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doi:10.15199/48.2024.09.54

New MISO Biquad Filter Based on CCCCTAs with Current Control

***Abstract**. This study shows a current-mode Multiple-Input Single-Output (MISO) biquad filter circuit with two grounded capacitors, one grounded resistor, and two CCCCTAs, which stand for current-controlled current conveyor transconductance amplifiers. The input choice determines which filter types are applied: band-pass filter (BPF), low-pass filter (LPF), high-pass filter (HPF), band-reject filter (BRF), and all-pass filter (APF). The quality factor (Q) of the bandpass filter (BPF) can be electronically adjusted using electronic methods, and it is observed that this adjustment does not impact the pole frequency. A Monte Carlo analysis is also done to see the effect of the external passive component built into the Multiple-Input Single-Output (MISO) filter. The simulation results utilize PSPICE software to demonstrate the effectiveness and functionality of the circuit.*

***Streszczenie.** W tym badaniu pokazano obwód filtra biquad MISO (Multiple-Input Single-Output) z dwoma uziemionymi kondensatorami, jednym uziemionym rezystorem i dwoma CCCCTA, co oznacza wzmacniacze transkonduktancji przenośnika prądu sterowanego prądem. Wybór wejścia określa, które typy filtrów są stosowane: filtr pasmowy (BPF), filtr dolnoprzepustowy (LPF), filtr górnoprzepustowy (HPF), filtr odrzucający pasmo (BRF) i filtr przepustowy (APF). Współczynnik jakości (Q) filtra pasmowoprzepustowego (BPF) można regulować elektronicznie za pomocą metod elektronicznych i zaobserwowano, że ta regulacja nie wpływa na częstotliwość biegunów. Przeprowadzono również analizę Monte Carlo, aby zobaczyć wpływ zewnętrznego komponentu pasywnego wbudowanego w filtr MISO (Multiple-Input Single-Output). Wyniki symulacji wykorzystują oprogramowanie PSPICE, aby zademonstrować skuteczność i funkcjonalność obwodu. (**Nowy filtr MISO Biquad oparty na CCCCTA z kontrolą prądu**)*

Keywords: Biquad filter, Quality factor, current-control, CCCCTA
Słowa kluczowe: Filtr Biquad, współczynnik jakości, sterowanie prądem, CCCCTA
.

Introduction

A filter circuit is an electronic circuit designed to selectively pass certain frequencies of an electrical signal while attenuating others. Filter circuits are commonly used in various applications, such as audio processing, telecommunications, instrumentation, and power electronics. Biquad filters are a type of analog filter commonly used in signal-processing applications to manipulate the frequency response of a system [1]. "Biquad" stands for "bi-quadratic," indicating that the filter operates with second-order transfer functions [2]. These filters are characterized by their simplicity, versatility, and efficiency in implementing various filter responses.

In the literature, there have been a variety of filter configurations available for different voltage and current mode operations [3]. These configurations encompass a range of devices for design purposes, such as the operational transconductance amplifier (OTA) [1,3-5], differential difference transconductance amplifier (DDTA) [2], the current feedback op-amp (CFOA) [6], the second-generation current conveyor (CCII) [7], The second generation current-controlled conveyor (CCCII) [8], the fully differential current conveyor (FDCCII) [9], the dual-output second-generation, the current-controlled, current conveyor (DO-CCCII) [10], the multi-output current-controlled current conveyor (MOCCCII) [11], current-controlled conveyor transconductance amplifier (CCCTA) [12], the current-controlled current conveyor transconductance amplifier (CCCCTA) [13-20], the multiple output current-controlled current conveyor transconductance amplifier (MO-CCCCTA) [21-24], the current-controlled current follower transconductance amplifier (CCCFTA) [25], and the differential voltage current conveyor (DVCC) [26], IC LT1228 [27], the voltage differencing voltage transconductance amplifier (VDVTA) [28], the voltage differencing transconductance amplifier (VDTA)[29], the differential difference amplifier (DDA) [30], and the modified current follower transconductance amplifier (MCFTA) [30], among others.

In past designs, biquad filters have been celebrated for their numerous advantages. They offer engineers and researchers the capability to adjust pole frequencies using electronic means [1-2, 10, 12-19, 21-24, 27], decoupling the quality factor (Q) from pole frequency adjustments [1, 8, 12-13, 16, 18, 22, 24-25, 27, 31] and independently adjusting the gain of the output signal [2, 20-21]. Additionally, biquad filters provide both current and voltage output options, exhibit low sensitivity to temperature variations [1-2, 13], and boast simple design methodologies [6, 26]. However, despite their merits, biquad filters have encountered certain drawbacks in some applications. Challenges such as the inability to electronically adjust pole frequencies [6, 9, 30], limitations in Q factor adjustments [3-5, 9-11, 14-15, 17, 20-21, 23, 26, 28, 30], the necessity for floating capacitor connections [14,19,20], and a requirement for numerous components have been noted [13,24,27,31]. Moreover, achieving usable output often necessitates significant current reflections [9, 12, 15, 24, 26, 29], and some designs may only accommodate certain filter functions [4-5, 7-9, 12-13, 15-16, 19, 22, 25-27, 29].

The objective of this article is to present the MISO biquad filter circuit in current mode. The circuit proposed offers the following advantages:

- The circuit employs capacitors with ground straps.
- High-impedance outputs enable seamless integration with subsequent stages of the circuit.
- Pole Frequencies and quality factor can be controlled electronically.

Overall, the presented MISO filter circuit in current mode offers several advantages, including efficient IC utilization, high impedance output, simplified design, and electronic control of key parameters. These attributes make it well-suited for a wide range of applications requiring current mode filtering capabilities.

Circuit design

The basic data of CCCCTA

The CCCCTA was first introduced in 2007[14]. It is a basic building block that has gained popularity in designing electronic circuits. The voltage input at a high impedance is at the y terminal. The x terminal is input and can accept both voltage and current, which has an internal resistance of R_x. The z terminal is the current output at the mirror from the x terminal, which has a high impedance. The o terminal is the current output, controlled by the voltage at the Z terminal (V_Z) and transconductance gain (g_m). The ensuing hybrid matrix in the equation denoted the characteristics of an ideal CCCCTA:

$$\begin{vmatrix} I_y \\ V_x \\ I_z \\ I_o \end{vmatrix} = \begin{vmatrix} 0 & 0 & 0 & 0 \\ R_x & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & g_m & 0 \end{vmatrix} \begin{vmatrix} I_x \\ V_y \\ V_z \\ V_o \end{vmatrix}. \quad (1)$$

The controllable internal resistance R_x is controlled by an electronic through the DC bias current I_{B1} as shown in the following equation:

$$R_x = \frac{V_T}{2I_{B1}}, \quad (2)$$

and the gm is controlled by the ratio of the thermal voltage (V_T = 26 mV) and the DC bias current I_{B2}, as shown in the equation:

$$g_m = \frac{I_{B2}}{2V_T}. \quad (3)$$

The CCCCTA equivalent circuit and symbol are illustrated in Fig. 1. The internal structure of the CCCCTA utilizing BJT is depicted in Fig. 2.

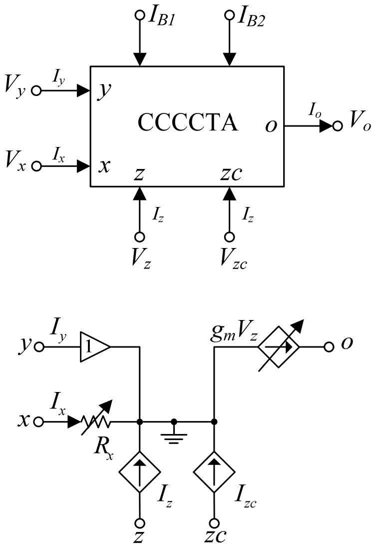

Fig. 1. The CCCCTA (a) electrical Symbol (b) Equivalent circuit

The proposed MISO biquad filter

The proposed current-mode multiple-input single-output filter is illustrated in Fig. 3. It includes two CCCCTAs, two capacitors, and one resistor. The CCCCTA characteristics are used to analyze the proposed circuit, obtaining the equation:

$$I_o = \frac{-s\frac{Rg_{m1}}{R_{x1}C_1}I_{in1} + \frac{g_{m2}}{R_{x1}C_1C_2}I_{in2} + \left(s^2 + s\frac{Rg_{m1}}{R_{x1}C_1} + \frac{g_{m2}}{R_{x1}C_1C_2}\right)I_{in3}}{s^2 + s\frac{Rg_{m1}}{R_{x1}C_1} + \frac{g_{m2}}{R_{x1}C_1C_2}}. \quad (4)$$

From equation (4), the output function (LPF, HPF, BPF, BRF, and APF) of the MISO filter can be selected from the input sig, as shown in Table 1.

Table 1. The input selections for each filter function response

Filter Responses	Input Selection		
I_o	I_{in1}	I_{in2}	I_{in3}
LPF	0	1	0
HPF	1	-1	1
BPF	1	0	0
BRF	1	0	1
APF	2	0	1

It is possible to calculate the pole frequency (ω_p) and Q of each transfer function as follows:

$$\omega_p = \sqrt{\frac{g_{m2}}{R_{x1}C_1C_2}} \quad (5)$$

and

$$Q = \frac{1}{Rg_{m1}}\sqrt{\frac{R_{x1}C_1g_{m2}}{C_2}} \quad (6)$$

When replacing $R_{x1} = \frac{V_T}{2I_{B1}}$, $R_{x2} = \frac{V_T}{2I_{B3}}$, $g_{m1} = \frac{I_{B2}}{2V_T}$, $g_{m1} = \frac{I_{B2}}{2V_T}$ and defining $C_1 = C_2 = C$ in equations (5) and (6), the pole frequency can be expressed as

$$f_p = \frac{1}{2\pi CV_T}\sqrt{I_{B1}I_{B4}} \quad (7)$$

and the quality factor is given to be

$$Q = \frac{V_T}{RI_{B2}}\sqrt{\frac{I_{B4}}{I_{B1}}}. \quad (8)$$

According to the results of equations (7) and (8), the quality factor, which is not dependent on the pole frequency, can be obtained electronically via I_{B2}.

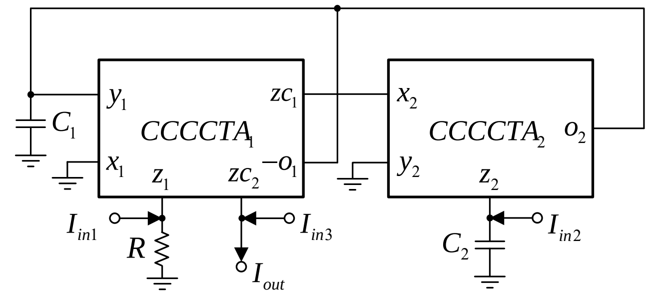

Fig. 3. The proposed MISO biquad filter

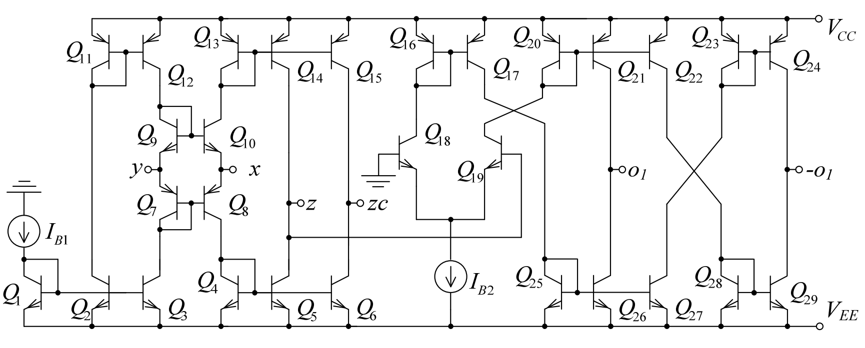

Fig.2 The structure of the CCCCTA utilizing BJT

The non-ideal analysis

The practical implementation of CCCCTA provides tracking errors for current and voltage, in addition to parasitic elements. Because errors and parasitic elements impact the efficacy of the proposed circuits, it is crucial to investigate their impact.

These tracking errors should, in an ideal arrangement, equal 1. The defective internal structures of CCCCTAs, nevertheless, are the source of their voltage and current tracking errors. These errors can be shown as a matrix:

(9)
$$\begin{vmatrix} I_y \\ V_x \\ I_z \\ I_o \end{vmatrix} = \begin{vmatrix} 0 & 0 & 0 & 0 \\ R_x & \gamma & 0 & 0 \\ \alpha & 0 & 0 & 0 \\ 0 & 0 & \pm\beta g_m & 0 \end{vmatrix} \begin{vmatrix} I_x \\ V_y \\ V_z \\ V_o \end{vmatrix}$$

The parasitic elements appearing on the y, z, and o terminals have high impedance, with each terminal having a capacitor and a resistor connected to the ground. There is internal resistance (R_{xi}) at the x terminal. Fig. 4 shows the parasitic components of CCCCTA, and when the circuit in Fig. 3 is reanalyzed, the equations can be rewritten as follows:

(10)
$$I_o = \frac{-s\dfrac{R\beta_1 g_{m1}}{R_{x1}C_1}I_{in1} + \dfrac{\beta_2 g_{m2}}{R_{x1}C_1C_2}I_{in2} + \left(s^2 + s\dfrac{R\beta_1 g_{m1}}{R_{x1}C_1} + \dfrac{\beta_2 g_{m2}}{R_{x1}C_1C_2}\right)I_{in3}}{s^2 + s\dfrac{R\beta_1 g_{m1}}{R_{x1}C_1} + \dfrac{\beta_2 g_{m2}}{R_{x1}C_1C_2}}.$$

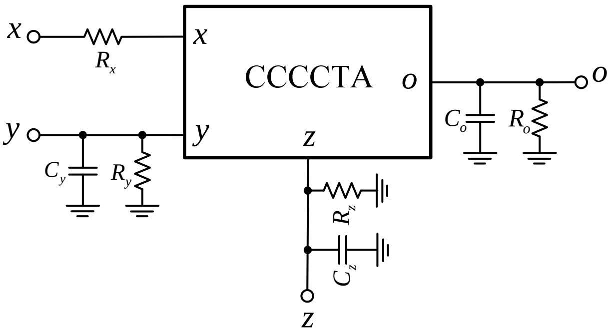

Fig.4. Parasitic component of CCCCTA

Performance Verifications

Simulation results

The theoretical analysis of the circuit proposed in Fig. 3 was verified by executing a simulation utilizing the ALA400 transistor array from AT&T, which comprises PR200N and NR200N bipolar transistors. The simulated structure of CCCCTA is illustrated in Fig. 2.

The voltage supplied is set to ±2.5 V, with capacitance values of $C_1 = C_2 = 1$ nF and a resistor value of R = 1 kΩ. The simulation is configured with Q = 1, and the pole frequency is set at 612.13 kHz, with bias currents $I_{B1} = I_{B4} = 100$ μA and $I_{B2} = 26$ μA

The output current gain of frequency response for the BPF, LPF, HPF, and BRF is depicted in Fig. 5, while the APF is illustrated in Fig. 6. The choice of filter type depends on the input selection, as specified in Table 1.

The simulation results indicate a pole frequency of 616.595 kHz. However, if calculated using equation (7), the expected pole frequency is 612.13 kHz, resulting in a deviation of approximately 0.565%. This deviation may arise from current tracking errors in the voltage and current of the CCCCTA.

Fig. 7 depicts the simulation results of the pole frequency for the Bandpass Filter (BPF) with I_{B1} and I_{B4} set to 50 μA, 100 μA, and 200 μA. The obtained pole frequency responses are 306.196 kHz, 616.595 kHz, and 1.177 MHz, respectively.

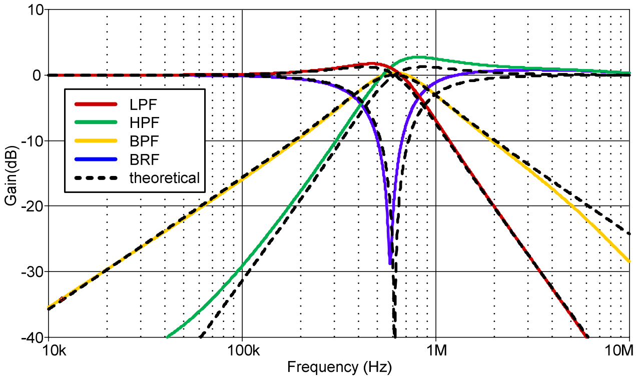

Fig. 5. The simulated results of LPF, BPF, HPF and BRF responses

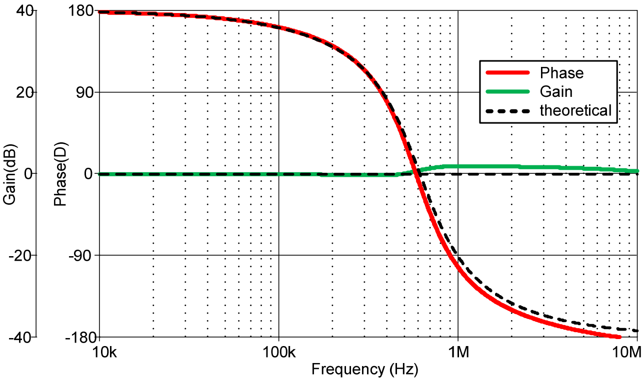

Fig. 6. The current gain and phase responses of APF

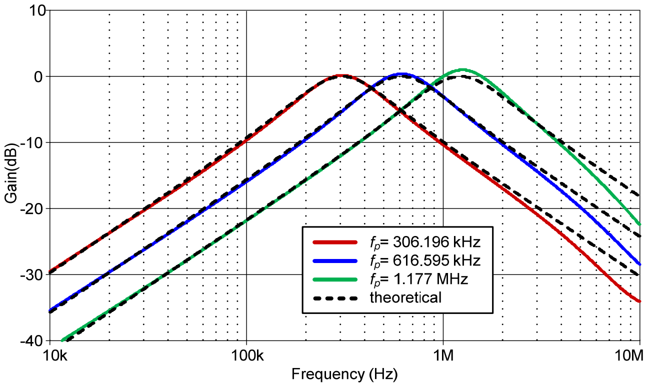

Fig. 7. The simulated of BPF responses with tuning f_p

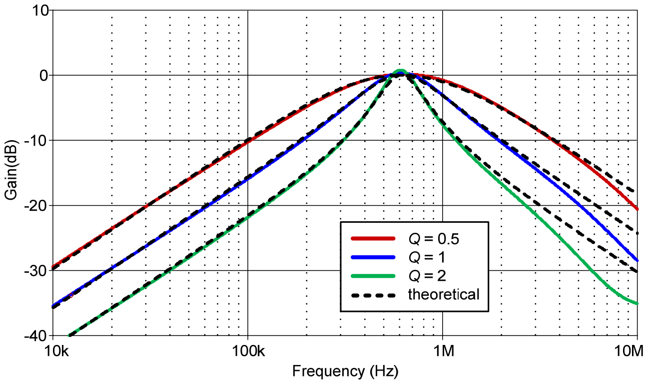

Fig. 8. The Q are varied with differences the bias currents I_{B2}

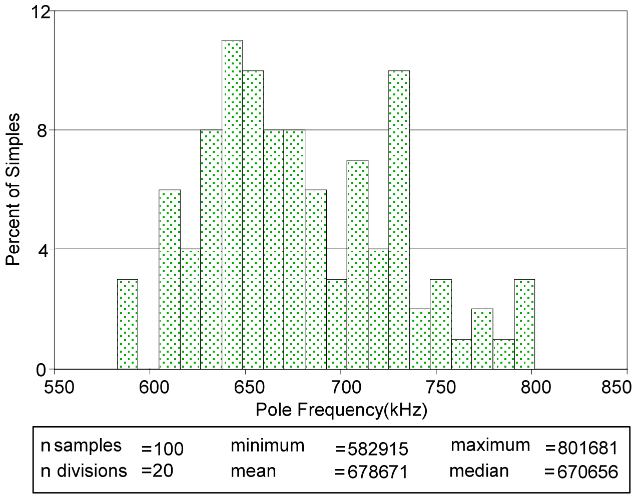

Fig. 9. Result of Monte-carlo simulation of the pole frequency

The Q of the BPF can be changed electronically by setting IB2 to 13, 26, and 52 μA, as shown in Fig. 8. This gives Q values of 0.5, 1, and 2, in that order. This adjustment is consistent with equation (8), and it is observed that it does not affect the pole frequency.

Fig. 9 shows the histogram of the analysis of the external embedded components affecting the MISO filter, referred to as the Monty Carlo analysis. The results of this analysis are the mean, median, and sigma of pole frequencies, which are 678.671 kHz, 670.656 kHz, and 502.280 kHz, respectively. The minimum pole frequency is 582.915 kHz, and the maximum frequency is 801.681 kHz.

Conclusions

The proposed new MISO biquad filter based on CCCCTAs with current control. The advantages of the presented circuit are as follows:

1. This circuit can perform five functions depending on the input signals selection.
2. The properties of pole frequency and quality factor can be controlled using electronic methods, providing independence. This means that adjustments to both parameters can be made without mutual interference.
3. The output of the circuit has a high output impedance, which makes it easier to cascade with other circuits.

All the aspects mentioned are consistent with the PSPICE software simulation results and align well with the theoretical analysis.

Financing

This research was supported by the Faculty of Engineering, Rajamangala University of Technology Isan, Khon Kaen Campus, Khon Kaen, Thailand, Contract No. ENG 11/67.

Acknowledgments

We would like to express our sincere gratitude to Asst.Prof.Dr. Adirek Jantakun and Dr. Saksit Summart for their valuable contributions to this research. Their expertise and guidance have been instrumental in the success of this paper. The Faculty of Engineering at Rajamangala University of Technology Isan, Khon Kaen Campus, Khon Kaen, Thailand, supported and funded this research.

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