Design Aspects and Sensitivity Analysis of Tenth Order Active Bandpass Filter

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ABSTRACT

The design and sensitivity aspects of five stages tenth order active bandpass filter suitable for signal processing in electronic circuits are introduced. Simulation process performed is started by evaluating the voltage transfer function of the filter using the nodal approach to the second order activenet work model which represents each stage. The sensitivity analysis with respect to some parameter changes such as resonance frequency and quality factor is treated for proper choice of component values. The computational difficulties in the analog domain manipulations that arises through the cascaded arrangement of the filteris overcome by factorizing the terms in the denominator of the stated voltage transfer function with the aid of MATLAB 7.10.0(R2010a)software program. It was found that the increasing in the quality factor increases the magnitude, phase responses, higher deviation in magnitude sensitivity due to change in resonance frequency and lower frequency range due to change in quality factor. An increasing in the resonance frequency results in a better impulse and step response. The phase sensitivity due to change in resonance frequency shows that an increase in the quality factor gives higher deviation and this deviation is less in the sensitivity due to change in the quality factor. The simulation process of the circuit is done via the introduction of the Multisim software package version 9.0.155, offers good agreements with the results obtained.

Keywords: Nodal Approach, Transfer Function, Filter Design, Higher-Order Filter, Sensitivity.

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سمات التصميم وتحليل الحساسية لمرشح أمرار الحزمة الفعال ومن الرتبه العاشرة

الخلاصة

تم تقديم سمات التصميم وتحليل الحساسية لمرشح أمرار الحزمة الفعال ومن الرتبه العاشرة والمتكون من خمسة مراحل والملائم لمعالجات الاشارة في الدوائر الالكترونية .ان التحليل وعملية المحاكاة مؤدية بتقييم وظيفة نقل فولتية المرشح باستعمال النظرة العقدية لنموذج شبكة الرتبة الثانية لتمثيل كل مرحلة.ان تحليل الحساسيةفيما يتعلق بتغييرات عوامل التردد الزاوي وعامل الجودة قد تم معالجتها للوصول الى الاختيار الامثل لقيم مكونات الدائرة. تظهر الصعوبات الحسابية في المدى التماثلي من خلال الترتيب المتعاقب للمرشح وامكن التغلب عليها عن طريق تحليل الشروط في مقام كسر دالة وظيفة نقل الفولتية بواسطة البرنامج .MATLAB 7.10.0 (R2010a)

وقد وجد انه بزيادة عامل الجودة فانه تزداد قيمة الاستجابة العددية والطورية مع انحراف اعلى في قيمة الحساسية وفقا لتغيير التردد الزاوي ومدى ترددي قليل للحساسبة وفقا لتغيير عامل الجودة. كما وظهر خلال التحليل ايضا ان زيادة التردد الزاوي ينتج عنه تحسن في رد الاندفاع ورد العتبة. واخيرا تم تحليل الحساسية الطوريةوفقا لتغيير التردد الزاوي وقد وجد انه بزيادة عامل الجودة يكون الانحراف اعلى في هذه الدالة وتكون قيمته اقل في دالة الحساسية وفقا لتغيير عامل الجودة.

INTRODUCTION

In the field of telecommunications, band-pass filters are used in the audio frequency range $(0\,\text{kHz to }20\,\text{kHz})$ for modems and speech processing [1]. Active filters using resistors, capacitors and active devices (usually operational amplifiers), which can all be integrated, can improved performance and a simple design can be achieved compared with that of passive filters and can realize a wide range of functions as well as providing voltage gain in spite of their limitation in bandwidth and quality factor in some applications. However, for many applications, particularly in voice and data communications, the economic and performance advantages of active *RC* filters far outweigh their disadvantages [2].

For higher order filters, from the design point of view, second-order transfer function plays an important role in the analysis of the structure of these networks. The desired characteristics of such networks depends on the input and output relationships of a complex network. Depending on the fundamentals of the network theory, the analysis of high order filters can be accomplished and the response can be obtained at a given excitation.

NODAL APPROACH FOR A SECOND-ORDER FILTER

The basic network configuration is chosen as a multiple-loop feedback second-order active bandpass filter [3]. The active element is an inverted operational amplifier has infinite gain. The network has two feedback paths from the output to the network. The multiple-loop feedback network shows less overall sensitivity [4], [5]to component variations and has superior high-frequency performance compared to Sallen-Key network [6]. The method considered in treating the network is the nodal approach [7], some literature uses the modified nodal approach to the Sallen-Key network [8], and so a reference node is selected and associates a voltage with the other nodes of the network. As depicted from Fig. 1, the node voltages are V_i, V_1, V_2, and V_o where $V_i$and V_o are the input and output voltages. The ground is to be the zero point (reference point). The following two equations describe the nodal equations for the network

$$(G_1 + G_2 + G_3 + G_4)V_1 - G_3V_2 - G_4V_o - G_1V_i = 0 \qquad (1)$$

$$(G_3 + G_5)V_2 - G_3V_1 - G_5V_o = 0 \qquad (2)$$

Where

$$G_1 = 1/R_1,\ G_2 = 1/R_2, G_3 = C_1 s, G_4 = C_2 s, G_5 = 1/R_3$$

and s is the Laplace variable,since $V_2 = 0$ as a virtual ground, Eq. 2 can be written as

$$V_1 = -\frac{G_5}{G_3}V_o \qquad ..(3)$$

Substituting of Eq. 3 into Eq. 1 yields

$$(G_1G_5 + G_2G_5 + G_3G_5 + G_4G_5 + G_3G_4)V_0 + G_1G_3V_i = 0 \qquad (4)$$

Rearranging gives

$$\frac{V_o}{V_i} = \frac{-G_1G_3}{G_1G_5 + G_2G_5 + G_3G_5 + G_4G_5 + G_3G_4} \qquad (5)$$

The steady state transfer function of the network is obtained as

$$\frac{V_0(s)}{V_i(s)} = \frac{-s/R_1C_2}{s^2 + \left[\left(\frac{1}{C_1} + \frac{1}{C_2}\right)/R_3\right]s + \left(\frac{1}{R_1} + \frac{1}{R_2}\right)/R_3C_1C_2} \qquad (6)$$

The general form for the transfer functionof second-order active bandpass filter is given by

$$F(s) = \frac{Ms}{s^2 + \left(\frac{\omega_o}{Q}\right)s + \omega_o^2} \qquad (7)$$

Where $s = j\omega$, ω is the radian frequency, ω_o is the resonance frequency and Q is the quality factor and is defined as the ratio of center frequency to the -3 dB bandwidth. Comparing Eq. 6 with Eq. 7, M is given by

$$M = -1/R_1C_2 \qquad (8)$$

The resonance frequency ω_o can be determined as

$$\omega_o = \frac{\sqrt{1+\frac{R_2}{R_1}}}{\sqrt{R_2 R_3 C_1 C_2}} \tag{9}$$

and Q as

$$Q = \frac{\sqrt{1+\frac{R_2}{R_1}}}{\sqrt{\frac{C_1 R_2}{C_2 R_3}} + \sqrt{\frac{C_2 R_2}{C_1 R_3}}} \tag{10}$$

The phase responseis given by

$$\varphi(j\omega) = 90 - \tan^{-1}\frac{\omega\omega_o}{Q(\omega_o^2 - \omega^2)} \tag{11}$$

It is useful to find the peak value of the transfer function $|F(j\omega)|_{max}$, so substitution of $s = j\omega$ into Eq. 7 yields the relative magnitude of the transfer function

$$|F(j\omega)| = \frac{\omega M}{\sqrt{(\omega_o^2 - \omega^2)^2 + \frac{\omega_o^2\omega^2}{Q^2}}} \tag{12}$$

the value of $|F(j\omega)|_{max}$ occurs at $\omega = \omega_o$, so

$$|F(j\omega)|_{max} = \frac{MQ}{\omega_o} = \frac{-\frac{1}{R_1 C_2}\frac{\sqrt{1+\frac{R_2}{R_1}}}{\sqrt{\frac{C_1 R_2}{C_2 R_3}}+\sqrt{\frac{C_2 R_2}{C_1 R_3}}}}{\frac{\sqrt{1+\frac{R_2}{R_1}}}{\sqrt{R_2 R_3 C_1 C_2}}} = \frac{R_3/R_1}{1 + C_2/C_1} \tag{13}$$

Design of the Filter Network

The transfer function for the multiple-loop feedback second-order bandpass filter network can be expressed as

$$F(s) = \frac{A\frac{\omega_o}{Q}s}{s^2 + \frac{\omega_o}{Q}s + \omega_o^2} \quad (14)$$

Where A is the peak value or the gain at resonance, i.e. the mid-band gain. The coefficient of s is of most importance for selecting a band of frequencies through the quality factor and the later can be controllable [9]. The network design is started by choosing the values of the capacitors $C_1 = C_2 = C$, A and Q for an appropriate frequency ω_o and finding the resistors values as

$$R_1 = \frac{Q}{C\omega_o A} \quad (15)$$

$$R_2 = \frac{Q}{\omega_o C(2Q^2 - A)} \quad (16)$$

$$R_3 = \frac{2Q}{\omega_o C} \quad (17)$$

TENTH ORDER CASCADED FILTER

In the present work, a cascading of five stages multiple-loop feedback second order active bandpass filter network connected in series is achieved to realize tenth-order filter for steeper roll-off. The network, depicted in Fig. 2, has no loading effect because of the operational amplifier that separates each stage. The transfer functionof the filter has the form

$$\mathrm{TFH}(s) = \frac{\frac{A_1A_2A_3A_4A_5\omega_{01}\omega_{02}\omega_{03}\omega_{04}\omega_{05}}{Q_1Q_2Q_3Q_4Q_5}s^5}{\left(s^2 + \frac{\omega_{o1}}{Q_1}s + \omega_{o1}^2\right)\left(s^2 + \frac{\omega_{o2}}{Q_2}s + \omega_{o2}^2\right)\left(s^2 + \frac{\omega_{o3}}{Q_3}s + \omega_{o3}^2\right)\left(s^2 + \frac{\omega_{o4}}{Q_4}s + \omega_{o4}^2\right)\left(s^2 + \frac{\omega_{o5}}{Q_5}s + \omega_{o5}^5\right)} \quad \ldots(18)$$

The high order filter is treated for the frequency response (Bode plot) and the time response (impulse and step) and is examined with the MATLAB

7.10.0(R2010a) computer program [10]. The values of the resistors and capacitors of the high order filter are also calculated with the aid of Equations (15, 16 and 17). An illustrated case is depicted in Table(1) by choosing different values of the gain at resonance frequency, here the numeric values are chosen to meet the standard resistors and capacitor values.

Table(1) Standard resistors and capacitor values of the tenth-order band pass filter for different values of mid-band gain and fixed values of resonance frequency and quality factor.

Parameter	First stage	Second stage	Third stage	Fourth stage	Fifth stage
Mid-band gain	2	4	6	8	10
Resonance frequency	2.5 kHz	2.5 kHz	2.5 kHz	2.5 kHz	2.5 kHz
Quality factor	9.65	9.65	9.65	9.65	9.65
Resistors values	$R_1 = 22$ kΩ $R_2 = 220$ Ω $R_3 = 82$ kΩ	$R_4 = 11$ kΩ $R_5 = 220$ Ω $R_6 = 82$ kΩ	$R_7 = 6.8$ kΩ $R_8 = 220$ Ω $R_9 = 82$ kΩ	$R_{10} = 5.1$ kΩ $R_{11} = 220$ Ω $R_{12} = 82$ kΩ	$R_{13} = 4.3$ kΩ $R_{14} = 220$ Ω $R_{15} = 82$ kΩ
Capacitor Values	$C_1 = 15$ nF $C_2 = 15$ nF	$C_3 = 15$ nF $C_4 = 15$ nF	$C_5 = 15$ nF $C_6 = 15$ nF	$C_7 = 15$ nF $C_8 = 15$ nF	$C_9 = 15$ nF $C_{10} = 15$ nF

The magnitude and the phase response for the filter for increasing values of qualityfactor, $Q_1 = 3, Q_2 = 5, Q_3 = 8, Q_4 = 10$, and $Q_5 = 12$, respectively, (labeled 1,2,3,4 and 5) at $\omega_o = 15700$ Hz and $A = 2$, depicted in Figure (3), show that the decibel level of the magnitude curve is increased and the phase values are increased also and since the phase response is important in applications such as time delay simulation and cascaded filter stages [11], and the signal is delayed as it is passed through the filter so the group delay is this case is increased with an increase number of stages.

The transient response of the filter exhibits damped oscillations before reaching steady state and that is clearly seen from the increased overshoot in the impulse and step response as depicted in Figures (4 and 5), respectively. The performance of the filter is also affected by the resonance frequency as depicted in the frequency response curve of Figure (6); here the resonancefrequency takes the values of $\omega_{o1} = 10676$ Hz, $\omega_{o2} = 12560$ Hz, ω_{o3}=15072 Hz, ω_{o4}=17584 Hz, and $\omega_{o5} = 19468$ Hz, respectively at $Q = 10$ and $A = 2$. From the observation of these Figures it can be seen that the magnitude is decreased and the signal suffers more delay as it passes through the filter but the filter exhibits better impulse and step response as depicted in Figures (7 and 8) through less overshoot and rapid decay, also it is desirable that the impulse and the step response be fast and sufficiently damped so the damping in both is less and the filter reaches the steady state in a lower time period.

SENSITIVITY ANALYSIS

The filter performance from a practical insight point of view is related to the sensitivity for variations in frequency and quality factor which is a measure of how much a circuit behavior changes as a passive and active components values change of the filter design [12], so it is important to know the sensitivitiesfor proper component selection, proper choice of topology and proper guard-band in the mathematical description [13]. The changes in the entire transfer functionrelative to a component variation can lead to the accuracy required within a required tolerance limit. The sensitivities have to be minimized by changing the optimal global filter structure, circuit arrangement, and passive and active component [14]. The sensitivity to component variations differs according to a filter topology and even within a single topology, sensitivities can vary as a function of a component values.

Gain Sensitivity

Equation 14 can be rewritten as

$$F_1(j\omega) = \frac{\frac{A_1\omega_{o1}}{Q_1}(j\omega)}{(j\omega)^2 + \frac{\omega_{o1}}{Q_1}(j\omega) + \omega_{o1}^2} \tag{19}$$

The magnitude of the transfer function can be calculated from the following formula

$$|F_1| = \frac{\frac{A_1\omega_{o1}}{Q_1}}{\left[(\omega_{o1}^2 - \omega^2)^2 + \frac{\omega^2\omega_{o1}^2}{Q_1^2}\right]^{1/2}} \tag{20}$$

$$|F_1|_{\text{dB}} = 20\log\frac{A_1\omega_{o1}\omega}{Q_1} - 10\log\left[(\omega_{o1}^2 - \omega^2)^2 + \frac{\omega^2\omega_{o1}^2}{Q_1^2}\right] \tag{21}$$

The change in magnitude per unit change in ω_{o1} is given by

$$Se_{\omega_{o1}}^{|F_1|}(s,\omega_{o1}) = \frac{d(|F_1|/F_1)}{d(\omega_{o1})/\omega_{o1}} = \frac{d(\ln|F_1|)}{d(\ln\omega_{o1})} = \omega_{o1}\frac{d(\ln|F_1|)}{d(\omega_{o1})}$$

$$= 8.6858\left[1 - \frac{2(1-\omega_{o1n}^2) + \frac{\omega_{o1n}^2}{Q_1^2}}{(1-\omega_{o1n}^2)^2 + \frac{\omega_{o1n}^2}{Q_1^2}}\right] \quad (22)$$

where $\omega_{o1n} = \omega/\omega_{o1}$ is the normalized frequency. Also

$$\frac{\Delta|F_1|}{|F_1|} = Se_{\omega_{o1}}^{|F_1|}\frac{\Delta\omega_{o1}}{\omega_{o1}} \quad (23)$$

The sensitivity function as a function of 1% variation in ω_{o1} is depicted in Figure (9). The Figure illustrates that the magnitude sensitivity to frequency is high as the quality factor goes high and the deviation in sensitivity is -0.25% dB, -0.48% dB, -0.7% dB, -0.88%dB and -1.25% dB, (labeled 1,2,3,4 and 5) for $Q = 3, 5, 8, 10$ and 12, respectively at $\omega_{o1} = 15700$ Hz. To keep the shape of the transfer function of the filter with a sections of different quality factors within the mentioned magnitudes, the poles frequency have to be accurate within -0.038% dB, -0.047% dB, -0.06% dB, -0.089% dB, and -0.146% dB. The Figure also showsthe resultant curve (labeled 6) when they are all simultaneously varied. Similarly, the sensitivity of the gain due to change in quality factor is given by

$$Se_{Q_1}^{|F_1|}(s, Q_1) = Q_1\frac{d(\ln|F_1|)}{d(Q_1)} = 8.6858\left[-1 + \frac{\frac{\omega^2\omega_{o1}^2}{Q_1^2}}{(\omega_{o1}^2 - \omega^2)^2 + \frac{\omega^2\omega_{o1}^2}{Q_1^2}}\right]$$

$$= 8.6858\left[-1 + \frac{\frac{\omega_{o1n}^2}{Q_1^2}}{(1-\omega_{o1n}^2)^2 + \frac{\omega_{o1n}^2}{Q_1^2}}\right] \quad (24)$$

The amplitude sensitivity to 1% variation in Q is shown in Figure (10);herein, the minimum occurs at $\omega_{o1} = 15700$ Hz and does not vary as Q varies but the frequency range over which the sensitivity affected is varied and that it is wider as Q goes lower. If the quality factor of the five stages is simultaneously varied, the maximum deviation from the ideal amplitude is -0.435% dB and occurs at low frequencies.

Phase Sensitivity

The phase shift in Equation (14) can be computed and it is given by

$$\varphi_1 = \tan^{-1}\frac{Q_1(\omega_{o1}^2 - \omega^2)}{\omega\omega_{o1}} \qquad (25)$$

and the sensitivity of the phase shift due to change in ω_{o1} is

$$Se_{\omega_{o1}}^{\varphi_1}(s,\omega_{o1}) = \omega_{o1}\frac{d(\ln\varphi_1)}{d\varphi_1} = Q_1\omega_{o1n}\frac{1+\omega_{o1n}^2}{[\omega_{o1n}^2 + Q_1^2(1-\omega_{o1n}^2)^2]} \qquad (26)$$

In a similar manner, the sensitivity of the phase shift due to change in Q is

$$Se_{Q_1}^{\varphi_1}(s,Q_1) = Q_1\frac{d(\ln\varphi_1)}{d\varphi_1} = Q_1\omega_{o1n}\frac{(1-\omega_{o1n}^2)}{[\omega_{o1n}^2 + Q_1^2(1-\omega_{o1n}^2)^2]} \qquad (27)$$

The normalized phase sensitivity to unit change in critical frequency is depicted in Figure (11) for the same values illustrated above. The sensitivity is maximum at the corner frequency and the deviation is higher for highest Q pole. If all are varied the phase shift deviation is 0.76% rad. Finally, a less maximum deviation in phase shift sensitivity due to Q and also occurs at the corner frequency; its value is 0.177% rad if all quality factors varied as depicted in Figure (12).

CONFIRMATION

From a practical point of view, it is interesting to implement the filter using the MultiSimsoftware package version 9.0.155 for the verification purposes of the results obtained. The circuit simulation is started by taking the case of the different quality factors at each stage, i.e $Q_1 = 3, Q_2 = 5, Q_3 = 8, Q_4 = 10,$ and $Q_5 = 12$, and a fixed values for both of resonance frequency, $\omega_o = 15700$ Hz, and mid-band gain, $A = 2$. Then the resistors values are evaluated using Equations 15, 16 and 17. The schematic representation of the circuit is depicted in Figure (13) with the input values depicted in Figure (14). It can be seen that the results obtained are in good agreement with that obtained from the theoretical design.

CONCLUSIONS

The theoretical treatment for the design and sensitivity considerations of multiple-loop feedback tenth-order active band pass filter is performed. The transfer function is obtained in a single expression and the factorized form of the denominator gives a better insight to the filter parameters. The analysis is aimed to compare the performance of the filter to meet desired specifications through the design of the electronic circuit, so the frequency and time responses at various resonance frequency and quality factor values are examined. The magnitude and phase responses are increased as the quality factor increases but the value of the amplitude response is less when the resonance frequency increases and there is no pronounced effect in the value of the phase response in each but the filter has better impulse and step response through less overshoot and rapid decay in the response compared with that of the increasing in the quality factors case. The derived magnitude sensitivity functions due to change in resonance frequency shows that the deviation is higher as the quality factor increases. For the magnitude sensitivity functions due to change in quality factor shows that the frequency range over which the sensitivity affected varied is wider as quality factor goes lower. Finally, the phase sensitivity due to change in resonance frequency shows that the maximum occurs at the corner frequency and the deviation is higher for highest quality factor pole, and the maximum deviation in phase shift sensitivity due to quality factor is less and occurs also at the corner frequency.

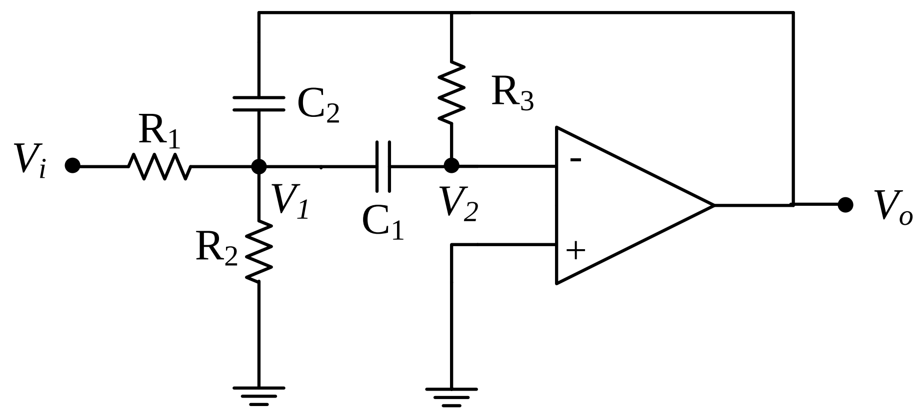

Figure (1) Multiple-loop feedback Second-order bandpass active filter network.

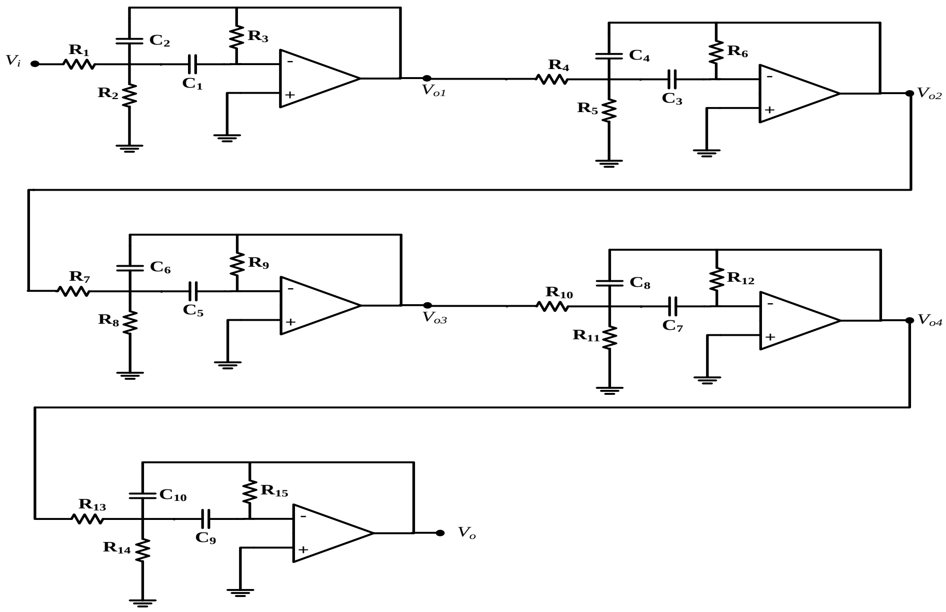

Figure (2) Multiple-loop feedback tenth order bandpass active filter network.

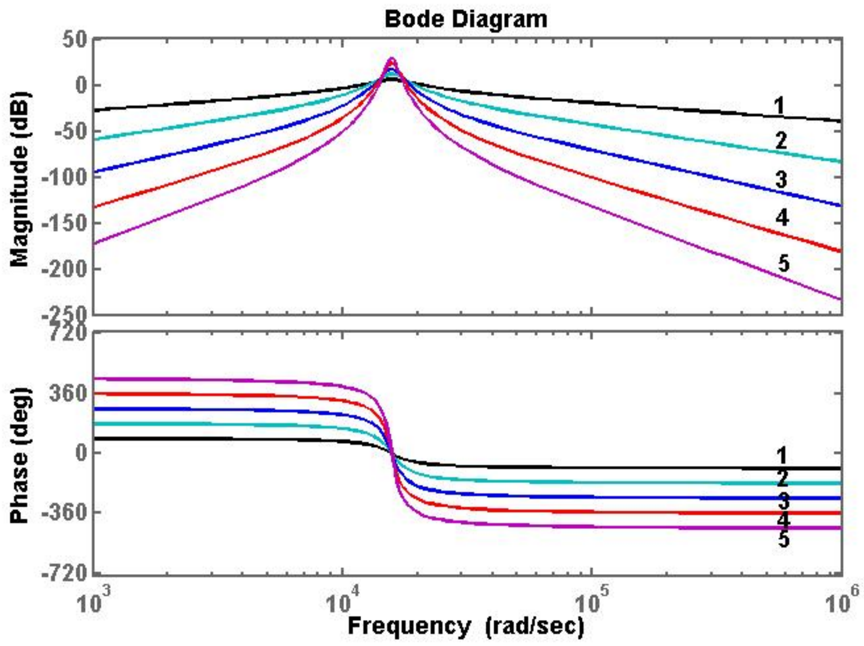

Figure (3) Bode plot for the of the tenth order multiple-loop feedback bandpass filter for different values of quality factor in each stage.

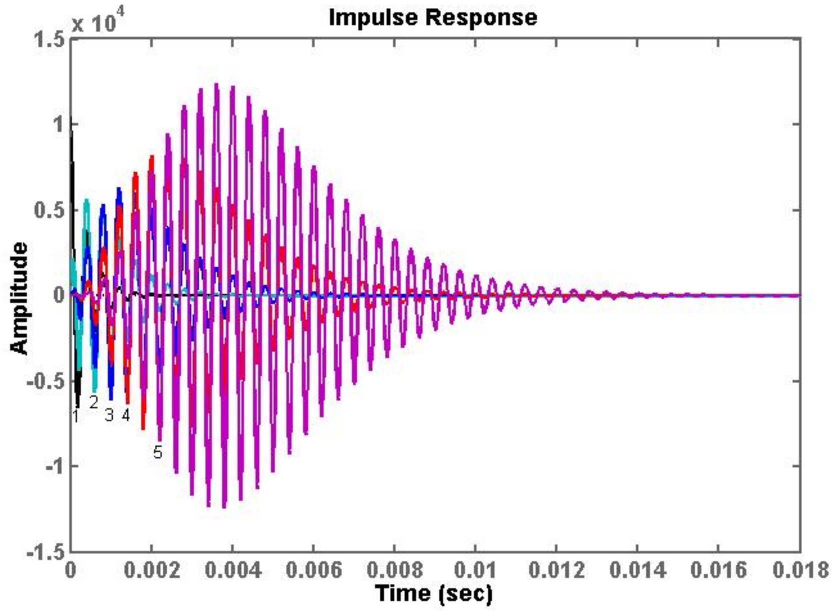

Figure (4) Impulse response for the multiple-loop feedback bandpass filter for different values of quality factor in each stage.

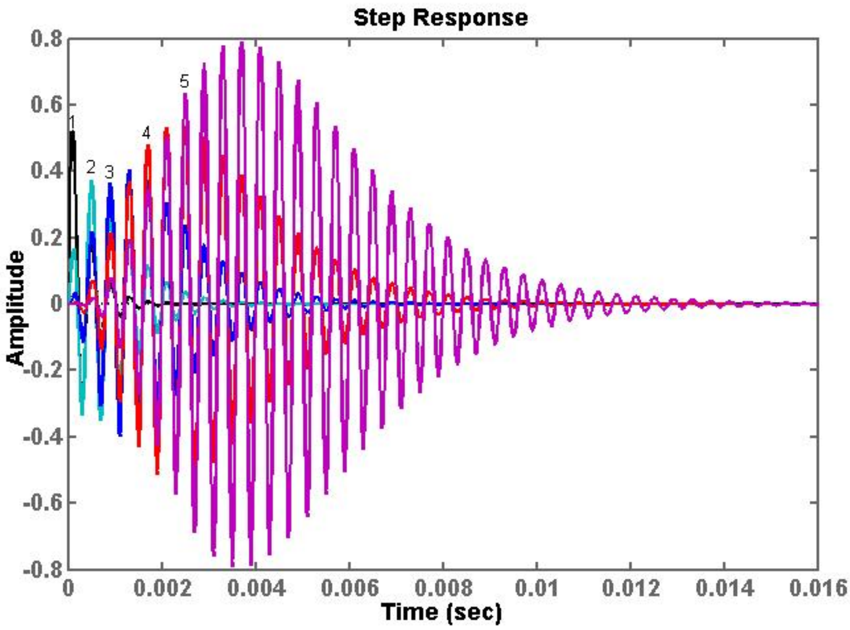

Figure (5) Step response for the multiple-loop feedback bandpass filter for different values of quality factor in each stage.

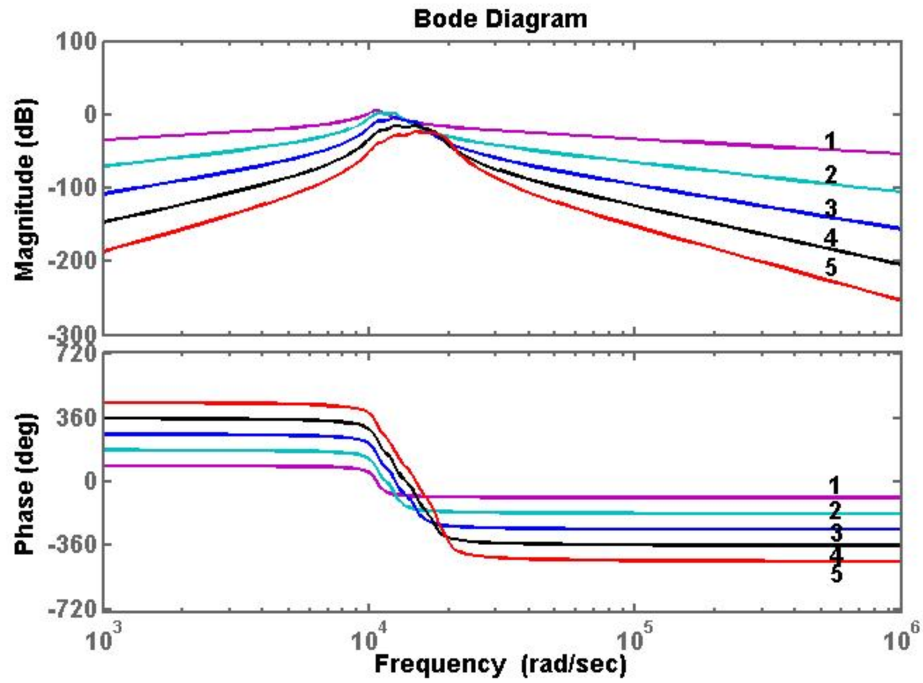

Figure (6) Frequency response of the tenth order multiple-loop feedback bandpass filter for different values of resonance frequency in each stage.

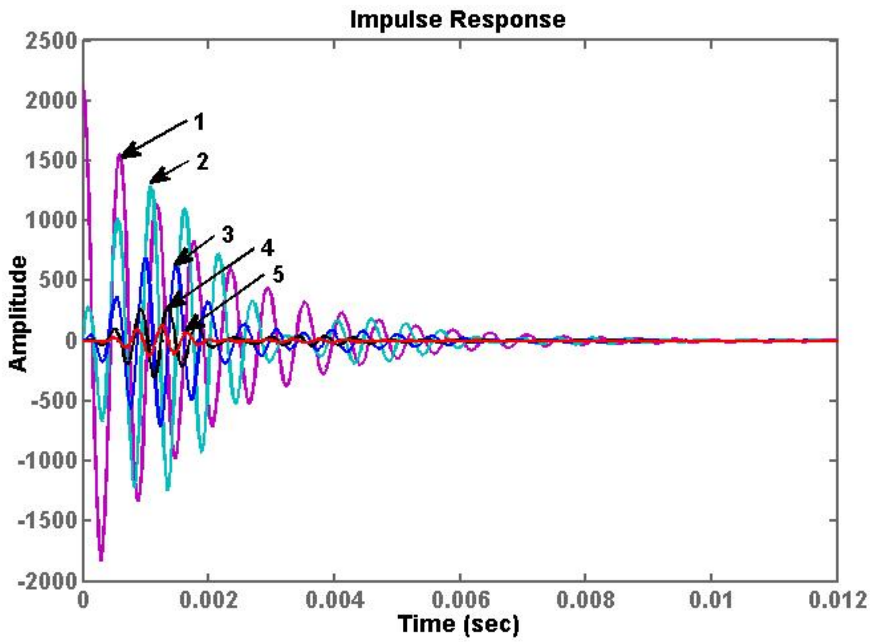

Figure (7) Impulse response for the multiple-loop feedback bandpass filter for different values of resonance frequency in each stage.

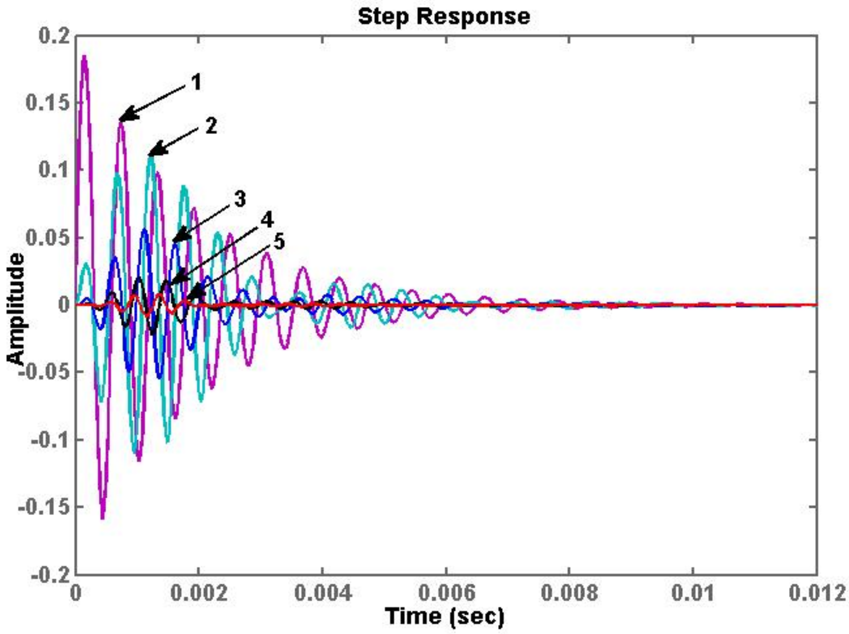

Figure (8) Step response for the multiple-loop feedback bandpass filter for different values of resonance frequency in each stage.

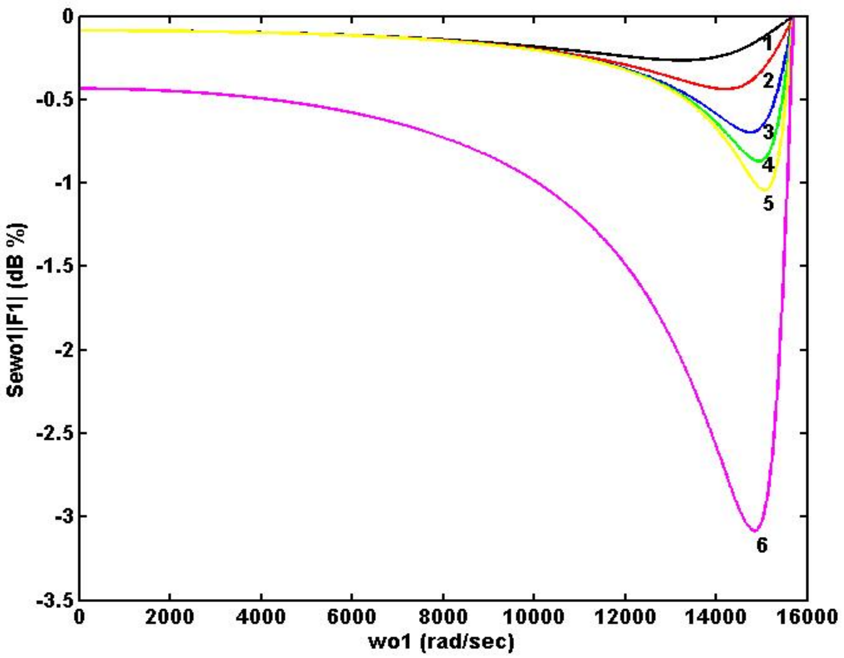

Figure (9) Gain sensitivity against angular frequency variation for the multiple-loop feedback bandpass filter for different values of quality factor in each stage.

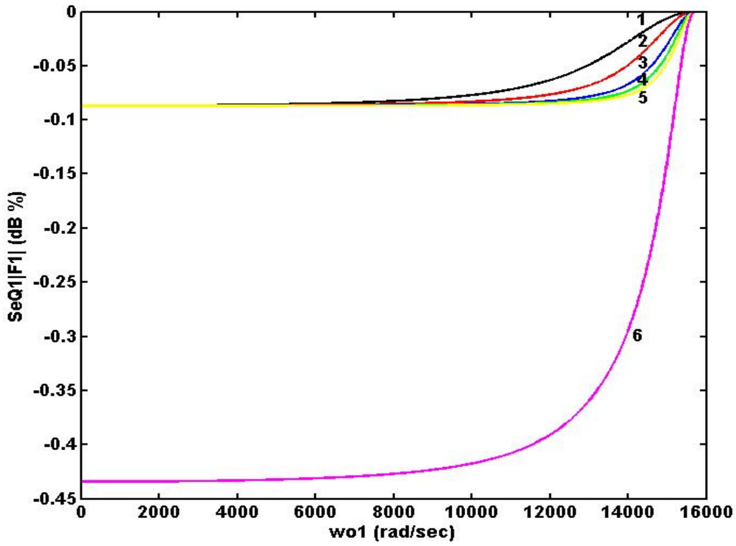

Figure (10) Gain sensitivity against quality factor variation for the multiple-loop feedback bandpass filter for different values of quality factor in each stage.

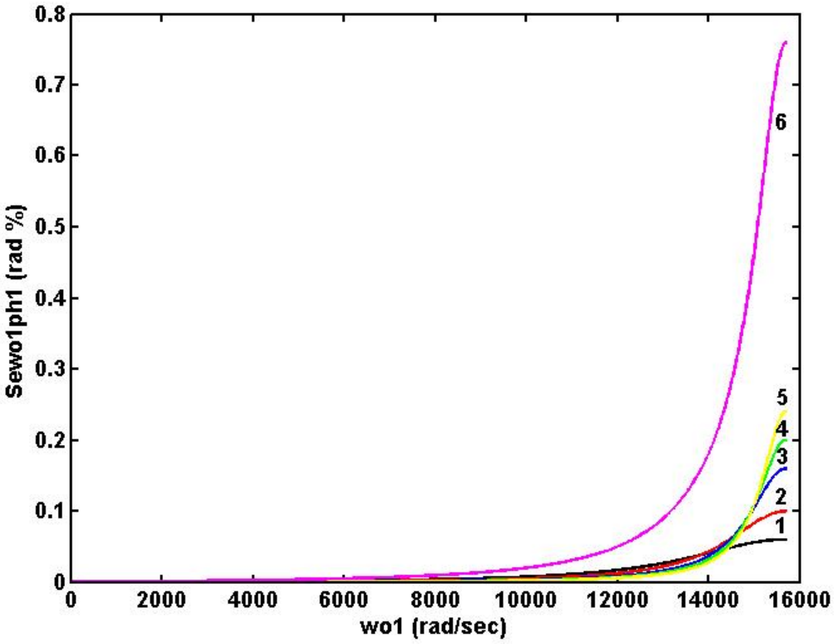

Figure (11) Phase sensitivity against angular frequency variation for the multiple-loop feedback bandpass filter for different values of quality factor in each stage.

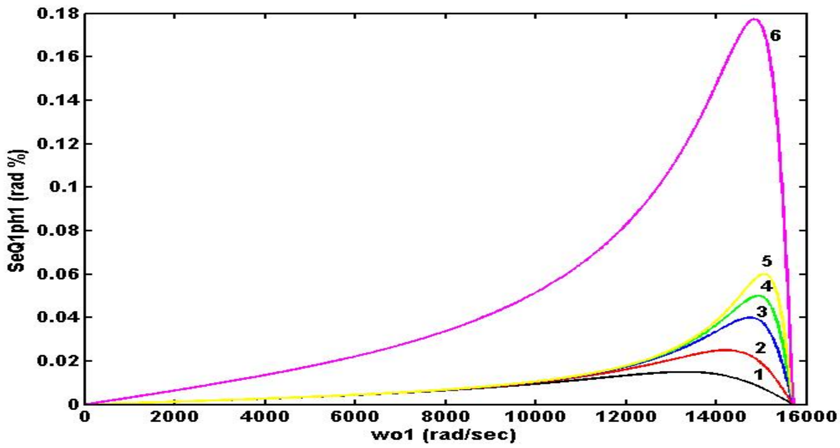

Figure (12) Phase sensitivity against quality factor variation for the multiple-loop feedback bandpass filter for different values of quality factor in each stage.

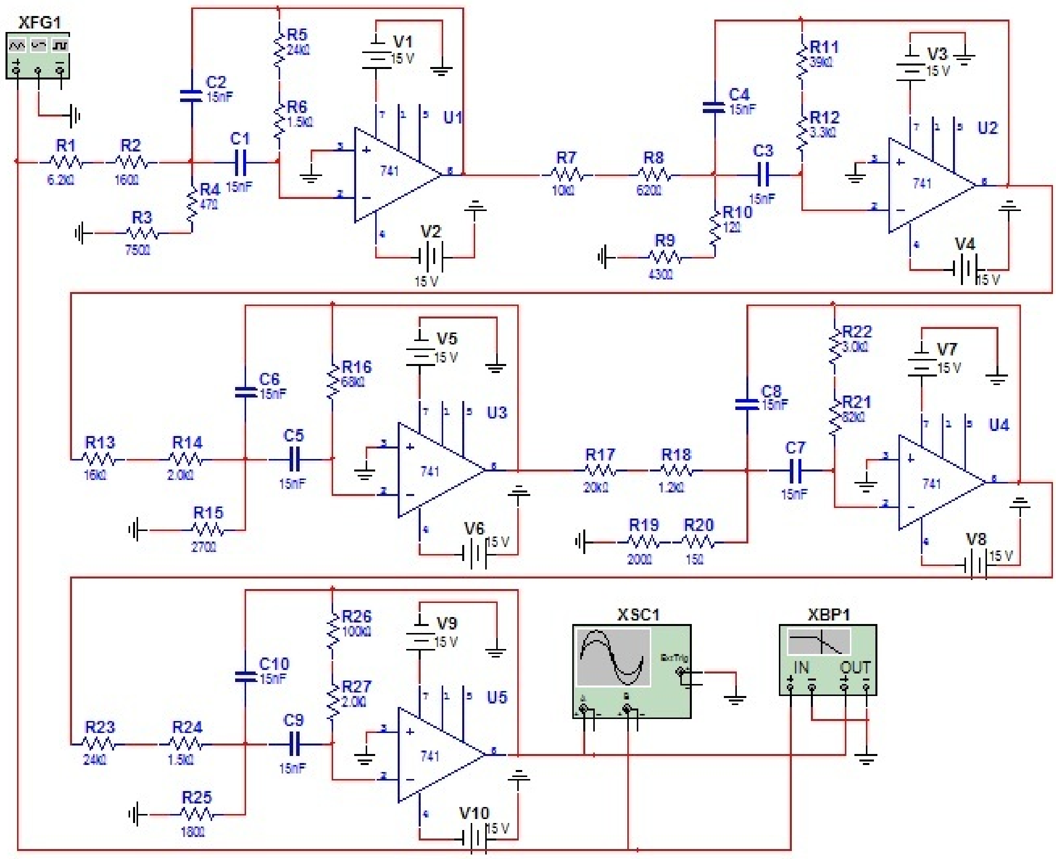

Figure (13) Multisim simulation of the multiple-loop feedback bandpass filter network.

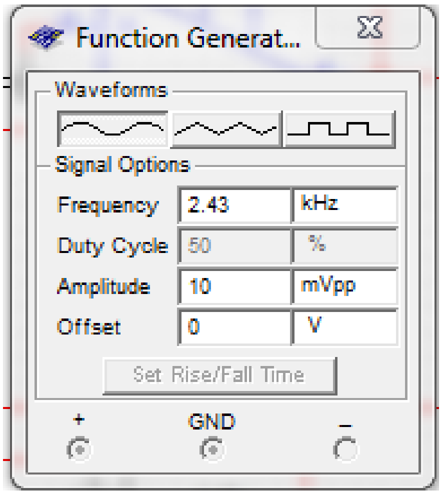

Figure (14) Input values to the network in Figure (13).

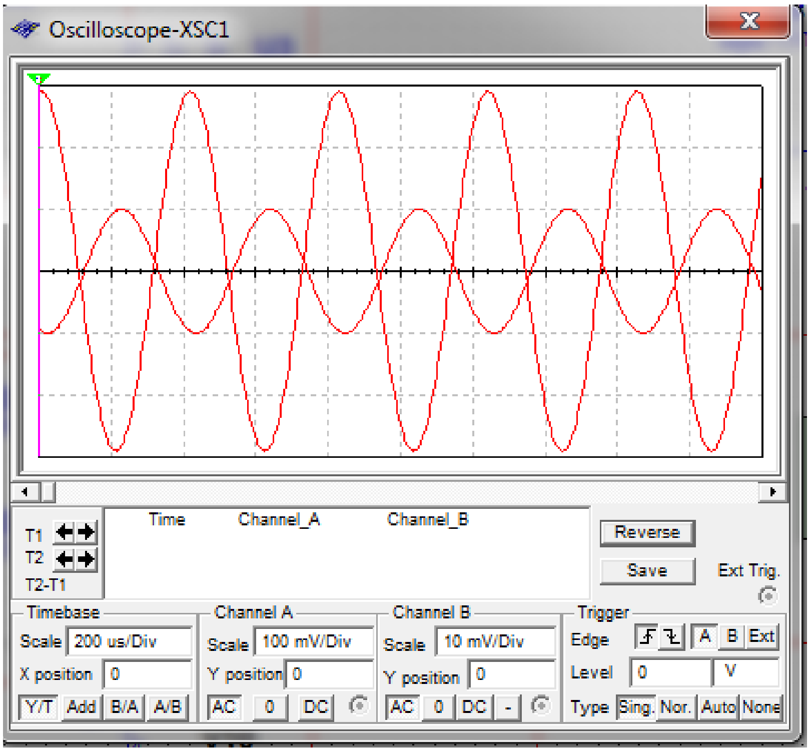

Figure (15) Input and output waveforms of the filter.

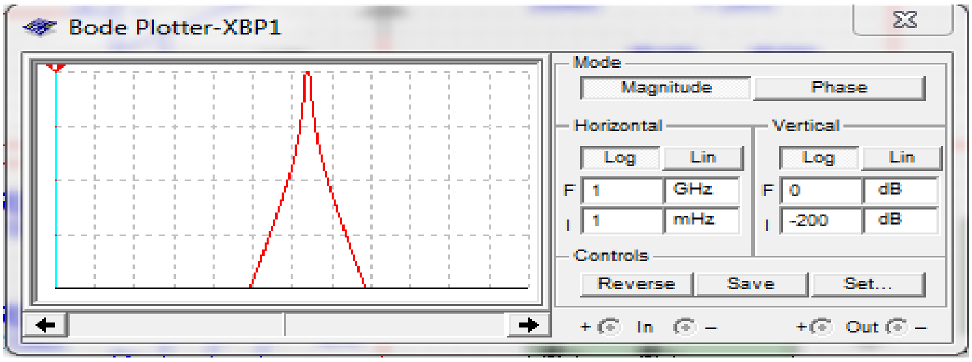

Figure (16) Multiple-loop bandpass filter response characteristic.

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