Current-mode Universal Biquad with Orthogonal $\omega_o$-$Q$ Tuning Using OTAs

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Abstract — A two-input two-output (TITO) current-mode universal biquad using only four dual-output operational transconductance amplifier (DO-OTAs) and two grounded capacitors is described. By appropriately connecting the input and output terminals, the proposed circuit can provide lowpass, bandpass, highpass, bandstop and allpass current responses. The filter also offers an independent electronic control of the natural frequency ($\omega_o$) and the quality factor ($Q$) through the transconductance gain ($g_m$) of the DO-OTAs. No critical matching conditions are imposed for realizing all the filter responses, and all the incremental parameter sensitivities are low.

Keywords — Operational Transconductance Amplifier (OTA), universal filter, current-mode circuit

I. INTRODUCTION

In the last few years, several realizations of universal biquadratic filters using OTAs as active elements have received considerable attention [1]-[8]. Ramirez-Angulo et al. proposed a method to implement current-mode biquad filters with transconductance amplifiers [1]. In 1994, Wu described two current-mode realizations of high-order OTA-C filters based on the simulation of a signal flow graph for general all-pole lowpass transfer function [2]. Tsukutani et al. proposed a new current-mode biquad using two operational amplifier and three multiple-output OTAs (MO-OTAs) without external passive elements [3]. In the same year, Tsukutani et al. also proposed a versatile current-mode biquad filter employing four MO-OTAs and two grounded capacitors [4]. In 1996, Sun and Fidler introduced the design technique for realizing a second-order current-mode filter by using only four dual-output OTAs (DO-OTAs) and two grounded capacitors [5]. Wu and El-Masry proposed three configurations of current-mode bandpass filters using OTAs as active components [6]. In [7], the author presented some OTA-C based filter structures with multiple inputs and multiple outputs. Chang and Pai described a universal current-mode biquad with minimum components using two MO-OTA and two grounded capacitors [8]. Although various biquadratic filter functions can be obtained from previously mentioned configurations, considerably less attention has been given to the realization of current-mode universal filters with multiple inputs and multiple outputs (MIMO). The employment of the MIMO configuration may lead to a reduction of a number of active elements for circuit realization. This type of filter provides a variety of circuit characteristic with different input and output currents, and usually does not require any parameter matching conditions. Moreover, to realize all the standard biquadratic filter functions, the configuration with multiple inputs and multiple outputs seems to be more suitable than the single input configuration.

In this paper, a new current-controlled current-mode universal biquadratic filter with two inputs and two outputs (TITO) is presented. The proposed circuit uses only four DO-OTAs and two grounded capacitors, which offers the advantage of an electronic tuning capability and is especially interested from the IC fabrication point of view. By appropriately connecting two input and two output signals, the circuit can realize all the five standard biquadratic filtering functions, i.e., lowpass (LP), bandpass (BP), highpass (HP), bandstop (BS) and allpass (AP), without critical component matching conditions. The filter provides orthogonal current controllability of the natural frequency ($\omega_o$) and the quality factor ($Q$), as well as low active and passive sensitivities. Moreover, the high-$Q$ filter can easily be obtained by properly setting the bias current ratio of the DO-OTA.

II. CIRCUIT DESCRIPTION

The circuit representation of the DO-OTA is shown in Fig.1, where its characteristic can be expressed as :

$$i_o = g_m(v^+ - v^-)$$  \hspace{1cm} (1)

where $g_m$ is the transconductance gain of the DO-OTA. In general, the $g_m$ can linearly be tuned by the bias voltage or the bias current over several decades, which lends electronic controllability to circuit parameters.

Various techniques can be used to implementation the DO-OTA. However, in this work, a possible bipolar-based realization of the DO-OTA shown in Fig.2 is chosen. As can be deduced from this circuit, the parameter $g_m$ is therefore given by:
\[ g_m = \frac{I_B}{2V_T} \]  

(2)

where \( V_T \) is the thermal voltage (26 mV at room temperature), and \( I_B \) is the bias current which is linearly adjustable over several decades [9].

\[ V_T = \frac{g_m}{2C} \]

Fig. 1: Circuit representation of the DO-OTA

\[ I_{o1} = -\left( \frac{g_m g_m 2}{C_1 C_2} \right) I_1 \frac{D(s)}{D(s)} \]

(3)

and

\[ I_{o2} = \left( \frac{g_m g_m 2}{g_{m2} C_1} \right) I_2 - \left( \frac{g_m g_m 4}{g_{m2} C_1} \right) I_1 \frac{D(s)}{D(s)} \]

(4)

where

\[ D(s) = s^2 + \left( \frac{g_m g_m 4}{g_{m3} C_1} \right) s + \left( \frac{g_m g_m 2}{C_1 C_2} \right) \]

(5)

and \( g_m (= I_B/2V_T) \) and \( I_B \) denote \( g_m \) and \( I_B \) of the \( i \)-th DO-OTA \( (i = 1, 2, 3, 4) \), respectively. From equations (3)-(5), it can be summarized as follows.

1) The LP function is realized with \( I_1 = I_{in} \), \( I_2 = 0 \) and \( I_{o1} = I_{out} \).
2) The BP function is realized with \( I_1 = I_{in} \), \( I_2 = 0 \) and \( I_{o2} = I_{out} \).
3) The BS function is realized with \( I_1 = I_2 = I_{in} \) and \( I_{o2} = I_{out} \).
4) The AP function is realized with \( I_1/2 = I_2 = I_{in} \) and \( I_{o2} = I_{out} \).
5) The HP function is realized with \( I_1 = I_2 = I_{in} \) and \( I_{o1} = I_{out} \).

Fig. 2: Circuit diagram of an ordinary DO-OTA

Fig. 3 shows the proposed current-mode universal filter with two input terminals and two output terminal. The proposed filter is mainly composed of four DO-OTAs and two grounded capacitors. The employment of only grounded capacitors conduces to integrated-circuit implementation [10-11]. From the derived filter circuit, the current transfer functions from two input signal currents \( (I_1 \) and \( I_2) \) to two output currents \( (I_{o1} \) and \( I_{o2}) \) can respectively be expressed as:

\[ g_m = \frac{I_B}{2V_T} \]  

(2)

Fig. 3: Proposed TITO current-controlled current-mode universal filter using DO-OTAs and grounded capacitors
Thus, the proposed TITO filter can realize all the five standard types of the biquadratic filtering functions from the same circuit configuration. Note also that there are no critical component-matching conditions or cancellation constraints in the design. Moreover, the circuit needs no inverting-type current input signal for realizing any biquadratic functions. The natural frequency ($\omega_0$) and the quality factor ($Q$) of the proposed filter are given by:

$$\omega_0 = \frac{g_{m1}g_{m2}}{C_1C_2}$$  \hspace{1cm} (6)

and

$$Q = \frac{g_{m3}g_{m2}C_1}{g_{m4}g_{m1}C_2}$$  \hspace{1cm} (7)

In this case, the incremental active and passive sensitivities of the parameters $\omega_0$ and $Q$ are calculated as:

$$S_{\omega_0}^{\omega_0} = S_{g_{m2}}^{\omega_0} = \frac{1}{2}, \quad S_{g_{m2}}^{\omega_0} = S_{g_{m4}}^{\omega_0} = 0$$  \hspace{1cm} (8)

$$S_{\omega_0}^{\omega_0} = S_{C_2}^{\omega_0} = \frac{-1}{2}$$  \hspace{1cm} (9)

$$S_{\omega_0}^{\omega_0} = -S_{C_1}^{\omega_0} = 1, \quad S_{C_1}^{\omega_0} = -S_{g_{m2}}^{\omega_0} = \frac{-1}{2}$$  \hspace{1cm} (10)

and

$$S_{C_1}^{\omega_0} = S_{C_2}^{\omega_0} = \frac{-1}{2}$$  \hspace{1cm} (11).

All active and passive sensitivities are not more than unity in magnitude. Thus, the proposed circuit exhibits a low sensitivity performance.

Moreover, for simplicity, if we set $C_1 = C_2 = C$ and $g_{m1} = g_{m2} = g_m = I_B/2V_T (I_B = I_{B1} = I_{B2})$, then the parameters $\omega_0$ and $Q$ from equations (6) and (7) can now be rewritten as:

$$\omega_0 = \frac{g_m}{C} = \frac{I_B}{2V_TC}$$  \hspace{1cm} (12)

and

$$Q = \frac{I_{B3}}{I_{B4}}$$  \hspace{1cm} (13).

It should be noted from equations (12) and (13) that $\omega_0$ and $Q$ can orthogonally adjustable. It means that $\omega_0$ can electronically be adjusted without affecting the parameter $Q$ by linearly varying $I_B$, whereas the $Q$-value can be tuned independently by changing the dc bias current ratio $I_{B3}/I_{B4}$. Also, the high-$Q$ biquads can be realized by appropriately setting the current ratio $I_{B3}/I_{B4}$. Moreover, the $Q$-value is also temperature independent. Although the $\omega_0$ is temperature dependent, a temperature compensation scheme can be employed [12].

III. SIMULATION RESULTS

The performances of the proposed current-mode filter of Fig.3 have been simulated using PSPICE simulation program to verify the theoretical prediction. The DO-OTA has been simulated using the bipolar structure of Fig.2 with the transistor model of PR100N (PNP) and NP100N (NPN) of the bipolar arrays ALA400 from AT&T [13]. The DC supply voltages are selected as $+V = -V = 3 \, V$.

Fig.4 shows the simulated responses of the LP, BP and HP filter functions of the proposed circuit. In simulations, equal bias current values of $I_{B1} = I_{B2} = I_{B3} = I_{B4} = 100 \, \mu A$, and capacitance values of $C_1 = C_2 = 1 \, nF$ were chosen to obtain the natural frequency of $f_0 = \omega_0/2\pi \cong 318 \, kHz$ and the quality factor of $Q = 1$. With the same bias current and capacitance values, the gain and phase responses of the BS and AP filters are respectively illustrated in Figs. 5 and 6. It can be seen from both figures that all the simulation results are found to be in good agreement with the theoretical results.

![Fig.4 : LP, BP and HP current responses of the proposed current-mode universal filter in Fig.3.](image1)

![Fig.5 : BS current response of the proposed current-mode filter.](image2)
To demonstrate the orthogonal current tuning of $f_o$, the dc bias currents $I_B$ (i.e., $I_B = I_{B1} = I_{B2}$) were simultaneously adjusted for the values 10 $\mu$A, 100 $\mu$A, 200 $\mu$A, and 500 $\mu$A, respectively, while keeping $I_{B3} = I_{B4} = 100$ $\mu$A for a constant $Q = 1$. The resulting responses of the BP filter for different bias currents $I_B$ when $C_1 = C_2 = 1$ nF are given in Fig.7.

For the controllability of the $Q$-value without disturbing $f_o$, the dc bias currents were set to be constant at $I_{B1} = I_{B2} = 100$ $\mu$A and $I_{B3} = 10$ $\mu$A. The corresponding current characteristics of the BP filter when $I_{B3}$ is varied are shown in Fig.8. It is important to note that high values of the $Q$ can be easily obtained from high values of $I_{B3}$.

IV. CONCLUSION

A TITO current-controlled current-mode universal biquadratic filter using DO-OTAs is proposed. The circuit uses only four DO-OTAs and two grounded capacitors, which is advantageous from the IC implementation point of view. The proposed filter can realize the LP, BP, HP, BS and AP current responses from the same circuit configuration without component matching conditions. The $\alpha_i$ can be adjusted electronically and independently from the tuning of the $Q$. Moreover, the high $Q$-value filter can easily be achieved by appropriately adjusting the dc bias current ratio. The filter also has low passive and active sensitivities.

REFERENCES