ECE 332 Lab 16d

Bandpass and Band-Reject Filters

This Laboratory Exercise is to be an team effort. There should be NO collaboration with anyone except the members of your team, course instructors or technicians. Each student must completely document any assistance received from others as well as any references used. If no help is received, state *Documentation: None.*

Goals

In this laboratory exercise, you will design two filters with desired characteristics to meet frequency response requirements:

- Cascaded first-order broadband.
- Second order, high Q.

Introduction

Broadband Filters

Cascaded first-order filters are useful for applications where we want a slow roll-off and a relatively flat pass-band or band-reject response. Your filter design will need to meet stringent conditions including interface requirements.

First-order filters are either HP or LP but can be combined to produce BP or BR responses. Your filters will have passband gain requirement as well.

Low-pass, first-order prototypes have the transfer function

$$H_{LP}(s) = \frac{K\omega_c}{s+\omega_c}$$

where K is the passband gain of the filter and ω_c is the cutoff frequency.

High-pass first-order prototypes are defined by:

$$H_{HP}(s) = \frac{Ks}{s+\omega_c}$$

where, as before, K is the passband gain of the filter and ω_c is the cutoff frequency.

Bandpass filters can be designed by cascading a LPF and a HPF, active or passive, where the high-pass filter's cutoff is the low-frequency cutoff of the BPF and the low-pass filter's cutoff is the high-frequency cutoff of the BPF. Note how these seem to be reversed!

Band-reject filters are designed by splitting the input and sending it into a LPF and HPF in parallel, then summing the output in a summing circuit. In this case the high-pass filter becomes the high-frequency cutoff of the BRF and low-pass filter's cutoff becomes the low-frequency cutoff of the BPF.

Narrowband Filters

High-Q filters are those defined by a very narrow pass-band or rejection band. High-Q bandpass (BP) filters are often called tuned (T) filters, while high-Q band-reject (BR) filters are often referred to as notch (N) filters. These filters find considerable use in communication systems, but are used in other applications as well, such as powerline noise suppression.

A measure of a filter's response that relates to the narrowness of its passband or rejection band is given by a quality factor called Q. Q is defined as

$$Q = \frac{\omega_o}{B}$$

where ω_o is the filter's center frequency and B is its bandwidth. Bandwidth is defined as:

$$B = \omega_{cHigh} - \omega_{cLow}$$

In both broadband and narrowband cases the two critical frequencies ω_{cHigh} and ω_{cLow} are places where the magnitude of the filter's transfer function has been reduced to 0.707 of the maximum magnitude of the filter's passband.

Filter circuits can be either passive or active; both filter-types have limitations. Passive filter circuits may be simple to design and require no power but can have large insertion loss. This means they tend to reduce all signals, even those that are not intentionally blocked. Active filters require power to operate but can make up for the insertion loss by providing gain.

Although band-pass and band-reject filters can be made by cascading two appropriate first-order filters, second order filters are often more efficient.

Second Order Filters

A second-order transfer function for a band-pass filter is:

$$H_{BP}(s) = \frac{KBs}{s^2 + Bs + \omega_o^2}$$

while that of a band-reject filter is:

$$H_{BR}(s) = \frac{K(s^2 + \omega_o^2)}{s^2 + Bs + \omega_o^2}$$

In an analysis of the frequency response of these transfer functions, the relationship of the bandwidth B and the quality factor Q is:

$$Q = \frac{\omega_o}{B} = \frac{1}{2\zeta}$$

It becomes clear that a high-Q filter requires a small ζ. A passive filter that places restrictions on R often results in high insertion loss, which means that you trade attenuation for high Q. One can restore the signals in the passband with an amplifier, but that's no longer a passive filter.

Using an active, band-pass, second order filter makes achieving both the required gain and the narrow filtering possible. Nevertheless, passive high-Q filters are used in many applications because of their inherent simplicity and no need for power. An example of an active high-Q band-pass filter's transfer function Q = 100 and K=10 is:

$$H_{BP1}(s) = \frac{55s}{s^2 + 5.5s + 305.000}$$

A circuit to realize this transfer function is shown in Figure 1

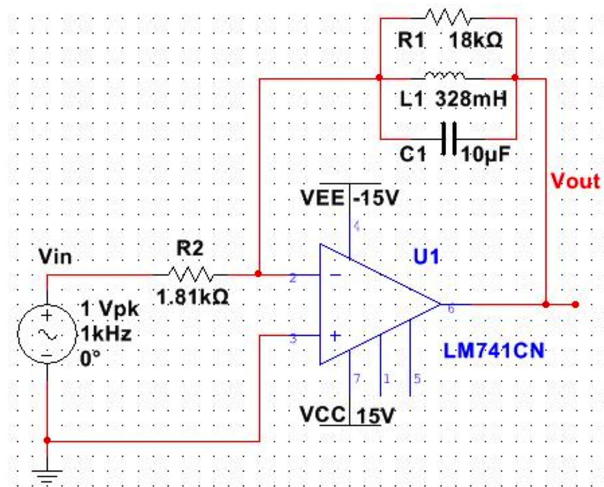

Figure 1: High-Q BPF

The magnitude response of the circuit in Figure 1 is shown in Figure 2.

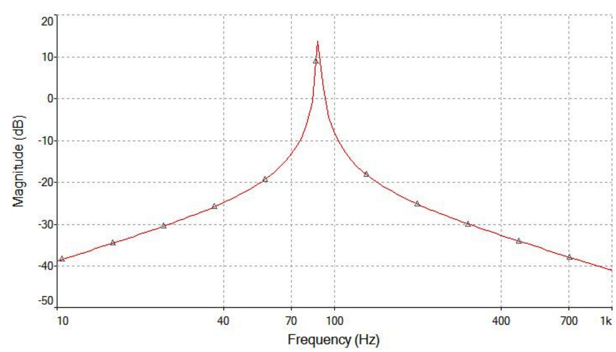

Figure 2: Magnitude Response for Fig. 1

A band-reject filter with Q = 10 and K = 1 has the transfer function:

$$H_{BR3}(s) = \frac{s^2 + 142,000}{s^2 + 37.6s + 142,000}$$

This circuit is shown in Figure 3 and its magnitude response is shown in Figure 4.

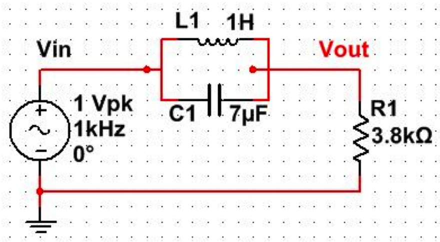

Figure 3: Passive BRF

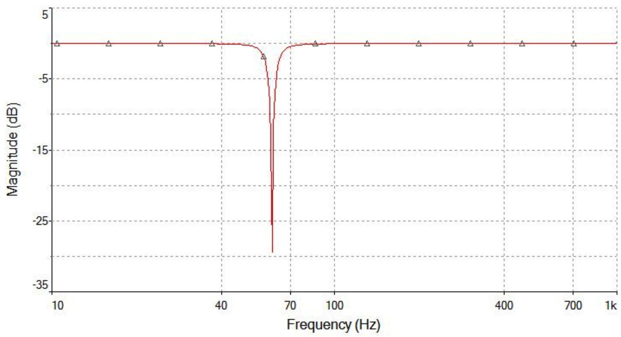

Figure 4: Magnitude Response of Fig. 3

The following transfer function is for a BPF with a broadband response.

$$H_{BP5}(s) = \frac{10^6 s}{s^2 + 10250s + 25 \times 10^6}$$

The circuit is shown in Figure 5 and the magnitude response is shown in Figure 6

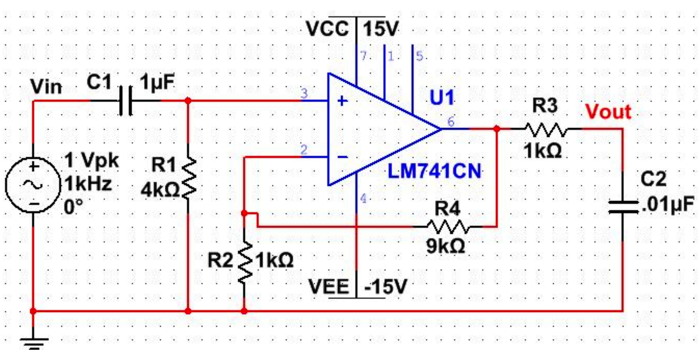

Figure 5: Broadband BPF

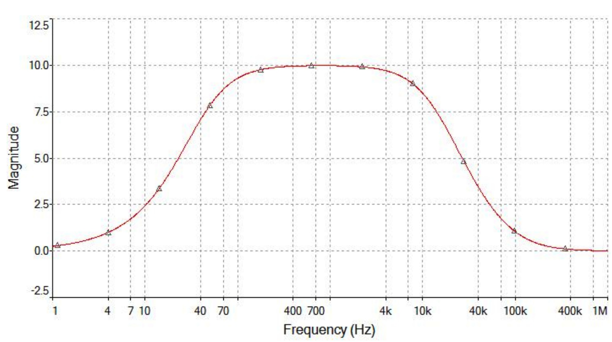

Figure 6: Magnitude Response of Fig. 5

This response shows a gain of 10, a bandwidth of 16 kHz, and a center frequency of 800 Hz. The Q for this circuit is 0.05, which is expected for a broadband response.

Objectives

After this lab, you should be able to

- Apply the design paradigm of Figure 7.
- Predict filter performance using Matlab.
- Design a cascaded, first-order broadband filter.
- Design a second-order, high Q filter.
- Simulate and verify filter performance via Multisim.
- Build and test design and verify filter performance.
- Report on the performance of your design.

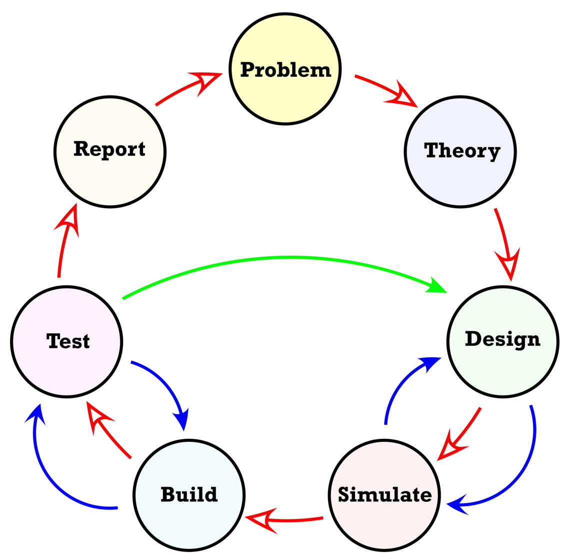

Figure 7: Engineering Design

Academic Direction

- Work in two-person teams with NO collaboration with other teams.

- You may only question any DFEC instructor or technician while doing your pre-lab work.
- Complete the pre-lab assignment before coming to the actual lab session because you will use your pre-lab work to implement your design. Pre-lab instructions are later in this document.
- Complete this lab and turn in the lab report by the due date shown in the course syllabus. Instructions for the report are at the end of this document.
- This lab is to reinforce the material you cover in the classroom, so questions on this lab may appear in quizzes, graded reviews, and the final examination.
- If you need to make up this lab, you must do it within 48 hours of the due date. Check with your instructor or e-mail our technician, Ms. Elmore at susan.elmore@usafa.edu to make arrangements for access.

Prelab and Design Constraints

Your team will be assigned two sets of requirements: a particular broadband filter and a particular high-Q filter. Your team is to design two filters that meet your assigned requirements as well as associated constraints. You are designing an interface circuit that will be connected between a source circuit and a load as shown in Figure 8 Note the filter characteristics are specified in hertz, while transfer functions are usually designed radian/second.

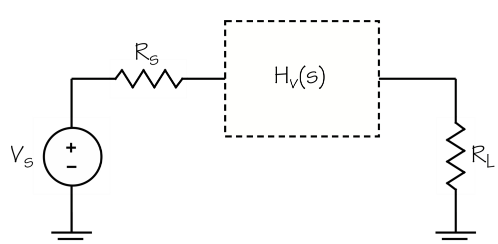

Figure 8: Circuit for Filter

Using the guidelines for band-pass and band-reject filters described above, in the text, and in the lecture, design a transfer function that meets each of your team's requirements. The transfer functions can be either positive or negative. Bring your transfer functions to the first lab class period and include them in your report.

Simulation

Begin your work by creating a notebook in Matlab as you have learned in previous labs. This will be your report document when you finish designing and testing your filters to show that they meet specifications.

Your prelab work is to include the following results:

- A pole-zero plot and a frequency response (Bode plot) for each of your proposed transfer functions using Matlab. This is your theoretical, predicted response since it uses actual design requirements.
- The transfer function's center frequency ω_0, the passband gain K, and the bandwidth B for each of your filter designs, measured from the Bode diagram, plus a computation of Q for each design. Compare these with requirements. Your transfer function must meet the requirements nearly perfectly (within $\pm 1\%$) since there are no restrictions on the values you can use for circuit elements.
- Circuit designs. Once you determine from Matlab that your transfer functions meet your team's requirements, design filters that will realize each of your transfer functions. In designing your filters, use actual available part values. Be mindful of loading issues and include both the source and load resistance. You may also want to include other parasitic resistances.

- Circuit simulation using Multisim, producing a frequency response (Bode magnitude) plot for each filter. Use as many standard values as possible and minimize the number of parts, especially potentiometers in your circuit. Heed the special requirements and maximum number of op-amps designated for your particular design.

- Descriptions of how well your filter appears to meet your team's filter requirements. Modify your filters to optimize its performance. You should consider power consumption, parts count, number of different part values, non-standard parts, pole and zero locations, loading concerns, and frequency domain performance. Note all parameters and specifications are $\pm 10\%$.

Each team will build and test its filters to verify performance requirements and then report on that performance.

Prelab Checklist

All of the following should be included in the evolving notebook report:

- Matlab pole-zero plot and Bode plot.
- Circuit designs that meet your specifications using available parts.
- Multisim circuit design schematics.
- Multisim frequency response (Bode plot).
- Overlay plot of Matlab and Multisim Bode plots.

Realization Effort

Construct each of your filters on a protoboard from your design using the parts you selected from the available parts list and successfully simulated. Test, with MyDAQ's help, the individual modules/stages of each of your designs (if your design has more than one module). Be certain you understand the intended function of each module and be certain to explain how each actually performed (gain stage, high-pass stage, low-pass stage, notch filter, tuned filter, etc.) to validate the overall performance of each filter. Include your analysis, diagrams, graphs and tables in your reports.

Generate the Bode plots that show how your filters perform, which are to become part of your report. Keep the two design tasks separate in your data collection, your write-up and your report. Be sure that your filter designs produce the required transfer functions and meet all design constraints: bandwidth, center frequency, passband gain, and quality factor.

Create a complete report of your team's work, including Matlab outputs, Multisim circuit diagram and Bode plots, MyDAQ oscilloscope displays, tabulated frequency data collected from your Bode plots, and your analyses to determine whether your designs have met the specified requirements in support your team's conclusion. Points will be deducted for any missed specification.

Post-Lab Report

The report for this exercise is a formal, professional report produced using Matlab and Word coupled as a notebook. There should be no handwriting on your report. Your lab grade will be based mostly on the report. Use well-written, edited English. Grades will stress technical content (80%) and effective communications (20%) including content, organization, completeness, style, spelling, readability, and neatness. Pay close attention to details such as including all pertinent references for completeness.

Your report should include the following major sections:

- Specifications Assigned.
- Design approaches to meeting specifications.
- Circuit designs with element values.
- Simulations, including plots of outcomes.
- Measurements to verify performance.
- Comparisons, analyses, measures of performance.

Submit your completed Word-based report to your instructor. Provide a hard-copy. Color prints are not required.

Summary

In this lab you should have become familiar with the prediction, design, simulation, building and testing of broadband and high-Q filters. In completing this lab you have employed several analytical tools such as Matlab and Multisim, and laboratory tools such as a myDAQ, including power supply, DMM, function generator and oscilloscope, and LCR meter.

Broadband Filter Requirements

Team	BP or BR	B (kHz)	f_{low} (kHz)	Max Op Amps	Passband Gain (dB)	Load R_L (kΩ)
0,1	BP	12	1	2	5	2
2,3,4	BP	5	0.5	2	10	1
5,6	BR	12	1	3	6	5
7,8,9	BR	5	0.5	3	10	2

High-Q Filter Requirements

Team	Notch or Tuned	Q	f_o (kHz)	Max Op Amps	Passband Gain (dB)	Load R_L (kΩ)
0,1	N	5	1	2	0	1
2,3,4	N	10	2	2	0	5
5,6	T	5	2	2	0	2
7,8,9	T	10	1	2	0	5