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Two lossy integrator loop based current-mode electronically tunable universal filter employing only grounded capacitors

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ABSTRACT

In this paper, a novel single-input and multiple-output second-order current-mode universal filter is proposed where lossy integrator blocks, scaling blocks and summing blocks are employed. The proposed filter can simultaneously generate all the five universal filter responses namely; low-pass, high-pass, band-pass, notch and all-pass responses without requiring any critical passive component matching conditions. It uses only two grounded capacitors as passive components and BJTs as active elements; thus, it can be classified as an active-C filter. Both resonance frequency and quality factor of the proposed filter can be tuned electronically. Approximately 1.5 decades adjustable input frequency range for all the universal filter responses and high quality factor for band-pass response are obtained. Obtained PSpice simulation results confirm the theoretical design. Non-ideality and Monte Carlo analyses are also given. A practical realization of the single lossy integrator is accomplished. All the presented results are discussed.

1. Introduction

In the design of analog filters, interests in flexibility and functionality have been growing interest for the last decades. Simultaneous realization of five fundamental second-order universal filter responses and electronically controllability can provide some advantages such as adjusting sensitive calibration, flexibility, etc. In addition to these, current-mode (CM) signal processing circuits in which some parameters can be controlled by external currents have low power consumption, greater linearity, a smaller number of components and larger dynamic range, wider bandwidth when compared to voltage-mode counterparts such as operational amplifiers [1].

In the related open literature, a number of electronically tunable second-order CM filters [2]-[39] have been reported. Electronically tunable second-order CM filters can be mainly divided into four categories. The first one is use of active building blocks (ABBs) [2]-[26] such as current controlled current conveyors (CCCIIs) [2]-[18], electronically tunable current followers (CFs) [19], current controlled current conveyor transconductance amplifiers (CCCCTAs) [20], current differencing transconductance amplifiers (CDTAs) [21,22], Z-copy current follower transconductance amplifiers (ZC-CFTAs) [23]-[25] and operational transconductance amplifiers (OTAs) [26]. The second one is usage of log domain filter [27]-[34]. However, differential class-AB log domain second-order filters [27,28] use four capacitors which occupy large chip area in integrated circuit (IC) fabrication. Also, the circuit of [28] can provide only notch filter response. Class A log domain filter [33] has multiple current inputs; thus, it requires extra circuitry. The third one is use of square-root domain filters [35]-[39]. Nonetheless, they need blocks consisting of tens of MOS transistors. The topology of [36] can realize only all-pass filter response while one of [37] is not universal filter. Also, the configuration of [38] can provide only fifth-order low-pass filter response. The fourth one is direct design method. However, the best knowledge of the authors, second-order universal filters with direct design techniques have not been developed so far.

The previously published ABB based second-order CM filters [2]-[26] have the following drawbacks:

- Do not provide all the five second-order universal filter responses simultaneously [2,3,5]-[9,13]-[15,19]-[22,24]-[26].
- Do not provide second-order universal filter responses [9,21].
- Do not employ identical active devices [2,4–6,8,10]-[12,14]-[18,20,23,24,26].
- Use floating capacitor(s) [5,13,15].
- The use of capacitor number is not canonical [6,8,9].
- Output current(s) are obtained with complex combination of input current signals [3,7,14,19,20,22,26].
- Do not provide high output impedance responses [21].
- Capacitor(s) are connected in series to X terminal of the ABB [5,6,8,9,13]; accordingly, high frequency performances of the filters

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are limited [8].

- Use of OTAs as active devices [26]; thus, high frequency performances of the filters are limited [40].
- Do not provide orthogonal control of quality factor (Q) and angular resonance frequency (ω_0) [2]-[5,11,13]-[15,19], [21,26].

On the other hand, some CM filters [41–56] with lack of electronic tunability have been reported in open literature. Also, the filter of [41] simultaneously realizing all the standard second-order CM filter responses cannot have the feature of orthogonal control of Q and ω_0. The proposed second-order single input multiple output (SIMO) CM universal filter configuration has following important features:

1) It can realize all the second-order CM universal filter responses simultaneously namely low-pass (*lp*), high-pass (*hp*), band-pass (*bp*), all-pass (*ap*) and notch (*n*) responses without changing structure and/or without using additional elements,
2) It can provide high output impedance responses; thus, it can be easily cascaded with other CM circuits,
3) Its pole frequency and quality factor can be controlled electronically and orthogonally,
4) It possesses advantages of all the CM circuits,
5) It employs a minimum number of only grounded capacitors as passive components; accordingly, it is suitable for IC process [57],
6) It does not need any critical passive component matching constraints,
7) Its resonance frequency can be obtained by small-valued capacitors when compared to log domain filters [27–34],
8) It can provide high Q for band-pass response with low component spread.

The paper is organized as follows: After introduction is given in Section 1, design procedure of the proposed universal filter is presented in Section 2. In this section, architecture of the proposed circuit is described in detail by giving a block schema. Section 3 deals with non-ideality analysis of the proposed filter structure. The simulations and performance analyses of the proposed circuit are presented in Section 4. In this section, PSpice simulations are performed in order to verify the theoretical results. In order to show the availability of the proposed structure, video filter application is presented in Section 5. An experimental test is achieved in Section 6. Finally, conclusions are given in Section 7.

2. The proposed filter topology

Topology of the proposed filter shown in Fig. 1 employs two lossy integrator blocks in overall feedback loops, six summing blocks and three multiplying blocks. All the blocks can be classified in two categories: dynamic block which is an integrator block and the other is a static block. The key aspect of the proposed biquad filter architecture is lossy integrator block which is obtained by using the method presented in [58]. It should be also noted that static block designs of the diagram can be easily obtained due to CM process. Also,

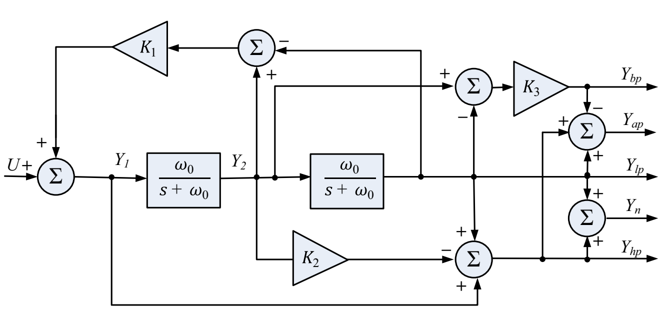

Fig. 1. Topology of the proposed filter [58].

a linear relationship which is multiplying factor among control currents can be obtained by using translinear design procedure [28].

After routine analysis of the block diagram given in Fig. 1, the relationships among outputs can be derived as given in matrix equation below.

$$\begin{bmatrix} Y_1 \\ Y_2 \\ Y_{lp} \\ Y_{hp} \\ Y_{bp} \\ Y_n \\ Y_{ap} \end{bmatrix} = \begin{bmatrix} 1 & 0 & K_1 & -K_1 & 0 & 0 & 0 & 0 \\ 0 & \frac{\omega_0}{s+\omega_0} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{\omega_0}{s+\omega_0} & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & -K_2 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & K_3 & -K_3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} U \\ Y_1 \\ Y_2 \\ Y_{lp} \\ Y_{hp} \\ Y_{bp} \\ Y_n \\ Y_{ap} \end{bmatrix} \tag{1}$$

Coefficients of the first row of matrix equation given in (1) determine Q. The matrix equation in (1) also yields respectively the following well-known five universal filter transfer functions (TFs) namely; *lp*, *hp*, *bp*, *n* and *ap* ones:

$$\frac{Y_{lp}}{U} = \frac{\omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \tag{2a}$$

$$\frac{Y_{hp}}{U} = \frac{s^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \tag{2b}$$

$$\frac{Y_{bp}}{U} = \frac{\frac{\omega_0}{Q}s}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \tag{2c}$$

$$\frac{Y_n}{U} = \frac{s^2 + \omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \tag{2d}$$

$$\frac{Y_{ap}}{U} = \frac{s^2 - \frac{\omega_0}{Q}s + \omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \tag{2e}$$

From Eq. (2e), the following phase response is obtained:

$$\phi(\omega) = -2\tan^{-1}\left(\frac{\frac{\omega\omega_0}{Q}}{\omega_0^2 - \omega^2}\right) \tag{3}$$

It is observed from Eq. (3) that phase angle varies from 0° to −360° as the frequency goes from zero to infinity. For all the cases in equations (2), ω_0 and Q depending on values of the DC current sources are given by following equations:

$$\omega_0 = \frac{I_E}{V_T C(\beta+1)} \tag{4a}$$

$$Q = \frac{1}{2-K_1} = \frac{1}{K_3} \tag{4b}$$

Here, C is capacitor value, I_E depicts DC current of BJT located in the integrator, V_T is thermal voltage defined as $V_T = kT/q$ and β is current gain [59]. The variable k represents Boltzmann constant, q is unit charge which is equal to 1.6×10^{-19}C, and T is temperature in Kelvin. Also, V_T is approximately equal to 25 mV at room temperature. It is shown from equations (4) that both of ω_0 and Q can be controlled orthogonally. For instance, by adjusting the DC current of integrator, ω_0 can be changed without disturbing Q and vice versa. Therefore, electronically tunable property is achieved. Using a single pole model [60], β can be represented as

$$\beta(\omega) = \frac{\beta_0}{1+\frac{j\omega}{\omega_\beta}} \tag{5}$$

Here, ω_β is an angular pole frequency which is ideally equal to infinity. Also, β_0 is a DC current gain of the BJT. Therefore, Eq. (4a) turns,