as Current Conveyors (CCs). Torres and Tlelo (2004) introduced the design of transconductors using two second generation CCs. Masmoudi *et al.* (2005) demonstrated its usefulness to design active filters. Salem *et al.* (2006) proved that CCs can reach high frequencies and Fakhfakh *et al.* (2007) introduced a symbolic procedure for noise characterization of this devices.

An analog IC designer has a trade-off to choose OTAs or CCs to design Gm-C filters. The authors recommend to use CCs because they facilitate the implementation of transconductors with multiple output-currents and because its design is based on the interconnection of voltage followers with either current followers or current mirrors. Elsewhere, in Torres and Tlelo (2004) is shown the design of CMOS CCs to synthesize a transconductor to implement Gm.

CONCLUSION

It has been introduced a method to transform VM opamp-RC filters to CM Gm-C filters. The method was applied to a second-order low-frequency opamp-RC filter with stable high Q.

The transformation process began by transforming a Y-network embedded in the original opamp-RC circuit, to a Δ network to eliminate one floating node. Second, three nodal equations were formulated from the opamp-RC circuit and the equations were arranged to have a general form suitable for synthesis purposes. Third, each equation was synthesized using OTA-C blocks to obtain a VM Gm-C filter with all capacitors connected to ground. SPICE simulation results were performed to show that the transformed VM Gm-C filter has the same frequency behavior than the opamp-RC filter. Further, the symbolic transfer functions were derived.

It were described the rules to transform a VM Gm-C filter to a CM Gm-C filter. SPICE simulations were performed to show that the adjoint CM Gm-C filter has the same frequency behavior that the original VM Gm-C filter. The symbolic transfer functions were derived to show that the VM ones are the same that the CM ones, so that one can conclude that both filters are adjoints and that they perform the same behavior than the original opamp-RC filter.

Finally, some guidelines to design the transconductors were briefly described to highlight the usefulness of current conveyors to design high-frequency active filters.

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