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Identification of characteristics for RC Low Pass, High Pass, Band Pass and Band Stop Filters

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Abstract

In signal processing, filters are essential components used to modify the frequency content of signals, enabling the separation of desired components from unwanted noise or interference. Among the most commonly used filters in electronic systems are RC (Resistor-Capacitor) filters, which include low-pass, high-pass, band-pass, and band-stop filters. These filters are simple to implement and widely utilized for tasks such as noise reduction, signal shaping, and frequency selection. The performance of these filters varies significantly with desired frequency, and understanding these variations is crucial for their optimal application. The designed parameters and values are calculated and the gain magnitude and phase response and bode response is simulated with MATLAB.

A. Introduction

In signal processing, filters are essential components used to modify the frequency content of signals, enabling the separation of desired components from unwanted noise or interference. Among the most commonly used filters in electronic systems are RC (Resistor-Capacitor) filters, which include low-pass, high-pass, band-pass, and band-stop filters. These filters are simple to implement and widely utilized for tasks such as noise reduction, signal shaping, and frequency selection. However, the performance of these filters varies significantly with different frequencies, and understanding these variations is crucial for their optimal application.

In the first literature, Teryima D. Kureve, Johnson A. Mise, Benard A. Atsuwe researched with the title “Implementation Of An Active RC Band-Pass Filter At Varying Quality Factors Using Matlab” , which an active second order RC band-pass filter is designed and simulated at different values of quality factor Q. The filter parameters and values for the passive components were calculated and the gain magnitude and phase response is then simulated with MATLAB. The simulation shows that at high Quality factors, the bandwidth of the filter response reduces considerably while its frequency selectivity increases without a shift in its center frequency.[1]

Each of these filters exhibits different behaviors in terms of frequency response, with distinct cutoff frequencies, attenuation rates, and phase shifts. Understanding these characteristics is crucial for selecting the appropriate filter for a given application. In this paper, it will be demonstrate the frequency and phase responses of RC low-pass, high-pass, band-pass, and band-stop filters using MATLAB, providing a visual and quantitative comparison of their behavior across a range of frequencies. [2][3][4][5][6][7][8][9]

By analyzing these filters, users can make informed decisions about which filter type to use based on the specific needs of a given system. The results will also highlight how frequencies interact with each filter type and the effects of various circuit parameters, such as resistance and capacitance, on the overall performance of the filter. [18][19][20]

The purpose of this study is to identify the characteristics of four common RC filters—low-pass, high-pass, band-pass, and band-stop—using MATLAB simulations.

B. Research Method

The effects of various circuit for LPF, HPF, BPF and BSF filter types in communication area is stated in the research. Block diagram of RC filter is shown in Figure1.

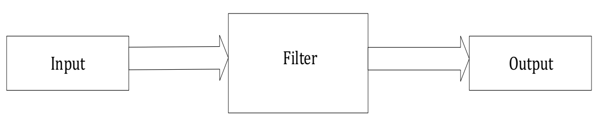

Figure 1. Block Diagram of RC Filter

There are four primary types of RC filters that are widely used: Low-Pass Filters (LPF), High-Pass Filters (HPF), Band-Pass Filters (BPF), and Band-Stop Filters (BSF). Each type has unique characteristics and is designed to perform specific tasks in frequency domain manipulation. [2][3][4][5][6][7][8][9]

Low-Pass Filter (LPF): This filter allows signals with frequencies below a specified cutoff frequency to pass through while attenuating higher frequencies. It is widely used in noise reduction and signal smoothing applications.[10] The LPF's cutoff frequency defines the boundary between passed and attenuated frequencies. Below the cutoff, the filter has negligible attenuation (close to 0 dB). Beyond the cutoff, the attenuation increases, typically following a slope of -20 dB per decade in the ideal case. LPF filters are commonly used in applications where high-frequency noise needs to be removed, such as audio signal filtering, power supply smoothing, and noise reduction in measurement systems. The ideal frequency response and phase shift of low pass filter is shown in Figure2.

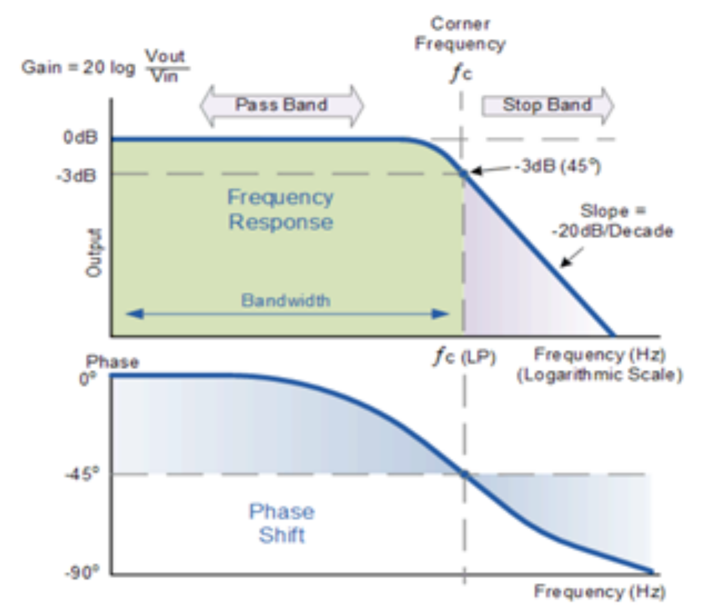

Figure 2. Ideal Frequency Response and Phase Shift of Low Pass Filter[10]

High-Pass Filter (HPF): The high-pass filter allows signals with frequencies above a specified cutoff to pass, while it blocks or attenuates lower frequencies. This filter is often used to eliminate low-frequency noise or to pass high-frequency components in communication systems. Below the cutoff frequency, the magnitude is attenuated significantly, often by 20 dB per decade, while frequencies above the cutoff are passed with little to no attenuation.High-pass filters are used in applications that require the elimination of low-frequency noise or to emphasize high-frequency components. Examples include eliminating hum from audio signals or removing DC components from signals in communication systems. The ideal frequency response and phase shift of high pass filter is shown in Figure3.[11]

Band-Pass Filter (BPF): A band-pass filter is designed to allow signals within a specific frequency range (between a lower and upper cutoff frequency) to pass through, while frequencies outside this range are attenuated. It is commonly used in applications like radio tuning, where only a narrow range of frequencies is desired.[12] The center frequency (also known as the resonant frequency) is where the filter has maximum transmission, with the filter sharply attenuating frequencies outside the defined band.The bandwidth (the difference between the upper and lower cutoff frequencies) controls the range of frequencies passed. Narrower bandwidths focus on a more specific frequency range.Band-pass filters are used in communication systems, such as in radio receivers and transmitters, to allow only the desired frequency band to pass, while rejecting all other frequencies. They are also used in audio processing and biomedical signal processing (e.g., filtering heart-rate signals). The ideal frequency response and phase shift of band pass filter is shown in Figure4.

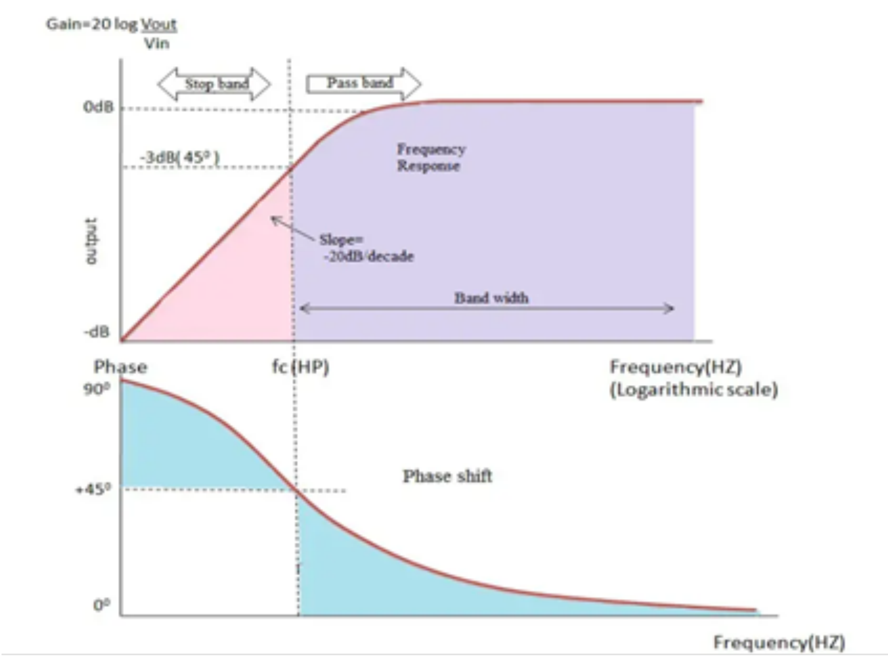

Figure 3. Ideal Frequency Response and Phase Shift of High Pass Filter[11]

Band-Stop Filter (BSF): In contrast to the band-pass filter, the band-stop filter attenuates signals within a specific frequency range while allowing signals outside this range to pass. It is typically used for eliminating unwanted narrowband interference or noise.[13] The band-stop filter is the inverse of the band-pass filter. It attenuates frequencies within a specific band and allows all other frequencies to pass. The magnitude response shows a "dip" in the range of the stopband, with a near-zero response within this band and relatively flat behavior outside it. The band-stop filter is characterized by its stopband, which is defined by two cutoff frequencies—lower and upper. Signals within this range are attenuated significantly, while frequencies outside this band are passed through. Similar to the BPF, the phase response of the BSF shows significant variations around the stopband frequencies.
Band-stop filters are used to remove unwanted interference or noise at specific frequencies, such as removing narrowband interference in communication channels. The ideal frequency response and phase shift of band stop filter is shown in Figure5.

For magnitude response, LPF and HPF exhibit smooth transitions around their cutoff frequencies, where one allows signals to pass (LPF for low frequencies, HPF for high frequencies) while attenuating the other end of the spectrum. BPF shows a peak in the middle of its passband, demonstrating its selectivity for a specific frequency range, while BSF shows a dip, indicating the rejection of a specific frequency band.

For phase response, LPF and HPF show a gradual phase shift as frequency increases. The phase shift becomes more prominent beyond the cutoff frequency. BPF and BSF both experience significant phase shifts near the edges of their passbands or stopbands. The phase shift in the BPF and BSF is more noticeable as the frequency moves toward the boundaries of their passbands and stopbands.

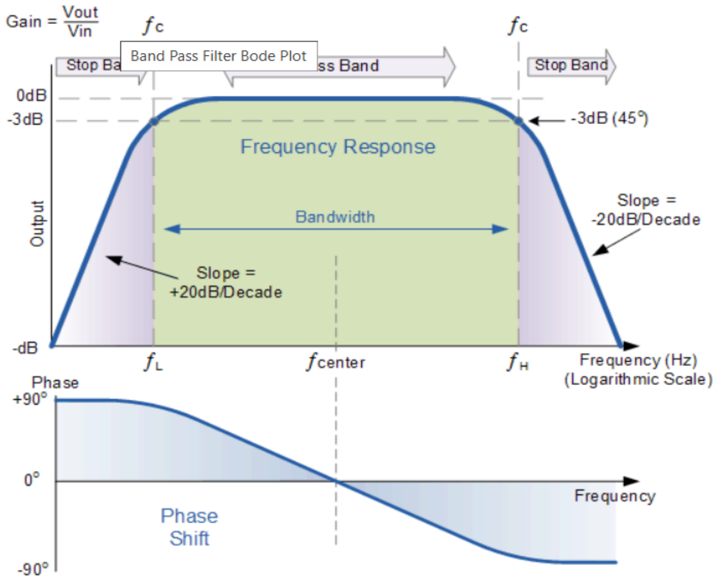

Figure 4. Ideal Frequency Response and Phase Shift of Band Pass Filter[12]

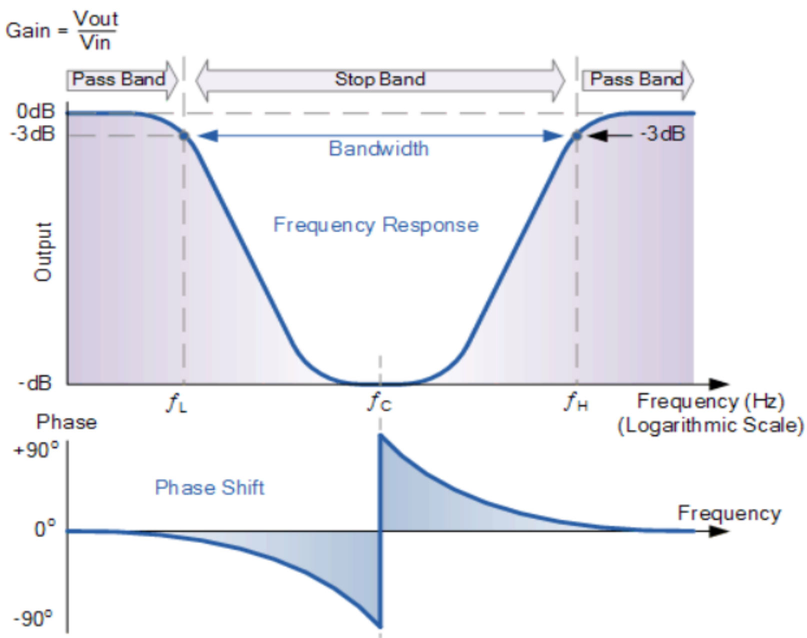

Figure 5. Ideal Frequency Response and Phase Shift of Band Stop Filter[13]

LPF and HPF are fundamental filters used in noise reduction, signal conditioning, and audio processing. For example, an LPF is useful for removing high-frequency noise from a signal, while an HPF can be used to block low-frequency hum. BPF and BSF serve specialized roles in frequency-selective applications. BPFs are critical in applications requiring a narrow frequency range to pass through, such as tuning circuits in radios. In contrast, BSFs are essential for eliminating specific interference, like power-line noise, in communication systems.[14]

Table 1. Characteristics of the Filters [14][15][16][17][18]

No	Filter Type	Passband Characteristics	Stopband Characteristics	Key Applications
1	Low Pass	Allows frequencies below f_c	Attenuates frequencies above f_c	Audio filtering, power supplies
2	High Pass	Allows frequencies above f_c	Attenuates frequencies below f_c	Signal processing, removing DC components
3	Band Pass	Passes frequencies between two cutoff points	Attenuates frequencies outside the band	Communications, radio tuners, medical applications
4	Band Stop	Attenuates frequencies within a band	Passes frequencies outside the band	Interference rejection, noise cancellation

The required responses for all types of filters such as magnitude response, phase response, bode response are represented with the following equations;

For LPF filter,

The transfer function is

$$H(j\omega) = \frac{V_{out}}{V_{in}} = \frac{1}{1 + j\frac{\omega}{\omega_C}} \quad (1)$$

The magnitude of transfer function is

$$|H(j\omega)| = \frac{1}{\sqrt{1 + (\frac{\omega}{\omega_C})^2}} \quad (2)$$

The phase of transfer function is

$$\angle H(j\omega) = -\tan^{-1}(\frac{\omega}{\omega_C}) \quad (3)$$

The unit step response is

$$V_{out}(t) = V_o(1 - e^{-t/(RC)}) \quad (4)$$

For HPF filter,
The magnitude of transfer function is

$$|H(j\omega)| = \frac{\omega}{\sqrt{\omega^2 + \omega_c^2}} \quad (5)$$

The phase of transfer function is

$$\angle H(j\omega) = \tan^{-1}\left(\frac{\omega_C}{\omega}\right) \quad (6)$$

For BPF filter,
The magnitude of transfer function is

$$|H(j\omega)| = \frac{\omega_0}{\sqrt{(\omega_0^2 - \omega^2)^2 + (\omega\frac{\omega_0}{Q})^2}} \quad (7)$$

The phase of transfer fuction is

$$\angle H(j\omega) = \tan^{-1}\left(\frac{\omega_0^2 - \omega^2}{\omega\frac{\omega_0}{Q}}\right) \quad (8)$$

For BSF filter,
The magnitude of transfer function is

$$|H(j\omega)| = \frac{\sqrt{(\omega_0^2 - \omega^2)^2 + (\omega\frac{\omega_0}{Q})^2}}{\omega_0} \quad (9)$$

The phase of transfer function is

$$\angle H(j\omega) = \tan^{-1}\left(\frac{\omega_0^2 - \omega^2}{\omega\frac{\omega_0}{Q}}\right) \quad (10)$$

Filters are classified according to the types of components that are used to implement the circuit. Passive filters use resistors, capacitors, and inductors; these components have no ability to provide amplification, and consequently a passive filter can only maintain or reduce the amplitude of an input signal. An active filter, on the other hand, can both filter a signal and apply gain, because it includes an active component such as a transistor or an operational amplifier.[14][15][16][17][18]

Figure6 is the schematic diagram of RC low pass filter. The RC LPF filter consist of a resistor(R) and a capacitor(C) in series, with the output taken across the capacitor. At low frequency, the capacitor is opened and the output signal is the same as the input. At high frequency, the capacitor is shorted and the output signal is reducing to ground.

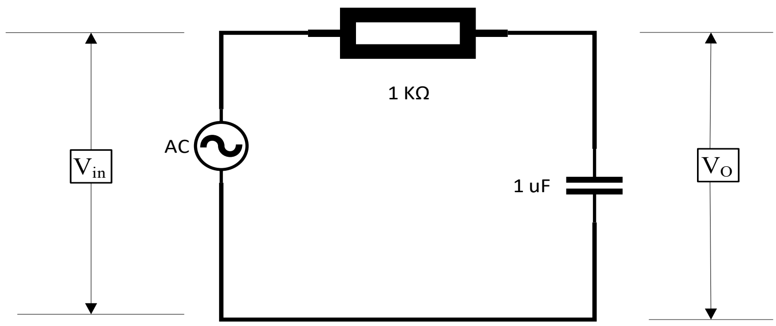

Figure 6. Schematic Diagram of RC Low Pass Filter

The RC high pass filter has the capacitor (C) in series with the input signal and the resistor(R) to ground with the across output. The schematic diagram of RC high pass filter is shown in Figure7.

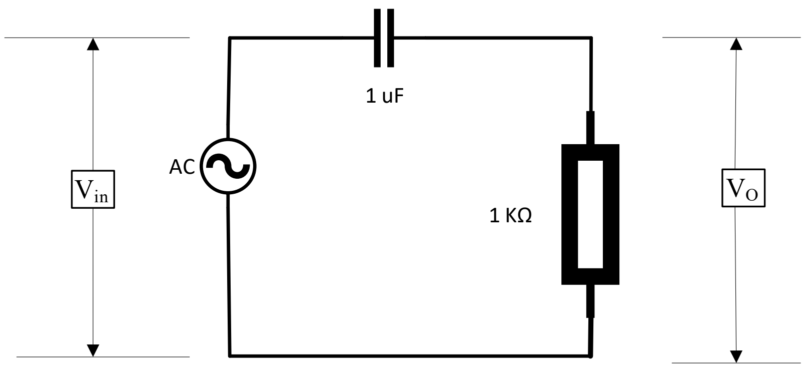

Figure 7. Schematic Diagram of RC High Pass Filter

A band pass filter is a low pass and a high pass filter in series combination. The frequency is passed which through from lower cutoff frequency and upper cutoff frequency while those outside are attenuated. The schematic diagram of RC band pass filter is shown in Figure8.

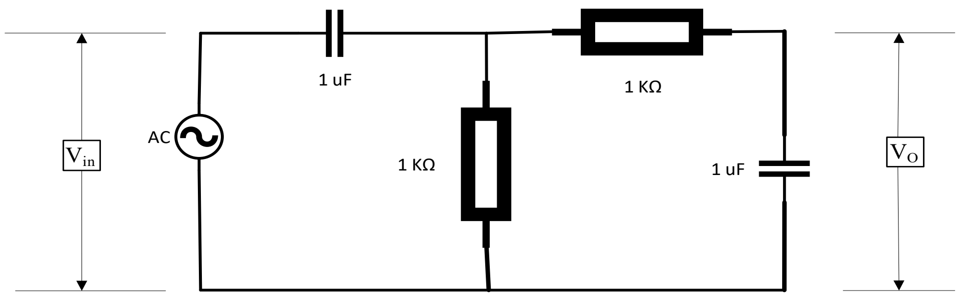

Figure 8. Schematic Diagram of RC Band Pass Filter

A band stop filter is a low pass filter and a high pass filter in parallel combination. The low-pass filter passes low frequencies and blocks high frequencies, while the high-pass filter passes high frequencies and blocks low frequencies. The band-stop filter thus attenuates a specific range of frequencies (the stopband) and passes frequencies outside this range.

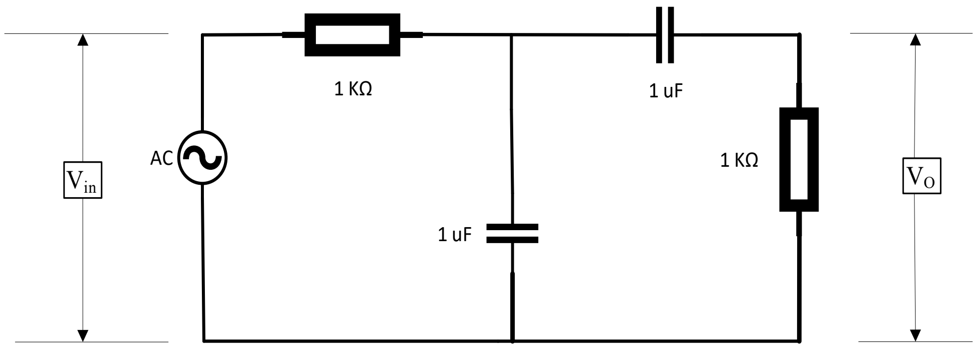

Figure 9. Schematic Diagram of RC Band Stop Filter

C. Result and Discussion

This section is discussed about the characteristic of LPF, HPF, BPF and BSF filters. Firstly, define the resistor and capacitor value to calculate the Cut-off frequency for computing transfer function. Generating the input signal to apply the RC LPF, ,HPF,BPF and BSF Filters. Finally, it is plotted the output signal to receive the bode response, step response and sine wave response.

Tests and results of the bode response, step response, and sine wave response of LPF filter are shown in Figure10, Figure11 and Figure12.

In Figure10, the output of the step response of LPF follows an exponential rise. This behavior aligns with the first-order RC circuit's response, where the capacitor charges exponentially towards the input voltage with a time constant.

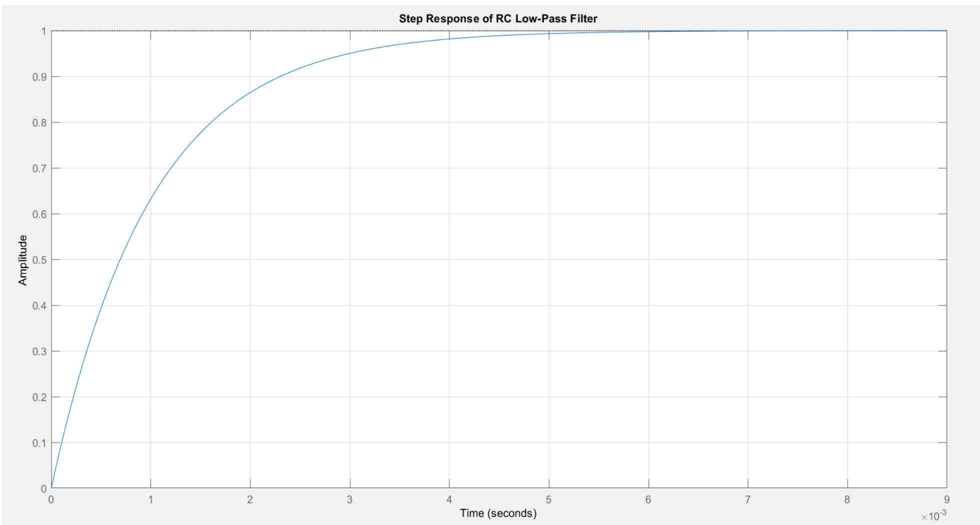

Figure 10. Step Response of Low Pass Filter

In Figure 11, the magnitude(dB) is attenuated - 3dB and phase is changing from 0 ° to -90 ° at -45 ° for LPF filter.

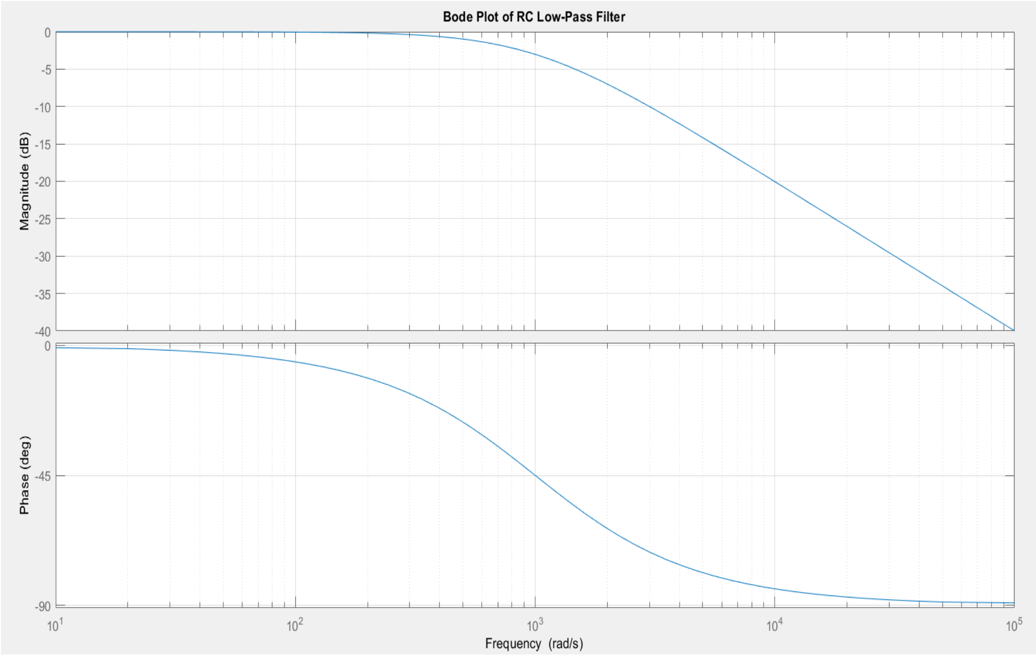

Figure 11. Bode Plot of Low Pass Filter

Figure 12, is the frequency response of RC LPF filter. At low frequency, the gain is 0 dB and it is attentuated – 3 dB at cut off frequency. And -20 dB per decade with higher than the cut off frequency.

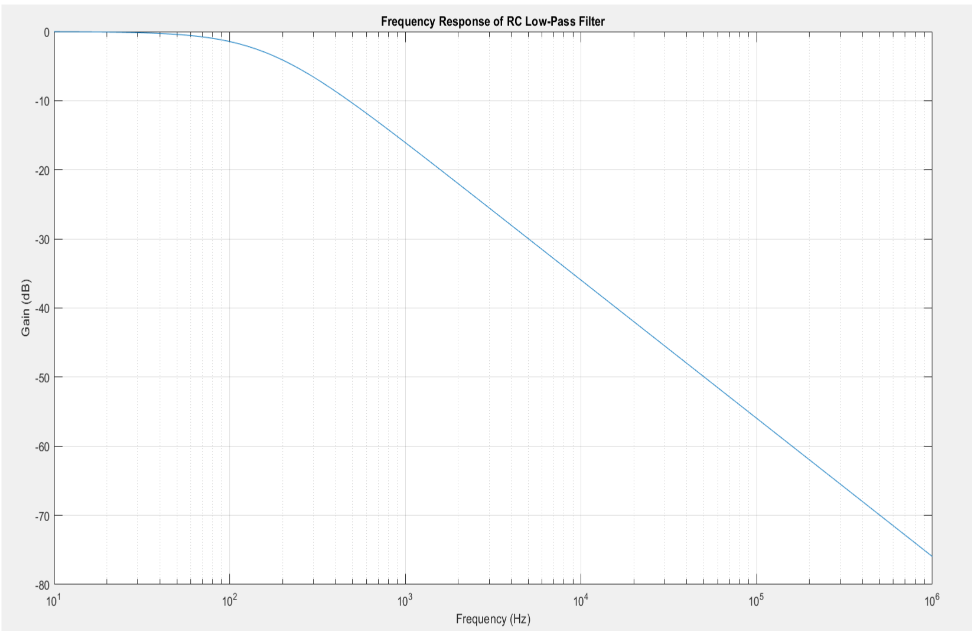

Figure 12. Frequency Response of Low Pass Filter

Tests and results of input and output signal of HPF filter, the bode response**,** frequency response are shown in Figure13 and Figure14.

In Figure13, the upper section is the input signal and the lower section is the output signal gradually reaches a steady value.

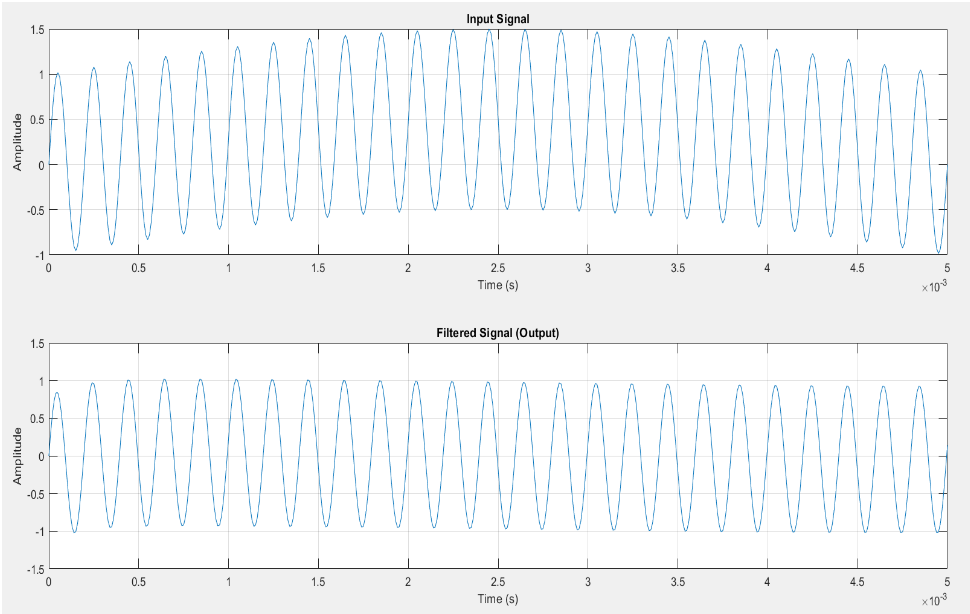

Figure 13. Input and Output of High Pass Filter

Figure14 is the bode plot of the RC HPF filter. The upper section of the figure is the varying of magnitude response with frequency and the lower section of the figure is the behaviour of the phase from 90 ° to 0 ° at 45 ° for HPF filter.

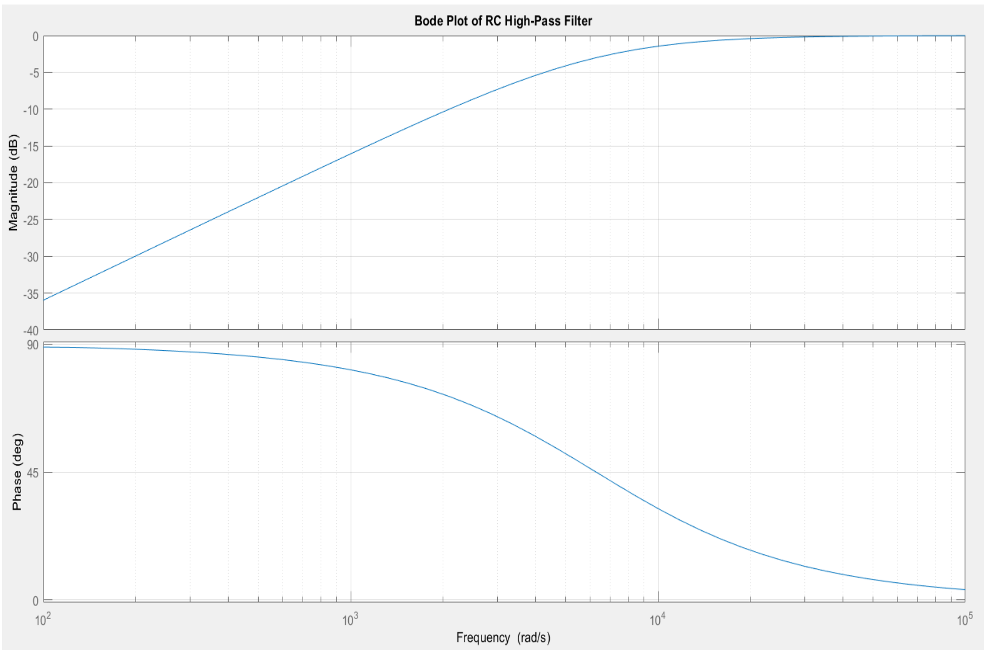

Figure 14. Bode Plot of High Pass Filter

Tests and results of input and output signal of BPF filter, the bode response**,** frequency response are shown in Figure15 and Figure16.

Figure15 is the frequency response of the input and output of the BPF filter. The output is received with smooth condition by comparing with the input signal of BPF filter.

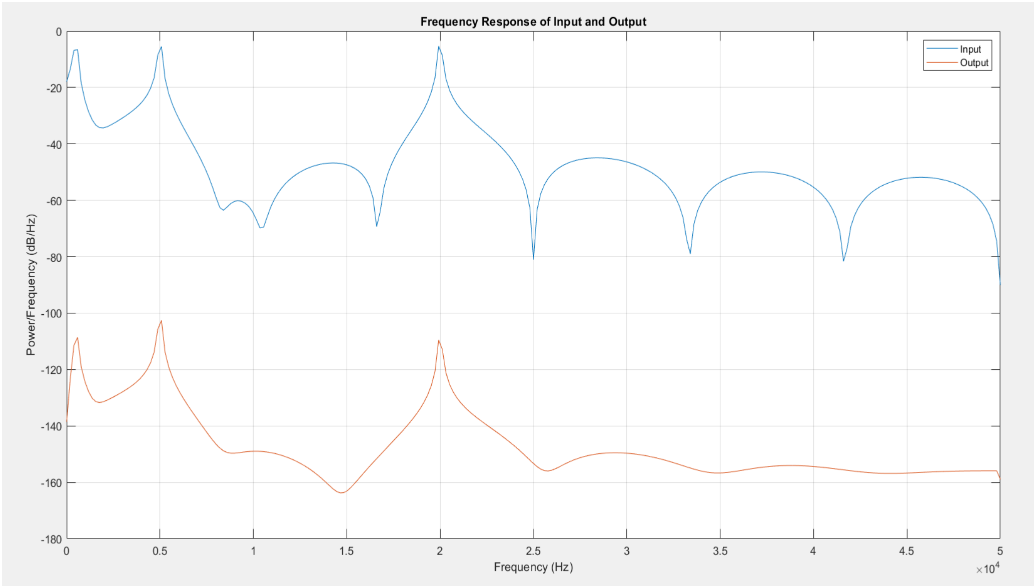

Figure 15. Frequency Response of Band Pass Filter

Figure16 is the bode plot of the BPF filer. The upper section is magnitude response with frequency and the lower section is the behavior of the phase response from 90 ˚ to - 90 ˚ at 0 ˚ for BPF filter.

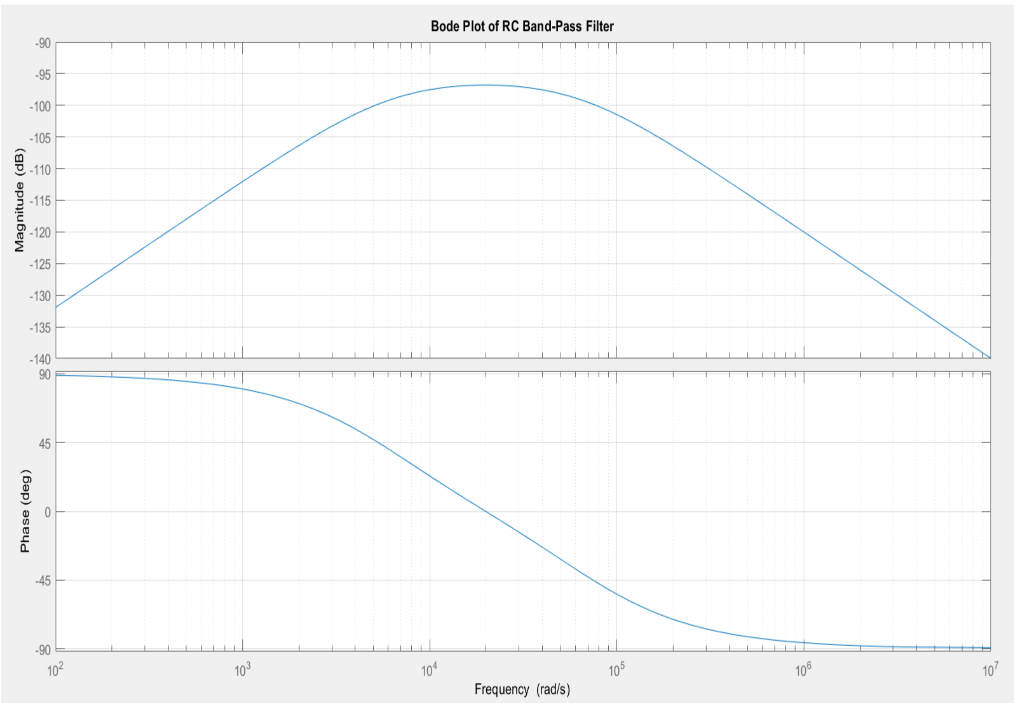

Figure 16. Bode Plot of Band Pass Filter

Tests and results of input and output signal of BSF filter, the bode response**,** frequency response are shown in Figure17 and Figure18.

Figure17 is the frequency response of BSF filter. The upper section of the figure is the magnitude with frequency and the lower section of the figure is the phase with frequency at the same center of frequency.

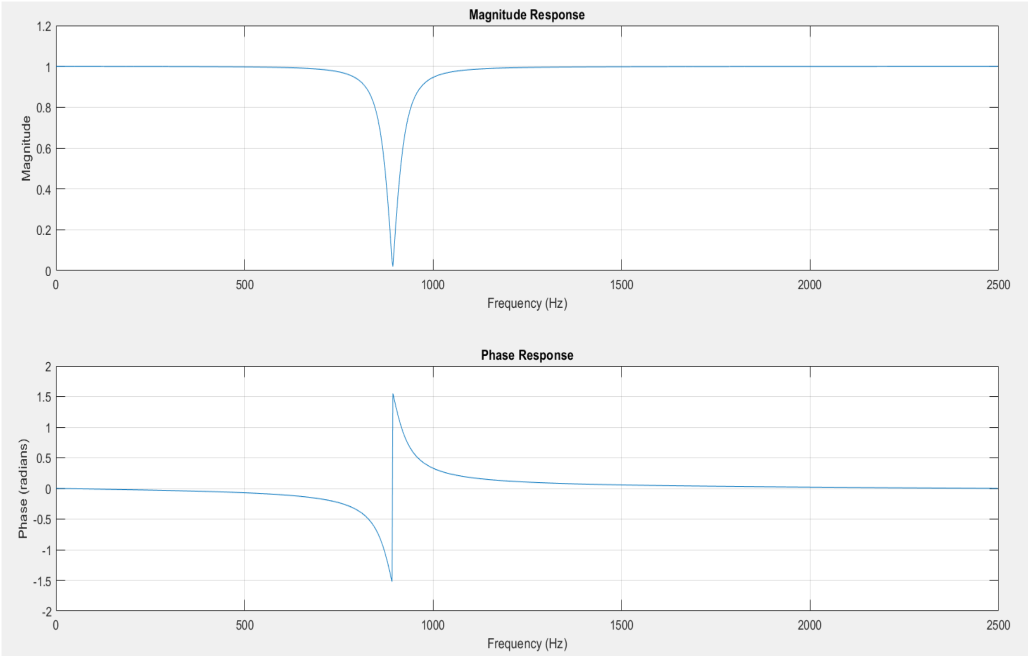

Figure 17. Magnitude Response of Band Stop Filter

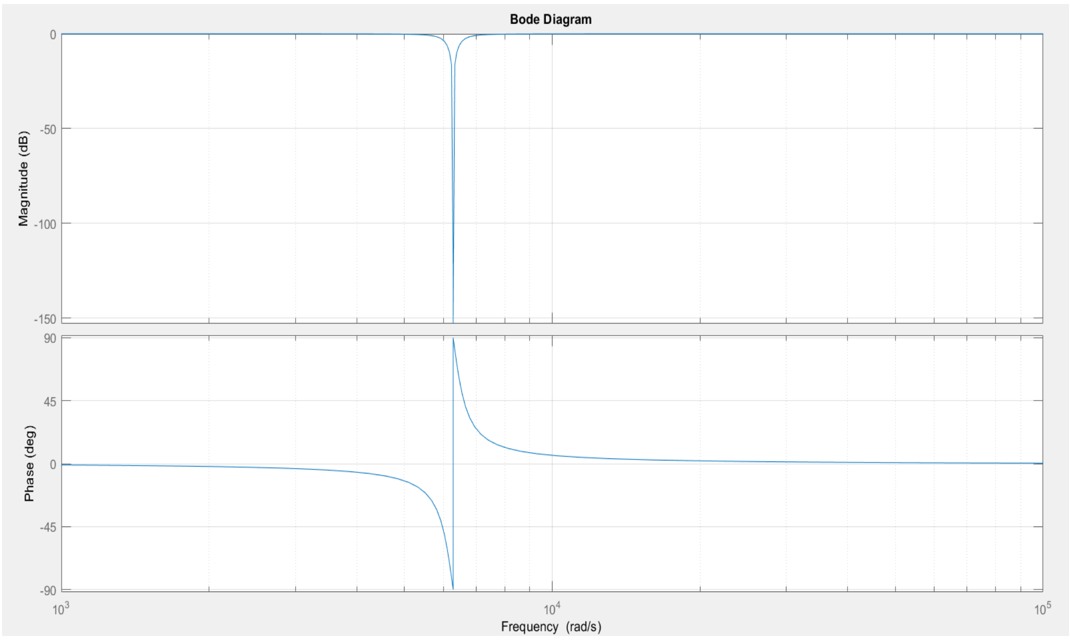

Figure 18. Bode Plot of Band Stop Filter

This paper is discussed about the characteristics of LPF, HPF, BPF and BSF filters such as step input response, magnitude response, phase response , bode plot and phase plot. All of the response curves are aligned with theory.

D. Conclusion

The identification of RC LPF, HPF, BPF and BSF filters provide a comprehensive understanding of how these filters behave and how they can be utilized for different signal processing tasks. The frequency and phase response characteristics of each filter type highlight their strengths and limitations in various applications. By choosing the suitable filter based on its frequency response, users can effectively manipulate signals for optimal performance in a large variety of systems, from singal processing for audio to communication and noise filtering applications. This studys contains the value of insight and the behavior of these filters to ensure the proper design and implementation of filtering solutions in real-world applications.

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