Introduction to Signals, Passive RC Filters and Opamps

LAB 1

Introduction

In this laboratory exercise you design, build and test some simple filter circuits. This is mainly for you to get comfortable with circuit design in the frequency domain, and as a brief introduction/review of filtering.

Filters are important blocks in all communication and instrumentation systems. A filter is abstractly represented in terms of the transfer function, H(jω), as shown in Figure 1. Filters are often categorized depending on the frequency domain behavior of the transfer function magnitude. Ideal frequency responses for lowpass, highpass, and *bandpass* filters are shown in Figure 2.

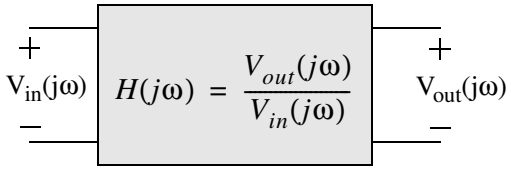

Figure 1 — Abstract two-port representation of a filter circuit.

Week 1: RC Circuits and Frequency Response

Design a passive (no active components; e.g. transistors or opamps) second-order low-pass filter which meets the following specifications (specs):

- The input impedance of the filter (Z_{in} in Fig. 1) should be sufficiently large compared to the signal-source output impedance which is 50Ω.
- The output impedance of the filter (Z_{out} in Figure 3 with input source grounded) should be sufficiently small compared to the input impedance of the load, which is 1MΩ and 100pF.
- A magnitude response that has 3dB signal attenuation at 1kHz and at least 20db signal attenuation at 10kHz.

The simplest possible circuit for this filter design is shown in Figure 3.

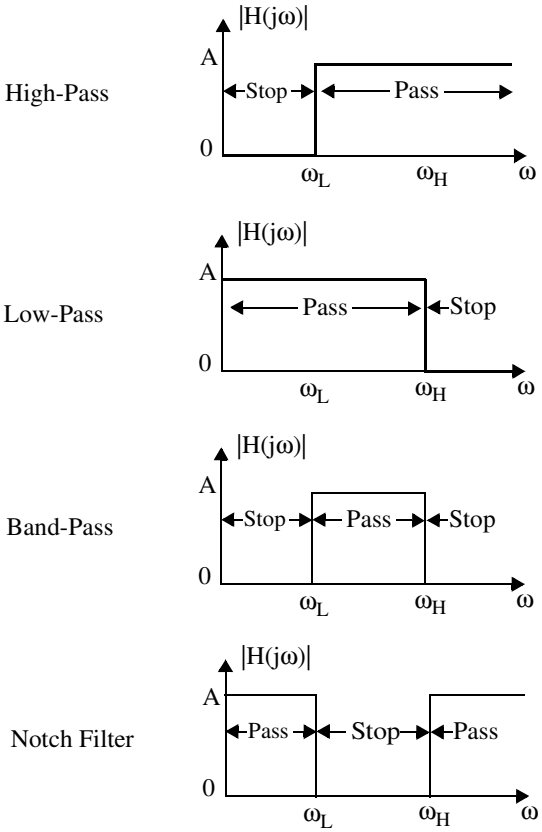

Figure 2 — Ideal filter characteristics.

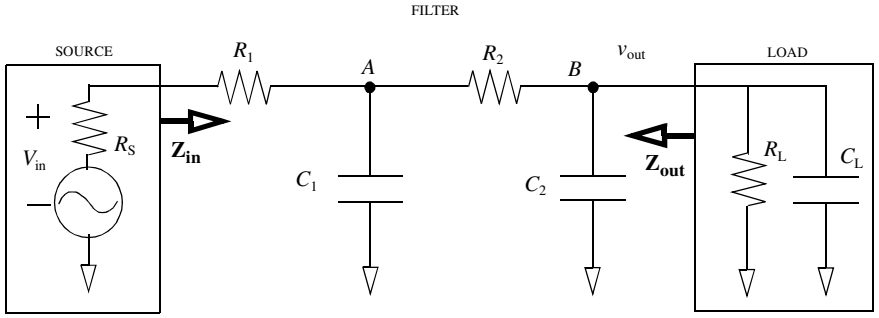

Figure 3 — A second-order RC low pass filter.

Design Procedure

Assuming that RS<<R1, CL<<C2, and the magnitude of Zout, the transfer function for this RC filter can be approximated as:

$$V_{out} = \frac{\dfrac{1}{R_1 R_2 C_1 C_2}}{s^2 + s\left(\dfrac{1}{R_1 C_1} + \dfrac{1}{R_2 C_1} + \dfrac{1}{R_2 C_2}\right) + \dfrac{1}{R_1 R_2 C_1 C_2}} V_{in} \qquad (4)$$

There are four design variables and two poles to achieve the required frequency response. The additional constraints come from the input and output impedance specifications. Explain how you selected your circuit values in your lab books and in your lab report.

Use your signal generator as the source, and your oscilloscope as the load to measure and plot the magnitude and phase responses of the output from 100 Hz to 1 MHz. Verify that your signal generator and oscilloscope are reasonably close to the actual source and load specifications. Plot your data on graphs in dB on a semi-log scale. Include on your graphs the Bode plots you obtain from the transfer function shown in equation (4).

In your report comment on your experimental results. How well does the Bode plot approximate the real response? If your design had an output impedance comparable to that of the scope, how would it affect the overall transfer function? Ideally what values would you want for the input and output impedances of your filter? Explain why it is not possible to approach these ideal values for this design.

Week 2: Filter Design using Opamps

Our filtering capabilities with passive components is quite limited. It is extremely difficult to meet aggressive specs and produce a reasonably high quality filter response. Opamps can be used with R's and C's (and L's) to create superior filters in terms of input and output impedances, and overall quality. With opamps, the pass-band regions can also be amplified if necessary.

Fig. 5 shows the active-RC (inductorless) implementation of a bandpass filter utilizing opamps. This circuit is actually a combined low-pass and high-pass filter to create a band-pass effect. Derive the expression for the transfer function H(jω) for this filter then select the R and C values to meet the following specs:

- f_L = 950 Hz, f_H = 1.05 kHz
- midband gain of 3.5 volts/volt.
- An input impedance >=10kΩ over all frequencies.

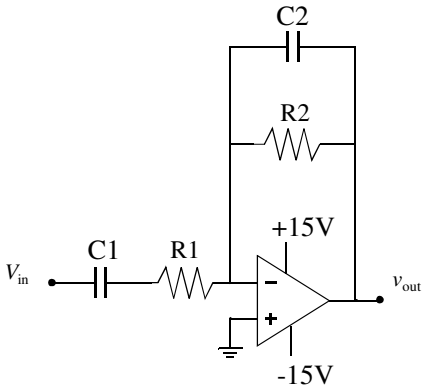

Figure 4 — 2nd order active-RC bandpass filter.

Measure the magnitude of the filter at the lower and upper 3dB frequencies. Comment on any discrepancies you observe between the 3dB frequencies you designed for and your measurements? Comment on the difference between your bandpass filter and the ideal transfer function model in Fig. 4. What suggestions, if any, do you recommend for an improved frequency response? If time permits, modify your design as required.

D. Notch Filter Design

Like the band pass filter, the notch filter is simply the combination of a low pass filter and a high pass filter. However, in the case of the band pass filter, the frequencies of interest are passed by both the low pass filter and the high pass filter. This allows the two filters to be connected as shown in Fig. 4. This scheme will NOT work for a notch filter, since most of the frequencies attenuated by the low pass filter are in the pass band of the high pass filter, and vice versa. Thus it is necessary to build a high pass filter and a low pass filter, and sum them using a summing amplifier. Design an active-RC notch filter to meet the following specs:

- at least 20 dB of attenuation at 10 kHz, which is the most attenuated frequency
- pass band gain of 3.5 V/V
- An input impedance >= 10kΩ over all frequencies.

Measure the magnitude of the filter at the lower and upper 3dB frequencies. Comment on any discrepancies you observe between the 3dB frequencies you designed for and your measurements? Comment on the difference between your notch filter and the ideal transfer function you found. What suggestions, if any, do you recommend for an improved frequency response? If time permits, modify your design as required. Explain whether or not this circuit performed as you had expected. If not, explain why.

Appendix A. Good Analog Design Techniques

In order to have an analog circuit that functions predictably and reliably, good analog design techniques are necessary. Here are some suggestions for making your lab experience less frustrating and more productive:

- If you have an old protoboard, (one that has at one point caught fire, melted, or one that has been corrupted by plugging in digital IC's from 18-240 lab) chances are you will need a new protoboard. Beneath all those little sockets are metal clips, which spread out every time you plug something into them. By the time you have done this several times, they no longer make good contact with wires or IC pins. As a result, you will see strange, noisy waveforms on your oscilloscope, get unpredictable results, or get no results at all. While your protoboard may be ok for the 1's and 0's of digital IC's, analog components are much more sensitive. Protoboards are available at Tech Electronics.

- Try to keep all signal lines away from power lines, and in general keep all lines a short as possible. Noise can and will find its way into your circuit wherever possible. Long signal paths and power supply lines kept near signal paths are susceptible to noise pickup and coupling.
- Try to keep all your component leads as short as possible. Having wires and components going an inch up into the air and then back into your protoboard will result in noisy and unpredictable performance, especially as you get up into higher frequencies. Clip component leads and wires, and try to get those components flush with the surface of your protoboard. Think about a real circuit board... you don't see components with bent leads an inch up in the air wiggling around!
- Make sure you have a solid ground reference. Without one, your circuit will be 'floating' and will perform miserably or not at all.
- It is unrealistic to put the whole circuit together and expect it to work. Instead, try to build your design in stages, and test it at every step along the way. Following these general guidelines will not only result in a circuit that works better, but will also make the debugging process much simpler. The extra time spent carefully cutting wires and leads and placing components will save you much more time in debugging later on.

Appendix B. About Your Lab Report

Your lab report should contain all of the lab results (data, graphs, drawings, etc.) It should be a self-contained self-explanatory report. It should be more than a list of answers to the questions in the lab notes. Your comments on the results should reflect your understanding of the lab exercises. Your well thought out reasoning and analyses of the experimental results will be appreciated and reflected in your grade. The report need not be typed or prepared with a word processor, however, points will be deducted for a sloppy, un-professional report.

Appendix C

C.1 Resistor Color Codes

Resistors are identified by four color bands. The fourth band is always gold or silver and indicates the resistor precision. If we consider the other bands as displayed in Figure 4, the value of the resistor can be described as follows,

$$[(B_1 \times 10) + B_2] \times 10^{B_3}$$

Thus, a resistor of colors Brown, Black, Red would have a value of,

$$[(1 \times 10) + 0] \times 10^2 \; = \; 10 \times 100 \; = \; 1000\Omega$$

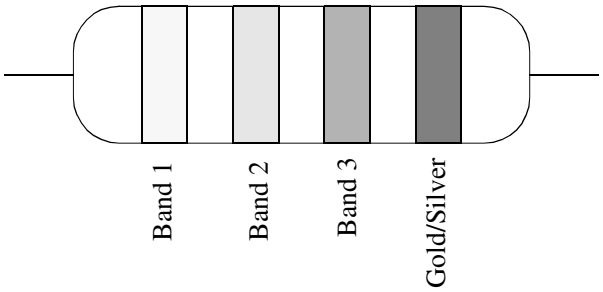

Figure 4. Resistor color bands.

Color	Value
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Grey	8
White	9

C.2 Measuring RMS values and Amplitudes

The RMS value of a periodic current/voltage signal is defined as a constant that is equal to the dc current/voltage that would deliver the same average power to a resistance, R. Thus,

$$P = RI_{rms}^2 = \frac{1}{T}\int_0^T RI^2(t)dt \quad (1)$$

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T I^2(t)dt} \quad (2)$$

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T V^2(t)dt} \quad (3)$$

The digital multimeter on your lab bench is reading in RMS units. You might want to compare this with the ac signals displayed on your oscilloscope for some sample signals from your signal generator. For the sinusoidal signals that you will be measuring most often, the peak value is related to the RMS value by:

$$V_{rms} = \frac{V_p}{\sqrt{2}}$$

Parts List

LM741 Operational Amplifiers

Resistors

Capacitors