SIGNAL FLOW GRAPH REALIZATION OF SINGLE-INPUT FIVE-OUTPUT CURRENT-MODE UNIVERSAL BIQUAD USING CURRENT FOLLOWER TRANSCONDUCTANCE AMPLIFIERS

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Key words: Signal flow graph (SFG), Current follower tranconductance amplifier (CFTA), Biquad filter, Current-mode circuit, Resistor-less circuit.

In this paper, a design procedure for the realization of all current-mode biquadratic transfer functions is presented. The synthesis technique is deduced from a signal flow graph representation using current follower transconductance amplifiers (CFTAs). The proposed configuration has single low-impedance input and five high-impedance outputs, and comprises three CFTAs and two grounded capacitors. No passive resistor is required for the circuit realization, thus it is an active-C structure suitable for integration.

1. **INTRODUCTION**

Recently, the conception of the current follower transconductance amplifier (CFTA) has been introduced [1]. This device is slightly modified from the conventional current differencing transconductance amplifier (CDTA) [2, 3] by replacing the current differencing unit with a current follower. Thus, the CFTA element is conceptually a combination of the current follower and the multi-output operational transconductance amplifier. Consequently, several structures for realizing current-mode active filters using CFTAs were developed [4–13]. Interesting circuit realizations of universal filters using signal flow graph (SFG) can be found in [4–8]. However, the filter structures in [4, 5] require external passive resistors. In [6], the circuit provides only three second-order filtering functions at most. Moreover, the works in [7, 8] employ a lot of active components.

Therefore, this work largely focuses on presenting a general synthesis procedure for realizing all standard second-order current transfer functions. The proposed method is based on drawing a SFG directly from the given transfer function and then obtaining, from the graph, the active C filter involving CFTAs. The resulting circuit using only three CFTAs and two grounded capacitors simultaneously realizes all the five standard second-order current transfer functions, namely

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Rev. Roum. Sci. Techn.– Électrotechn. et Énerg., **59**, *2,* p. 183–191, Bucarest, 2014

lowpass (LP), bandpass (BP), highpass (HP), bandstop (BS) and allpass (AP). All capacitors used are grounded, which make the circuit especially suitable for monolithic implementation. Computer simulation results obtained from PSPICE program illustrate the properties of the proposed design procedure.

2. **CURRENT FOLLOWER TRANCONDUCTANCE AMPLIFIER (CFTA)**

The CFTA device is mainly combined by the current follower and multi-output transconductance amplifier. The circuit representation of the CFTA is shown in Fig.1, where *f* is the low-impedance input terminal and *z*, + *x*, *x* are the high-impedance output terminals. The port relations of the CFTA can be described by :

$$v_f = 0\ ,\ i_z = i_f \ \text{ and } \ i_x = g_m v_Z\ , \tag{1}$$

where g_m is the transconductance gain of the CFTA. According to above terminal equation, the current of *z*-terminal (i_z) follows the current of *f* terminal (i_f). The voltage drop at *z*-terminal (v_z) is then converted to currents at +*x* and –*x* terminals by a transconductane g_m and $-g_m$, respectively. Generally, the g_m value is adjustable over several decades by a supplied bias current/voltage, which lends electronic controllability to design circuit parameters.

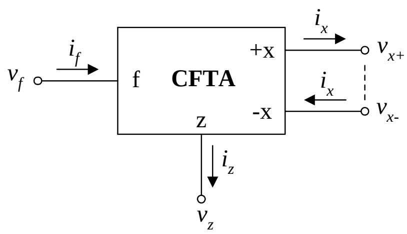

Fig. 1 – Circuit representation of the CFTA.

One possible implementation of CFTA in bipolar technology is shown in Fig. 2 [11, 12]. Transistors Q_1–Q_6 constitute a current follower stage that provides the current through the *z* terminal to follow the input current at the *f*-terminal and also exhibits the low-input resistance at the *f* terminal. The multiple-output transconductance amplifier formed by transistors Q_7–Q_{25} will convert to the currents i_x flowing through the *x* terminals. Thus, the transconductance (g_m) realized by the configuration in Fig. 2 is approximately found as :

$$g_m = \frac{I_O}{2V_T}\ , \tag{2}$$

where V_T is the thermal voltage (approximately 26 mV at 27°C) and I_O is the external bias current of the CFTA.

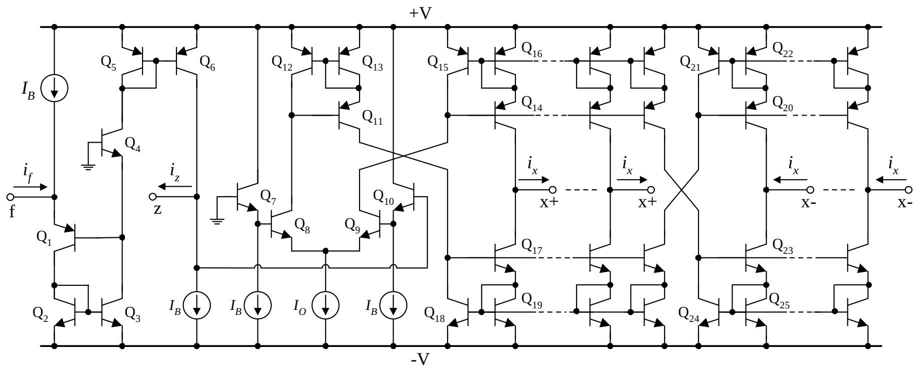

Fig. 2 – Bipolar implementation of the CFTA.

3. SFG REPRESENTATION AND CFTA REALIZATION

In this section, a SFG representation and coresponding CFTA-based circuit realization for a general biquadratic current transfer function synthesis are given. The synthesis procedure is based on drawing the SFG of the biquadratic filtering function, and then realizing the CFTA-C circuit from the given graph. In Fig. 3, the SFG for realizing a current-mode universal biquadratic filter is shown, which consists of two lossless integrators and unity-gain forward and feedback paths. According to the well-known Mason’s gain formula [14], the current transfer functions of this graph can be expressed as :

$$\frac{I_{HP}}{I_{in}} = \frac{b_2 s^2}{D(s)} \;, \quad \frac{I_{BP}}{I_{in}} = \frac{b_1 s}{D(s)} \;, \quad \frac{I_{LP}}{I_{in}} = \frac{1}{D(s)} \;,$$

$$\frac{I_{AP}}{I_{in}} = \frac{b_2 s^2 - b_1 s + 1}{D(s)} \;, \quad \frac{I_{BS}}{I_{in}} = \frac{b_2 s^2 + 1}{D(s)} \tag{3}$$

and $$D(s) = b_2 s^2 + b_1 s + 1,$$

where I_{HP}, I_{BP}, I_{LP}, I_{AP} and I_{BS} are the HP, BP, LP, AP and BS current responses, respectively. It should be noted that all the five standard biquadratic current transfer functions can be synthesized simultaneously from the graph of Fig. 3. This means that any circuit deduced from the SFG of Fig. 3 will function as a universal biquadratic filter.

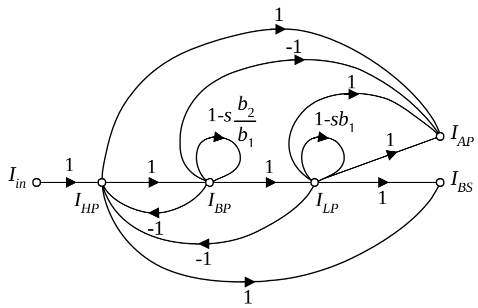

Fig. 3 – SFG for realizing general biquadratic transfer functions.

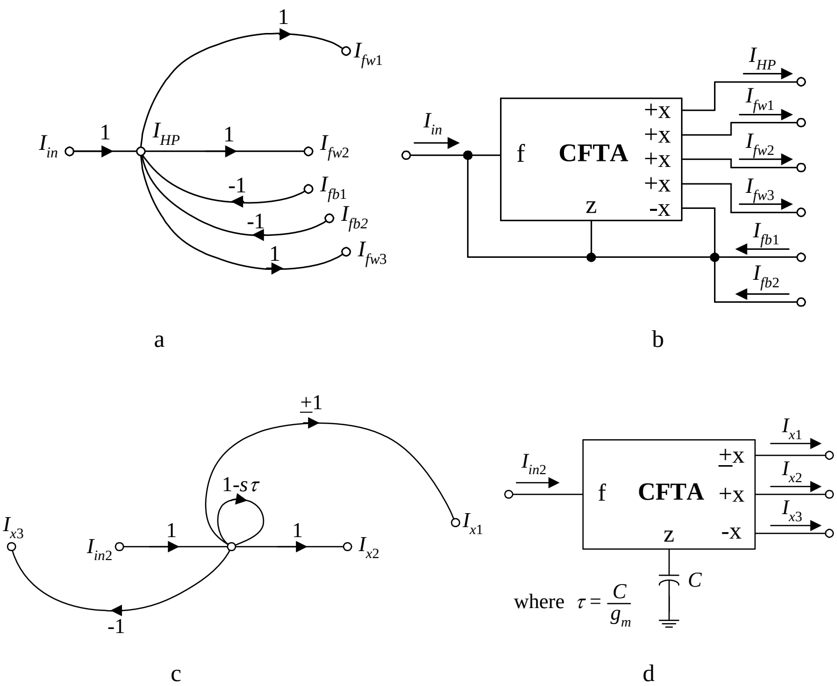

Fig. 4 – Sub-graphs and their corresponding CFTA-C sub-circuit realizations.

Considering the SFG synthesis of general biquadratic current transfer functions in Fig. 3. It is clearly seen that the graph consists of two basic operations, which are multi-output current follower and current lossless integrator, as redraw in Figs. 4 a and 4 c, respectively. Using the current and voltage relations of the CFTA given in equation (1), these two sub-graphs can be realized using CFTA by the corresponding sub-circuits as shown in Figs. 4 b and 4 d, respectively. For the CFTA-based realization, it can readily obtain the CFTA-C circuit by interconnecting the sub-circuits of Figs. 4 b and 4 d according to the overall SFG representation of

Fig. 3. Therefore, the CFTA-C circuit realizing universal second-order current transfer functions can be shown in Fig. 5. For this realization, the configuration contains three CFTAs as active elements and two capacitors as passive elements. Note that the circuit uses only grounded capacitors that is suitable for the integrated circuit implementation point of view, and also exhibits low-input impedance and high-output impedance terminals that are desirable for cascading in current-mode operation [9].

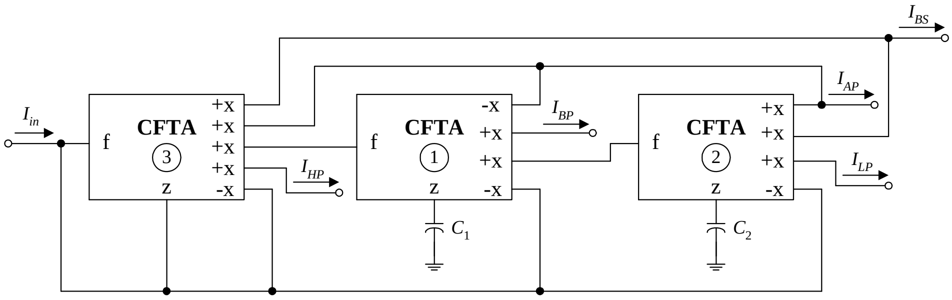

Fig. 5 – CFTA circuit realization of the SFG in Fig.3.

From Fig. 5, the design equations can be obtained through comparing Fig. 3 with Fig. 5. The results are summarized as follows :

$$\frac{b_2}{b_1} = \frac{C_1}{g_{m1}} \quad \text{and} \quad b_1 = \frac{C_2}{g_{m2}}. \tag{4}$$

Above expressions indicate that the coefficients b_i (i = 1, 2) of the realized functions can be tuned electronically by adjusting the g_{mi} value of the i-th CFTA.

In all cases, the natural angular frequency (ω_0), quality factor (Q) and bandwidth (BW) of the proposed filter are found as :

$$\omega_0 = \sqrt{\frac{g_{m1} g_{m2}}{C_1 C_2}}, \tag{5}$$

$$Q = \sqrt{\frac{g_{m2} C_1}{g_{m1} C_2}}. \tag{6}$$

It is to be noted from above relations that the resultant frequency filter provides the possibility of electronic tuning the characteristic frequency ω_0 and Q by the value of g_{m2}, independently of the parameter

$$BW = \frac{g_{m_1}}{C_1}. \tag{7}$$

4. **NON-IDEAL ANALYSIS**

In case of the non-ideal CFTA, the relationship of the terminal voltage and current given in equation (1) can be rewritten as :

$$v_f = 0 \ , \ i_z = \alpha i_f \ \text{ and } \ i_x = g_m v_Z \ , \tag{8}$$

where $\alpha = (1 - \varepsilon_i)$ and ε_i ($|\varepsilon_i| << 1$) is the current tracking error from *f* to *z* terminals of the CFTA. Therefore, taking the non-idealities of the CFTA into account, the modified parameters ω_0, *Q* and *BW* of the proposed filter given in Fig. 5 become :

$$\omega_0 = \sqrt{\frac{\mu\alpha_1\alpha_2 g_{m1} g_{m2}}{C_1 C_2}} \ , \tag{9}$$

$$Q = \sqrt{\frac{\alpha_2 g_{m2} C_1}{\mu\alpha_1 g_{m1} C_2}} \ , \tag{10}$$

$$BW = \frac{\mu\alpha_1 g_{m1}}{C_1} \ , \tag{11}$$

and

$$\mu = \frac{\alpha_3 g_{m3} r_{z3}}{1 - \alpha_3(1 + g_{m3} r_{z3})} \ , \tag{12}$$

where α_i is the parameter α of the *i*-th CFTA, and r_{z3} is the parasitic resistance at the *z*-terminal of the CFTA3.

The active and passive sensitivities of the parameters ω_0 , *Q* and *BW* for this biquad filter are calculated as below :

$$S^{\omega_0}_{\mu,\alpha_1,\alpha_2,g_{m1},g_{m2}} = -S^{\omega_0}_{C_1,C_2} = \frac{1}{2} \tag{13}$$

$$S^{Q}_{\mu,\alpha_1,g_{m1}} = -S^{Q}_{\alpha_2,g_{m2}} = -S^{Q}_{C_1} = S^{Q}_{C_2} = -\frac{1}{2} \ , \tag{14}$$

$$S^{BW}_{\mu,\alpha_1,g_{m1}} = -S^{BW}_{C_1} = 1 \ . \tag{15}$$

Sensitivity analyses show that all magnitudes of ω_0, *Q* and *BW* sensitivities are found to be not more than unity in magnitude.

5. **PERFORMANCE VERIFICATION AND DISCUSSION**

To verify the theoretical analysis, the proposed design procedure given above has been simulated with PSPICE simulation program. To implement the CFTA active device in simulations, the bipolar technology structure depicted in Fig.2 has been employed [11, 12] using transistor model PR100N (PNP) and NP100N (NPN) real process parameters. The DC supply voltages and bias current were selected as: $+V = -V = 2$ V and $I_B = 100$ μA, respectively.

As an example, the illustrative CFTA-based second-order current transfer function synthesis of Fig. 5 was designed with $f_0 = \omega_0/2\pi \cong 159$ kHz. For this purpose, the de-normalized component value were chosen as: $C_1 = C_2 = 1$ nF, $g_{m1} = 1.4$ mA/V ($I_{O1} \cong 74$ μA), $g_{m2} = 0.7$ mA/V ($I_{O2} \cong 37$ μA) and $g_{m3} = 1$ mA/V ($I_{O3} \cong 52$ μA). The simulated responses comparing with the theoretical values are shown in Figs. 6–8, respectively. From the results, it can be seen that the simulation results agree very well with theoretical predictions.

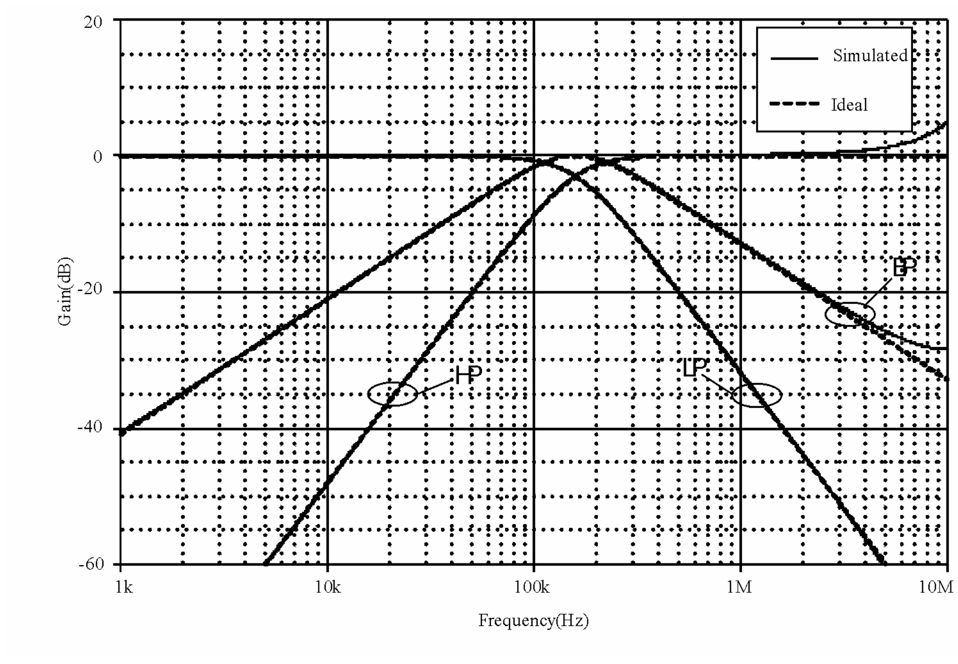

Fig. 6 – Ideal and simulated results for the LP, BP and HP current responses of the proposed circuit in Fig. 5.

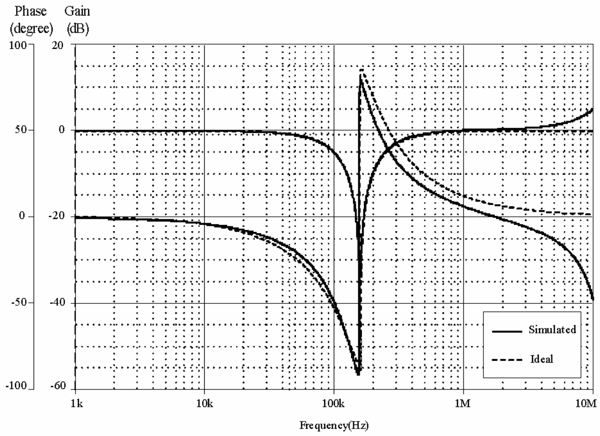

Fig. 7 – Ideal and simulated frequency characteristics for the BS response.

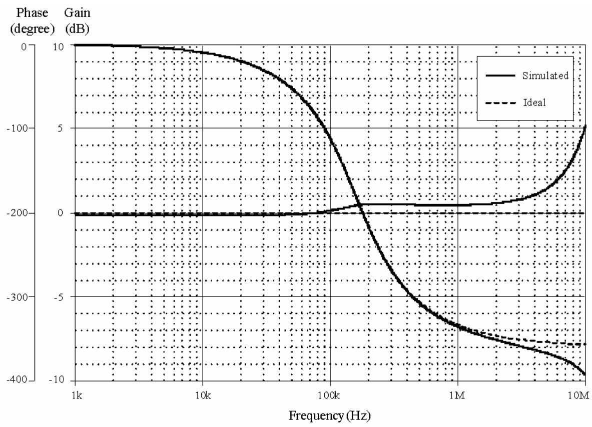

Fig. 8 – Ideal and simulated frequency characteristics for the AP response.

6. **CONCLUSION**

This work presents a synthesis procedure for realizing universal biquad filter by a resistor-less circuit. By using the SFG representation, the universal filters can be realized employing three CFTAs and two grounded capacitors. The resulting circuit obtained from the presented method is a canonical structure and especially suitable for integration. The proposed circuit can generate LB, BP, HP, BS and AP simultaneously. It has low-input and high-output impedances, and also convenient electronic controllability through the g_m value of the CFTA.

Received on 18 July, 2013

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