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# The Effect of Changing Q-factor on the Stability Response of Active-R Filter using Op-amps

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**Abstract:- This article illustrates a new configuration to realize the stability of third order active-R filter. If the resistive voltage-dividers have high input impedance and low output impedance, the circuit realizes concurrently three transfer functions low-pass, band-pass, and high-pass concurrently in single circuit with work at different nodes with gratified results. It observed that, the low-pass filter works for all values of quality factor and is extremely stable only when the quality factor is less or equal to one. Whereas, the band-pass filter works and is asymptotically stable for all values of quality factor. The high pass filter works for all values of quality factor and is asymptotically stable only when the quality factor is less or equal to one. The circuit has also low sensitivity to passive and active elements. From the results, it can be seen that when the quality factor is less or equal to one, the circuit has excellent low-pass performance and high-pass performance and for all values of quality factor, the circuit has excellent band-pass performance.**

***Keywords:-*** *Filter; Stability response; Third order; Active-R; Quality factor; OTA, Op-amp.*

## I. INTRODUCTION

A filter is basically a device designed to isolate, suppress or pass a group of signals from a combination of signals. Filters are widely used in signal processing, communications systems and in the electronic instrumentation.

Electrical Filters can be categorized at many stages based on the type of signals processed into analog and digital filters, based on the type of elements used in their construction into passive and active filters, and based on the type of function achieved into low pass, band pass, high pass and band stop (reject) filters.

Passive and active filters are distinguished by the passivity of the elements used in their construction. If an element needs power or unable of power gain, then it is known as a passive element. An element that is not passive is known as active elements.

Passive filters are constructed completely with passive elements i.e. (resistors, capacitors, and inductors) and do not use any active elements or power supply. An active filter uses an active element such as operational amplifiers, transistors, and operational transconductance amplifiers along with or without use any passive elements. The most used of filters are low pass, band pass, high pass, band stop (band reject) and all pass filters.

In recent years, the current mode analogue signal processing circuit techniques have received wide attention due to the high accuracy, the wide signal bandwidth, and the simplicity of implementing signal operations [1-2]. In filter circuit designs, current-mode active-R filters are becoming popular since they have many advantages compared with their voltage-mode counter parts, the current-mode active-R filters have large dynamic range, higher bandwidth, greater linearity, simple circuitry, low power consumption, etc. [3-4]. In filter circuit designs, current-mode filters are becoming popular since they have many advantages compared with their voltage-mode counter parts, the current-mode filters have large dynamic range, higher bandwidth, greater linearity, simple circuitry, and low power consumption etc, [5-6]. This

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article proposes a new circuit configuration for realizing concurrently $3^{rd}$-order active-R low pass, band pass, and high pass filters. The circuit configuration, circuit analysis, and designed equations have been discussed for different values of Q-factor. This active-R filter is designed with operational amplifiers, and resistors with three resistive voltage-dividers only.

## II. PROPOSED CIRCUIT CONFIGURATION

The proposed circuit configuration for realizing multiple-output $3^{rd}$-order active-R filter with feedforward input signal is shown in Figure 1. The circuit contains three OAs, and four resistors with three resistive voltage-dividers. Resistors (formed by $g_{ia}$ and $g_{ib}$) assist the resistive voltage-divider arrangement. The input sinusoidal low current signal is fed to the inverting terminal of the first op-amp, through the first resistive voltage-divider (formed by $g_{1a}$ and $g_{1b}$). The non-inverting terminal of the first op-amp, is grounded. The output of the first op-amp, is connected to the non-inverting terminal of the second op-amp, through the second resistive voltage-divider (formed by $g_{2a}$ and $g_{2b}$). The feed forward input sinusoidal signal is given to the inverting terminal of the second op-amp. The output of the second op-amp, is connected to the non-inverting terminal of the third op-amp, through the third resistive voltage-divider (formed by $g_{3a}$ and $g_{3b}$). The inverting terminal of the third op-amp, is grounded. If the resistive voltage-dividers have high input impedance and low output impedance the circuit attains the low pass, the band pass, and the high filters at three different nodes. The low pass, the band pass, and the high pass filters are as shown in Figure 1.

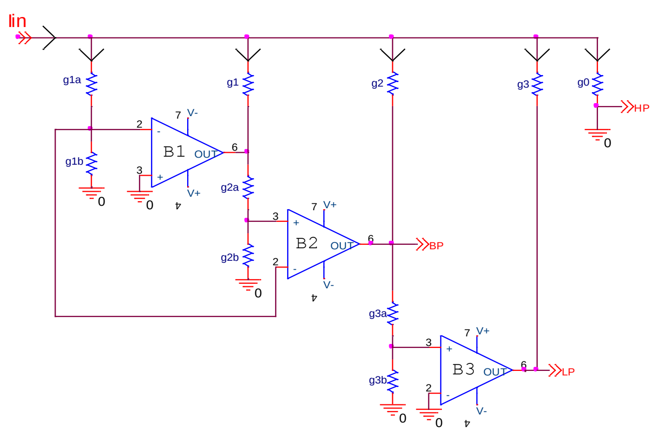


Fig 1 Circuit diagram of $3^{rd}$-order active-R filter.

*A Circuit Analysis and Design Equations:*

The open loop gain of an operational amplifier (LF356N) is an internally compensated op-amp, which is represented by a “single-order model”:

$$A(s) = (A_0 w_0/(S + w_0)) \qquad (1)$$

Where,

$A_0$ = open loop D.C. gain of op-amp, $w_0$= open loop -3dB bandwidth, β = $A_0 w_0$= gain bandwidth product of op-amplifier and S is the complex frequency variable.

For $S \gg w_0$.

$$A(s) = (A_0 w_0/S) = \beta_i/S \quad where\ i = 1,2,3, \ldots \qquad (2)$$

This shows that the op-amplifier is an “integrator”. Thus, the current-mode transfer functions of low pass, band pass and high pass are calculated as:

The current-mode transfer function for the low pass filter is given by:

$$T(S)_{LP} = \frac{k_1 k_2 k_3 \beta_1 \beta_2 \beta_3 g_3}{a_1 S^3 + a_2 S^2 + a_3 S + a_4} \qquad (3)$$

The current-mode transfer function for the band pass filter is given by:

$$T(S)_{BP} = \frac{k_1 k_2 \beta_1 \beta_2 g_2 S}{a_1 S^3 + a_2 S^2 + a_3 S + a_4} \qquad (4)$$

The current-mode transfer function for the high pass filter is given by:

$$T(S)_{HP} = \frac{g_0\, S^3}{a_1 S^3 + a_2 S^2 + a_3 S + a_4} \qquad (5)$$

Where

| | |
|---|---|
| $a_1 = g_0 + g_1 + g_2 + g_3$ | $k_1 = \{g_{1a}/(g_{1a} + g_{1b})\}$ |
| $a_2 = k_1\beta_1 g_1 + k_1\beta_2 g_2$ | $k_2 = \{g_{2a}/(g_{2a} + g_{2b})\}$ |
| $a_3 = k_1 k_2 \beta_1 \beta_2 g_2 + k_1 k_3 \beta_2 \beta_3 g_3$ | $k_3 = \{g_{3a}/(g_{3a} + g_{3b})\}$ |
| $a_4 = k_1 k_2 k_3 \beta_1 \beta_2 \beta_3 g_3$ | |

The circuit is designed using the coefficient matching technique i.e., by comparing the coefficients of denominator of the transfer functions with the coefficients of denominator of the general $3^{rd}$-order transfer function [7]. The general $3^{rd}$-order transfer function is given by:

$$T(s) = \frac{\alpha_3 S^3 + \alpha_2 S^2 + \alpha_1 S + \alpha_0}{S^3 + w_0\left(1+\frac{1}{Q}\right)S^2 + w_0^2\left(1+\frac{1}{Q}\right)S + w_0^3} \quad (6)$$

By comparing the coefficients of denominator of equations (3), (4), and (5) with the coefficients of denominator of equation (6), we get the design equations as:

$$g_0 + g_1 + g_2 + g_3 = 1 \quad (7)$$

$$k_1\beta_1 g_1 + k_1\beta_2 g_2 = w_0\left(1+\frac{1}{Q}\right) \quad (8)$$

$$k_1k_2\beta_1\beta_2 g_2 + k_1k_3\beta_2\beta_3 g_3 = w_0^2\left(1+\frac{1}{Q}\right) \quad (9)$$

$$k_1k_2k_3\beta_1\beta_2\beta_3 g_3 = w_0^3 \quad (10)$$

Using these equations, the values of $R_0 = \frac{1}{g_0}$, $R_1 = \frac{1}{g_1}$, $R_2 = \frac{1}{g_2}$, and $R_3 = \frac{1}{g_3}$ are calculated for different values of Q and $f_O$.

## III. SENSITIVITY

The passive and active sensitivities with respect to the parameters $g_0.g_1.g_2.g_3.k_1.k_2.k_3.\beta_1.\beta_2$ and $\beta_3$ are given by:

### A. $\boldsymbol{w_0}$ *Sensitivities:*

$$S_{g_0}^{w_0} = -\frac{1}{3}g_0 \quad (11)$$

$$S_{g_1}^{w_0} = -\frac{1}{3}g_1 \quad (12)$$

$$S_{g_2}^{w_0} = -\frac{1}{3}g_2 \quad (13)$$

$$S_{g_3}^{w_0} = -\frac{1}{3}\{g_3 - 1\} \quad (14)$$

$$S_{k_1}^{w_0} = S_{k_2}^{w_0} = S_{k_3}^{w_0} = \frac{1}{3} \quad (15)$$

$$S_{\beta_1}^{w_0} = S_{\beta_2}^{w_0} = S_{\beta_3}^{w_0} = \frac{1}{3} \quad (16)$$

### B. *Q Sensitivities:*

$$S_{g_0}^{Q} = -\frac{1}{3}(1+Q)g_0 \quad (17)$$

$$S_{g_1}^{Q} = -\frac{1}{3}(1+Q)g_1 \quad (18)$$

$$S_{g_2}^{Q} = -\frac{1}{3}(1+Q)g_2\left\{\frac{3}{(g_2+g_3)} - 1\right\} \quad (19)$$

$$S_{g_3}^{Q} = -\frac{1}{3}(1+Q)\left\{\frac{3g_3}{(g_2+g_3)} - (g_3+2)\right\} \quad (20)$$

$$S_{k_1}^{Q} = -\frac{1}{3}(1+Q) \quad (21)$$

$$S_{k_2}^{Q} = -\frac{2}{3}(1+Q)\left\{\frac{3g_2}{2(g_2+g_3)} - 1\right\} \quad (22)$$

$$S_{k_3}^{Q} = -\frac{2}{3}(1+Q)\left\{\frac{3g_3}{2(g_2+g_3)} - 1\right\} \quad (23)$$

$$S_{\beta_1}^{Q} = -\frac{2}{3}(1+Q)\left\{\frac{3g_2}{2(g_2+g_3)} - 1\right\} \quad (24)$$

$$S_{\beta_2}^{Q} = -\frac{1}{3}(1+Q) \quad (25)$$

$$S_{\beta_3}^{Q} = -\frac{2}{3}(1+Q)\left\{\frac{3g_3}{2(g_2+g_3)} - 1\right\} \quad (26)$$

In $w_0$ sensitivities, the passive sensitivities are smaller than unity, whereas the active sensitivity values are one third in magnitude. In Q sensitivities, the passive and the active

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sensitivities are smaller than unity. These values ensure the stability of the circuit.

## IV. RESULTS AND DISCUSSION

The circuit performance is studied for different values of Q-factor with a particular value of central frequency for the low pass, the band pass, and the high pass filters. The general operating range of this filter is 10 Hz to 6.392 MHz. The value of$\beta_i$ ($\beta_1 = \beta_1 = \beta_1$ is 2π (6.392) $\times 10^6 rad/sec$, and $k_i$ ($k_1 = k_2 = k_3$) is 0.5 mS.

Table 1 Resistors values for low pass, band pass, and high pass filters, with $f_O = 20\,kHz$.

| Q | $R_0$ (kΩ) | $R_1$ (kΩ) | $R_2$ (Ω) | $R_3$ (Ω) |
|---|---|---|---|---|
| 0.1 | 931.2 | 68.4 | 430.52 | 0.25 |
| 0.5 | 981.2 | 18.66 | 117.24 | 0.25 |
| 1 | 987.5 | 12.44 | 78.08 | 0.25 |
| 5 | 992.5 | 7.46 | 46.75 | 0.25 |
| 10 | 993.1 | 6.84 | 42.83 | 0.25 |
| 20 | 993.43 | 6.53 | 40.87 | 0.25 |

### *A. Stability Response of low pass filter for different values of Q-factor.*

The Figure 2 shows the stability response of a low pass filter for different values of Q-factor. The table 2 shows the data obtained from the analysis of the stability response curves shown in Figure 2. It is observed that the low pass filter works for Q ≥ 0.1. The gain margin decreases with an increase in the value of Q-factor, and is a positive value only for Q ≤ 1. For instance, it is 41.6 dB at 66.3 kHz for Q = 0.1 and is 9.54 dB at 28.3 kHz for Q = 1. Therefore, the low pass filter with respect to Q-factor is asymptotically stable only for Q ≤ 1 with $f_O = 20\,kHz$. The stability response shows the phase margin of $179^0$ at 0.173 kHz for Q =1. The peak gain takes place at 0 dB for Q ≤ 1, and for all other values of Q, it increases with an increase in the value of Q-factor.

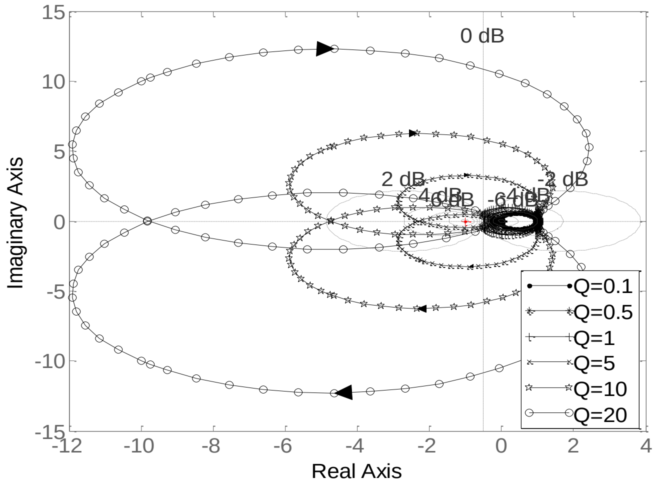


Fig 2 Stability response of a low pass filter with $f_O = 20\,kHz$.

Table 2 Graph analysis of Figure 2

| Q | Gain Margin ($G_M$) | | Phase Margin ($P_M$) | | Peak Gain | | Stability Status |
|---|---|---|---|---|---|---|---|
| | (dB) | $f_{GCO}$ (kHz) | (deg) | $f_{PCO}$ (kHz) | (dB) | $f_P$ (kHz) | |
| 0.1 | 41.6 | 66.3 | -180 | 0 | 0 | $4.04\times10^{-8}$ | *S* |
| 0.5 | 18.1 | 34.6 | -180 | 0 | 0 | $4\times10^{-16}$ | *S* |
| 1 | 9.54 | 28.3 | 179 | 0.173 | 0 | 0.04 | *S* |
| 5 | -7.13 | 21.9 | -27.7 | 25.1 | 10 | 20 | *NS* |
| 10 | -13.6 | 21 | -39.9 | 25.3 | 16 | 20 | *NS* |
| 20 | -19.8 | 20.5 | -45.9 | 25.4 | 22 | 20 | *NS* |

### *B. Stability Response of band pass filter for different values of Q-factor.*

The Figure 3 shows the stability response of a band pass filter for different values of quality factor Q. The table 3 shows the data obtained from the analysis of the stability response curves shown in Figure 3. The stability response is studied for quality factors (0.1, 0.5,1,5,10 and 20), with $f_O = 20\,kHz$. The band pass filter works for Q ≥ 0.1. The gain margin with respect to Q is infinite dB. Accordingly, the band pass filter with respect to Q-factor is extremely stable for all values of Q with $f_O = 20\,kHz$. The phase margin varies between the maximum value of $171^0$ at 7.88 kHz for Q =0.1 to the minimum value of $41^0$ at 27.1 kHz for Q =20. The peak gain varies from the minimum value of 0 dB at 6.9 kHz for Q =0.1 to the maximum value of 21.1 dB at 20 kHz for Q =20.

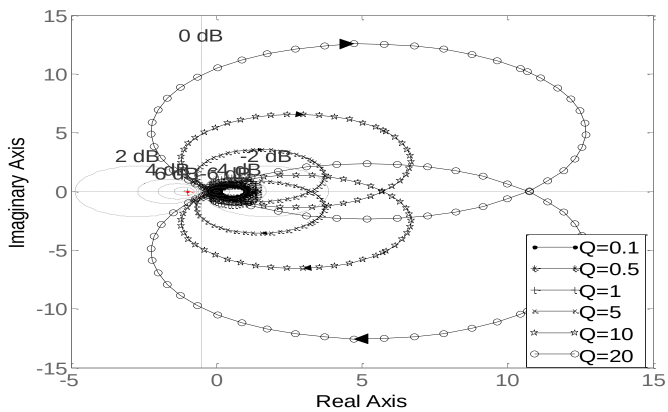


Fig 3 Stability response of a band pass filter with $f_O = 20\,kHz$.

Table 3 Graph Analysis of Figure 3

| Q | Gain Margin ($G_M$) | | Phase Margin ($P_M$) | | Peak Gain | | Stability Status |
|---|---|---|---|---|---|---|---|
| | (dB) | $f_{GCO}$ (kHz) | (deg) | $f_{PCO}$ (kHz) | (dB) | $f_P$ (kHz) | |
| 0.1 | Inf | Nan | 171 | 7.88 | 0 | 6.9 | $S$ |
| 0.5 | Inf | Nan | 127 | 22.1 | 1.2 | 14.5 | $S$ |
| 1 | Inf | Nan | 94.2 | 27.2 | 3.2 | 18 | $S$ |
| 5 | Inf | Nan | 52.4 | 27.8 | 12.3 | 20 | $S$ |
| 10 | Inf | Nan | 45.1 | 27.4 | 17 | 20 | $S$ |
| 20 | Inf | Nan | 41 | 27.1 | 21.1 | 20 | $S$ |

*C. Stability Response of high pass filter for different values of Q-factor.*

The Figure 4 shows the stability response of a high pass filter for different values of Q-factor. The table 4 shows the data obtained from the analysis of the stability response curves shown in Figure 4. The high pass filter works for all values of Q. It is observed that the gain margin with respect to Q decreases down with an increase in the value of Q-factor and is a positive value only for Q ≤ 1. For instance, it is 42.2 dB at 6.03 kHz for Q =0.1 and is 9.65 dB at 14.1 kHz for Q =1. Hence, the high pass filter with respect to Q is asymptotically stable only for Q ≤ 1 with $f_O = 20\ kHz$. The stability response shows the phase margin of infinite degree for Q ≤ 1. The peak gain takes place almost at 0 dB for Q ≤ 1, and for Q > 1, it increases with an increase in the value of Q-factor.

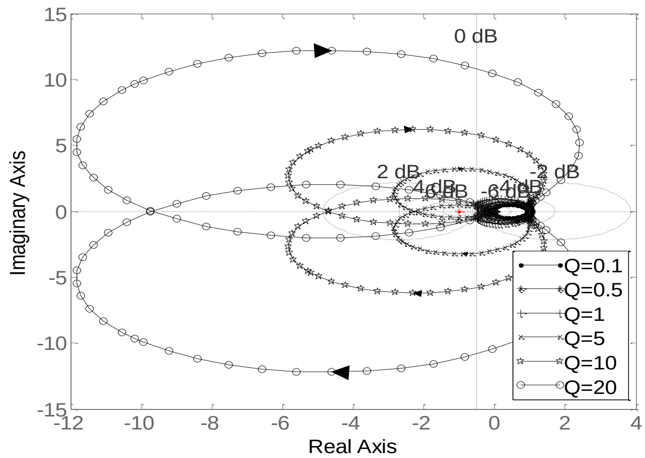


Fig 4 Stability response of a high pass filter with $f_O = 20\ kHz$.

Table 4 Graph Analysis of Figure 4

| Q | Gain Margin ($G_M$) | | Phase Margin ($P_M$) | | Peak Gain | | Stability Status |
|---|---|---|---|---|---|---|---|
| | (dB) | $f_{GCO}$ (kHz) | (deg) | $f_{PCO}$ (kHz) | (dB) | $f_P$ (kHz) | |
| 0.1 | 42.2 | 6.03 | Inf | Nan | -0.3 | $1.59\times10^{16}$ | $S$ |
| 0.5 | 18.2 | 11.5 | Inf | Nan | 0 | $1.59\times10^{16}$ | $S$ |
| 1 | 9.65 | 14.1 | Inf | Nan | 0 | $1\times10^{9}$ | $S$ |
| 5 | -7.07 | 18.3 | 27.5 | 16 | 10.8 | 20 | $NS$ |
| 10 | -13.5 | 19.1 | 39.8 | 15.8 | 16.8 | 20 | $NS$ |
| 20 | -19.7 | 19.5 | 45.8 | 15.8 | 22 | 20 | $NS$ |

## V. CONCLUSION

A realization of $3^{rd}$-order active-R filter with feedforward input signal has been proposed. The circuit consists of three operational amplifiers (OAs), and four resistors, with three resistive voltage-dividers (formed by $g_{ia}$ and $g_{ib}$). The input sinusoidal low current signal is applied to the inverting terminal of the first op-amp, through the first resistive voltage-divider (formed by $g_{1a}$ and $g_{1b}$). If the resistive voltage-dividers have high input impedance and low output impedance, the circuit realizes low pass, band pass, and high pass transfer functions at three different nodes. With respect to quality factor, the low pass filter works for all values of quality factor and is extremely stable only when Q ≤ 1. Whereas, the band pass filter with respect to quality factor works and is asymptotically stable for all values of Q. With respect to quality factor, the high pass filter works for all values of quality factor and is asymptotically stable only when Q ≤ 1. The circuit has also low sensitivity to passive and active elements. From the results, it can be seen that when Q ≤ 1, the circuit has excellent low pass performance and high pass performance and for all values of Q, the circuit has excellent band pass performance. The circuit realizes concurrently low pass, band pass, and high pass filters.

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