The Study of the Stability Response of a Versatile 3rd-Pole Active-OTA Filter for Different Values of Central Frequency f0

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Abstract— The study proposes the stability response of a versatile 3^{rd}-pole current-mode active-OTA filter for different values of f_0 with $Q = 10$. This paper illustrates a new circuit configuration for realizing the stability response of a versatile 3^{rd}-pole current-mode active-OTA filter. A new circuit configuration is composed only of three OAs with four dual current output operational transconductance amplifiers (OTAs). The Active-OTA filter can realize various 3^{rd}-pole current-mode transfer functions low-pass, band-pass, and high-pass in single circuit by suitably adjusting the current output branches. It is observed that, the low-pass filter works and extremely stable only for $f_0 \geq 25\ kHz$ with $Q = 10$ and the band-pass filter works and also is asymptotically stable for all values of f_O with $Q = 10$. The high-pass filter works and is extremely unstable for all values of f_O with $Q = 10$.

Key words: The Stability response, 3^{rd}-pole current-mode, active-OTA filter, extremely stable, asymptotically stable

I. Introduction

In recent years, the design of active filters with high performances has received much attention. In filter circuit designs, current-mode circuits are becoming popular, since they have many advantages (i.e. simplicity of signal operations, wide dynamic range, high-frequency operation, etc.) compared with their voltage-mode counterparts. Several filter designs based on active-R, active-C and active-RC syntheses have been discussed by using such active devices and passive elements [1]. Designs of current-mode filter employing active devices such as operational amplifiers (OAs), operational transconductance amplifiers (OTAs) and second generation current conveyors (CCIIs) have been reported in the literature [2-6]. Analog filters are important building blocks and widely used for continuous time signal processing [7-8]. The transconductance gain (gm), can be varied over several decades by adjusting an external DC bias current, I_{ABC}. The major limitation of existing OTAs is the restricted differential input voltage swing required to maintain linearity [9-10]. the R-filter network provides better selectivity, greater stop band attenuation and steeper cut-off at the edge of the pass band especially at higher Q-values [11].

`This paper focuses on a realization of 3^{rd}-pole current-mode active-OTA filter with a general class of circuit transfer functions using active elements only. The proposed circuit is composed only of three operational amplifiers (OAs) with four dual current output operational transconductance amplifiers (OTAs). It is shown that the circuit can realize various 3^{rd}-pole transfer functions by suitably selecting the current output branches. It is also shown that the circuit characteristics can be electronically tuned by adjusting the transconductance gains of OTAs.

II. Proposed Circuit Configuration

The proposed circuit configuration of a versatile 3^{rd}-pole current-mode active-OTA filter is as shown in Fig.1. The circuit is composed of three operational amplifiers (OAs) with four dual current output operational transconductance amplifiers (OTAs). The v_+ terminal of all operational transconductance amplifiers (OTAs) are grounded. The output terminal of the first operational transconductance amplifier carrying a positive polarity current is fed to the non-inverting terminal of the first operational amplifier and the inverting terminal of the first operational amplifier is grounded. The output of the first operational amplifier is fed to the non-inverting terminal of the second operational amplifier and to the v_- terminal of the second operational transconductance amplifier. The inverting terminal of the second operational amplifier is connected to the v_- terminal of the first operational transconductance amplifier. The output of the second operational amplifier is fed to the non-inverting of the third operational amplifier and to the v_- terminal of the third operational transconductance amplifier. The inverting terminal of the third operational amplifier is connected to the v_- terminal of the first operational transconductance amplifier. The output of the third operational amplifier is fed to the v_- terminal of the fourth operational transconductance amplifier. The output terminals of all operational transconductance amplifiers carrying the positive polarity current are fed to the inverting of the first operational amplifier, whereas the negative polarity current output terminals of all operational transconductance amplifiers are fed to give the output current of the circuit. The circuit can execute various 3^{rd}-pole current-mode transfer functions by suitably adjusting the current output branches.

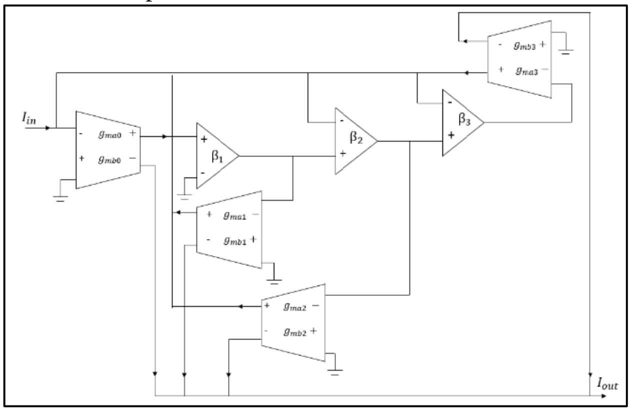

Fig. 1: A Versatile 3^{rd}-Pole Current-Mode Active-OTA Filter

III. Circuit Analysis and Design Equations

Op-amp (LF356N) is an internally compensated op-amp, which is represented by "a single-pole model",

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$$A(S) = \frac{A_0 w_0}{S} \quad (1)$$

Where,
A_0 = open loop D.C. gain, w_0= open loop -3dB bandwidth, $\beta = A_0 w_0$= gain bandwidth product of op-amplifier.

$$A(S) = \frac{A_0 w_0}{S} = \frac{\beta_i}{S} \quad (2)$$

Here $S \gg w_0$.
This shows that the op-amplifier is an "integrator". Thus, the current-mode transfer function at the output node is as follow.

$$T(s) = \frac{\alpha_3 S^3 + \alpha_2 S^2 + \alpha_1 S + \alpha_0}{x_1 S^3 + x_2 S^2 + x_3 S + x_4} \quad (3)$$

Where

$$\alpha_0 = \frac{g_{mb3}}{g_{ma0}} \beta_1 \beta_2 \beta_3$$

$$\alpha_1 = \left(\frac{g_{mb2}}{g_{ma0}} \beta_1 \beta_2 - \frac{g_{mb3}}{g_{ma0}} \beta_2 \beta_3\right)$$

$$\alpha_2 = \left(\frac{g_{mb1}}{g_{ma0}} \beta_1 - \frac{g_{mb2}}{g_{ma0}} \beta_2 - \frac{g_{mb3}}{g_{ma0}} \beta_3\right)$$

$$\alpha_3 = \frac{g_{mb0}}{g_{ma0}}$$

$$x_1 = 1$$

$$x_2 = \frac{g_{ma1}}{g_{ma0}} \beta_1 - \frac{g_{ma2}}{g_{ma0}} \beta_2 - \frac{g_{ma3}}{g_{ma0}} \beta_3$$

$$x_3 = \frac{g_{ma2}}{g_{ma0}} \beta_1 \beta_2 - \frac{g_{ma3}}{g_{ma0}} \beta_2 \beta_3$$

$$x_4 = \frac{g_{ma3}}{g_{ma0}} \beta_1 \beta_2 \beta_3$$

The circuit is designed by using coefficient matching technique i.e. by comparing this 3^{rd}-pole current-mode transfer function with the general 3^{rd}-pole current-mode transfer function [12]. The general 3^{rd}-pole current-mode transfer function is given by

$$T(s) = \frac{\alpha_3 S^3 + \alpha_2 S^2 + \alpha_1 S + \alpha_0}{S^3 + w_0\left(1 + \frac{1}{Q}\right) S^2 + w_0^2\left(1 + \frac{1}{Q}\right) S + w_0^3} \quad (4)$$

Comparing (3) with (4), we get the design equations as:

$$w_0^3 = x_4 \quad (5)$$

$$w_0^2\left(1 + \frac{1}{Q}\right) = x_3 \quad (6)$$

$$w_0\left(1 + \frac{1}{Q}\right) = x_2 \quad (7)$$

$$1 = x_1 \quad (8)$$

Using the design equations, the values of g_{ma1}, g_{ma2}, and g_{ma3} are calculated for different values of central frequency f_0 with Q-factor=10. By adjusting the parameters of numerator of 3^{rd}-pole current-mode transfer function in eq (3), the circuit configuration yields the following 3^{rd}-pole current-mode filter transfer functions:

The current transfer function for the low pass filter can be realized with, $g_{mb0} = 0$, $g_{mb1} = g_{mb2} + g_{mb3}$, $g_{mb2} = g_{mb3}$, and $\frac{g_{mb3}}{g_{ma0}} = 2.5 \times 10^{-6}$.

$$T(S)_{LP} = \frac{\alpha_0}{x_1 S^3 + x_2 S^2 + x_3 S + x_4} \quad (9)$$

The current transfer function for the band pass filter can be realized with, $g_{mb0} = 0$, $g_{mb1} = g_{mb2} + g_{mb3}$, $g_{ma3} = 0$, and $\frac{g_{mb2}}{g_{ma0}} = 1$.

$$T(S)_{BP} = \frac{\alpha_1 S}{x_1 S^3 + x_2 S^2 + x_3 S + x_4} \quad (10)$$

The current transfer function for the high pass filter can be realized with, $g_{mb1} = g_{mb2} = g_{mb3} = 0$, and $\frac{g_{mb0}}{g_{ma0}} = 1$.

$$T(S)_{HP} = \frac{\alpha_3 S^3}{x_1 S^3 + x_2 S^2 + x_3 S + x_4} \quad (11)$$

IV. SENSITIVITY

The sensitivities of w_0 and Q in this 3^{rd}-pole current-mode active-OTA filter are as follows.

w_0 Sensitivities:

$$S_{g_{ma0}}^{w_0} = -\frac{1}{3} \quad (12)$$

$$S_{g_{ma1}}^{w_0} = S_{g_{ma2}}^{w_0} = 0 \quad (13)$$

$$S_{g_{ma3}}^{w_0} = \frac{1}{3} \quad (14)$$

$$S_{\beta_1}^{w_0} = S_{\beta_2}^{w_0} = S_{\beta_3}^{w_0} = \frac{1}{3} \quad (15)$$

Q Sensitivities

$$S_{g_{ma0}}^{Q} = -\frac{11}{3} \quad (16)$$

$$S_{g_{ma1}}^{Q} = 0 \quad (17)$$

$$S_{g_{ma2}}^{Q} = -11 \frac{g_{ma2}}{(g_{ma2} - g_{ma3})} \quad (18)$$

$$S_{g_{ma3}}^{Q} = 11\left(\frac{g_{ma3}}{g_{ma2} - g_{ma3}} + \frac{2}{3}\right) \quad (19)$$

$$S_{\beta_1}^{Q} = -11\left(\frac{g_{ma2}}{g_{ma2} - g_{ma3}} - \frac{2}{3}\right) \quad (20)$$

$$S_{\beta_2}^{Q} = -\frac{11}{3} \quad (21)$$

$$S_{\beta_3}^{Q} = -11\left(\frac{g_{ma3}}{g_{ma3} - g_{ma2}} - \frac{2}{3}\right) \quad (22)$$

In w_0 and Q sensitivities, the circuit has low sensitivity to active elements. These values ensure the stability of the circuit.

V. EXPERIMENTAL SET UP

The circuit is composed only of three operational amplifiers (OAs) (LF356N) with four dual current output operational transconductance amplifiers (OTAs). The output terminals of all operational transconductance amplifiers carrying the positive polarity current are fed to the inverting of the first operational amplifier, whereas the negative polarity current output terminals of all operational transconductance amplifiers are fed to give the output current of the circuit. The circuit performance is studied for different values of f_0 with the circuit Q-factor of 10. The general operating range of this filter is 10 Hz to 6 MHz. The value of β_i (β_1=β_2=β_3) is ($2\pi \times 6.392 \times 10^6$rad/sec) for LF 356 N.

VI. RESULT AND DISCUSSION

The following observations are noticed for the stability of low-pass, band-pass and high-pass filters.

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A. The Stability Response of a Low-Pass Filter

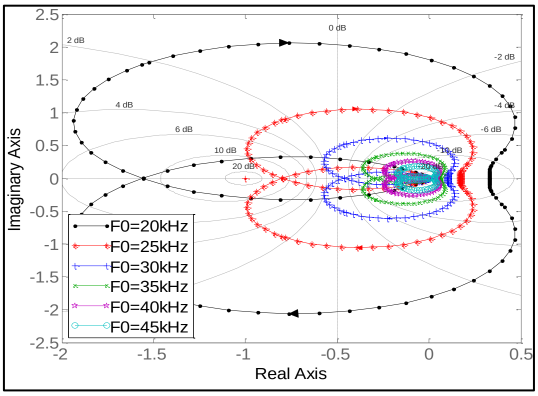

Fig. 1: Stability response of a low-pass filter with Q=10.

Low-pass filter with Q=10.							
	Gain Margin		Phase Margin		Peak Gain		
f_O(kHz)	(dB)	f_{PCO}(kHz)	(deg)	f_{GCO}(kHz)	(dB)	f_P(kHz)	Stability Status
20	-3.9	21	-18	21.8	7.36	19.9	NS
25	1.92	26.2	15.3	25.7	1.54	24.9	S
30	6.67	31.5	Inf	Inf	-3.21	29.9	S
35	10.7	36.7	Inf	Inf	-7.22	34.9	S
40	14.2	42	Inf	Inf	-10.7	39.9	S
45	17.2	47.2	Inf	Inf	-13.8	44.8	S
f_{PCO}: Phase Crossover Frequency. f_{GCO}: Gain Crossover Frequency.				f_P: Peak Frequency. S/ NS: Stable/ unstable			

Table 1: Graph analysis of Fig. 2.

The Fig. 2 is shown the stability response of a low-pass filter for different values of f_0 with Q-factor=10. The table 1 shows the data obtained from the analysis of the stability response curves shown in Fig. 2. The stability response is studied for different values of f_0 with Q = 10. It is observed that the low pass filter works $f_0 \geq 25\ kHz$ with Q = 10. It is observed that, for $f_0 \geq 25\ kHz$, the gain margin is a positive value and increases with an increase in the value of f_0. For instance, the gain margin is 1.92 dB at 26.2 kHz for $f_0 = 25\ kHz$, and is 17.2 dB at 47.2 kHz for $f_0 = 40\ kHz$. The phase margin is 15.3^0 at 25.7 kHz for $f_0 = 25\ kHz$ and for all other values of f_0, it is infinite degree. The peak gain decreases with an increase in the value of f_0. Thus, the f_0 controls the gain margin, the phase margin, and the peak gain. The low-pass filter is extremely stable only for $f_0 \geq 25\ kHz$ with $Q = 10$.

B. The Stability Response of a Band-Pass Filter

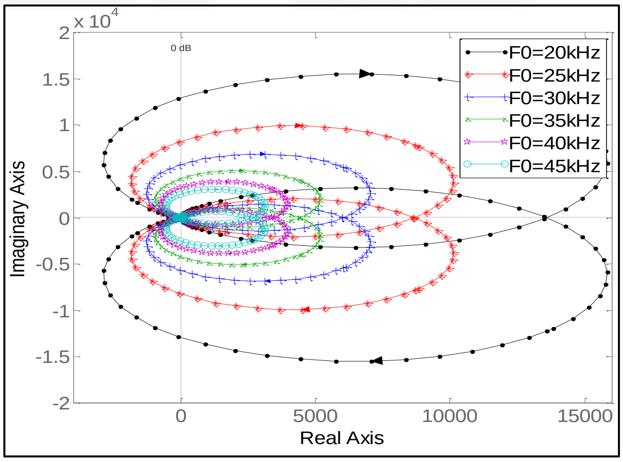

Fig. 2: Stability response of a band-pass filter with Q=10.

Band-pass filter with Q=10.							
	Gain Margin		Phase Margin		Peak Gain		
f_O(kHz)	(dB)	f_{PCO}(kHz)	(deg)	f_{GCO}(kHz)	(dB)	f_P(kHz)	Stability Status
20	Inf	Inf	1.24	1.02×10^3	85.2	20	S
25	Inf	Inf	1.55	1.02×10^3	81.4	25	S

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30	Inf	Inf	1.86	1.02×10^3	78.2	30	S
35	Inf	Inf	2.17	1.02×10^3	75.5	35	S
40	Inf	Inf	2.48	1.02×10^3	73.2	40	S
45	Inf	Inf	2.79	1.02×10^3	71.2	45	S

Table 2: Graph analysis of Fig. 3.

The stability response of a band-pass filter for different values of f_O with $Q = 10$ is shown in Fig. 3. The table 2 shows the data obtained from the analysis of the stability response curves shown in Fig. 3. The band-pass filter works for all values of f_O. It is observed that the stability response shows the gain margin of infinite dB for all values of f_O. The phase margin varies between the minimum value of 1.24^0 at $1.02\times10^3\ kHz$ for $f_O = 20\ kHz$ to the maximum value of 2.79^0 at $1.02\times10^3\ kHz$ for $f_O = 45\ kHz$. The peak gain decreases with an increase in the value of f_O. Therefore, the central frequency controls the phase margin, and the peak gain. The band-pass filter with respect to f_O is asymptotically stable for all values of f_O with $Q = 10$.

C. *The Stability Response of a High-Pass Filter*

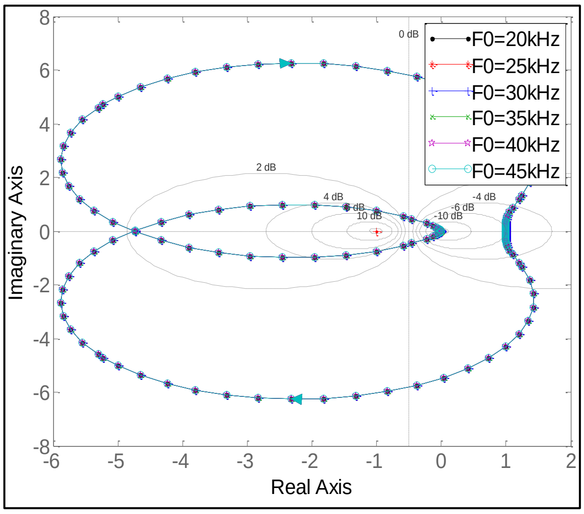

Fig. 3: Stability response of a high-pass filter with Q=10.

High-pass filter with Q=10.							
	Gain Margin		Phase Margin		Peak Gain		
f_O(kHz)	(dB)	f_{PCO}(kHz)	(deg)	f_{GCO}(kHz)	(dB)	f_P(kHz)	Stability Status
20	-13.6	19.1	39.9	15.8	17	20.1	NS
25	-13.6	23.8	39.9	19.7	17	25.1	NS
30	-13.6	28.6	39.9	23.7	17	30.1	NS
35	-13.6	33.4	39.9	27.6	17	35.1	NS
40	-13.6	38.1	39.9	31.6	17	40.1	NS
45	-13.6	42.9	39.9	35.5	17	45.1	NS

Table 3: Graph analysis of Fig. 4.

The Fig. 4 shows the stability response of a high-pass filter for different values of center frequency with $Q = 10$. The table 3 shows the data obtained from the analysis of the stability response curves shown in Fig. 4. It is observed that the high-pass filter works for all values of f_O. The gain margin with respect to f_O is a negative value for all values of f_O. The stability response shows the phase margin of 39.9^0 for all the values of f_O. The peak gain is 17 dB for all values of f_0. Therefore, the central frequency does not control the gain margin, the phase margin and the peak gain. Then, the high-pass filter with respect to f_O is extremely unstable for all values of f_O with $Q = 10$.

VII. Concluding Remarks

A versatile 3rd-pole current-mode active-OTA filter using OTAs and OAs has been proposed. It has been seen that the proposed circuit configuration can realize the low-pass, the band-pass and the high-pass filter functions. It is also shown that the circuit characteristics can be electronically tuned by adjusting the transconductance gains of OTAs. The proposed circuit configuration has very low sensitivity to the circuit active elements. the low-pass filter works and extremely stable only for $f_0 \geq 25\ kHz$ with $Q = 10$ and the band-pass filter works and also is asymptotically stable for all values of f_O with $Q = 10$. The high-pass filter works and is extremely unstable for all values of f_O with $Q = 10$.

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