EE283 Lab 9
Series RLC
Bandpass Filter

Objective:

In the Lab 8 Exercise we learned about active lowpass filters which pass all low frequencies below the cutoff frequency and reject all high frequencies above the cutoff frequency. In this lab exercise we will learn about passive bandpass filters which pass a certain band of frequencies (the passband frequencies) and reject all frequencies above and below the passband frequencies. A passive filter contains only resistors, capacitors and inductors.

Theory:

Figure 1 shows the magnitude response of a typical bandpass filter. At the resonate frequency, ω_0, the filter has a maximum gain (V_{OUT}/V_S). At frequencies, ω_L and ω_U, the gain has decreased to 0.707 (-3db) times the maximum gain. For bandpass filters, β is called the bandwidth and is equal to $\omega_U - \omega_L$. The series RLC circuit to be investigated in this exercise is a passive bandpass filter.

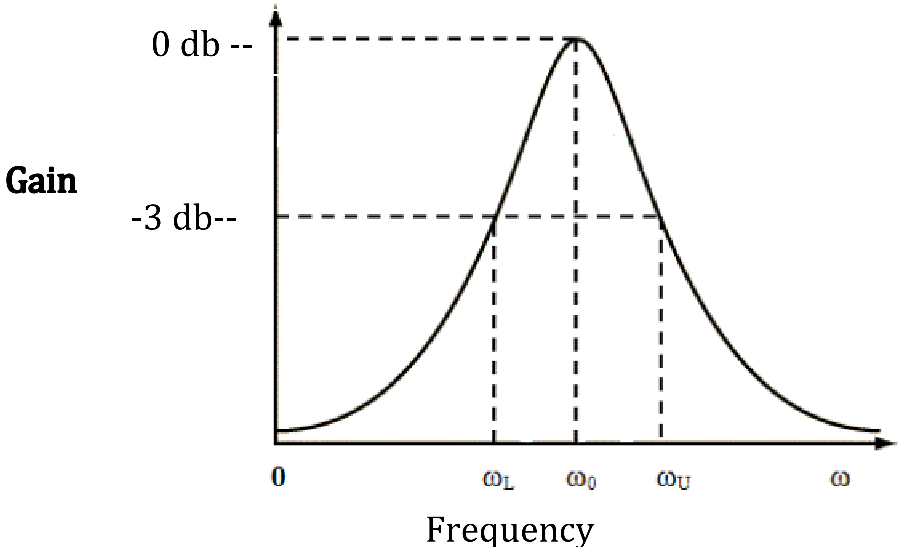

Figure 1

Frequency Response of a Bandpass Filter

A series resonant circuit is shown in Figure 2.

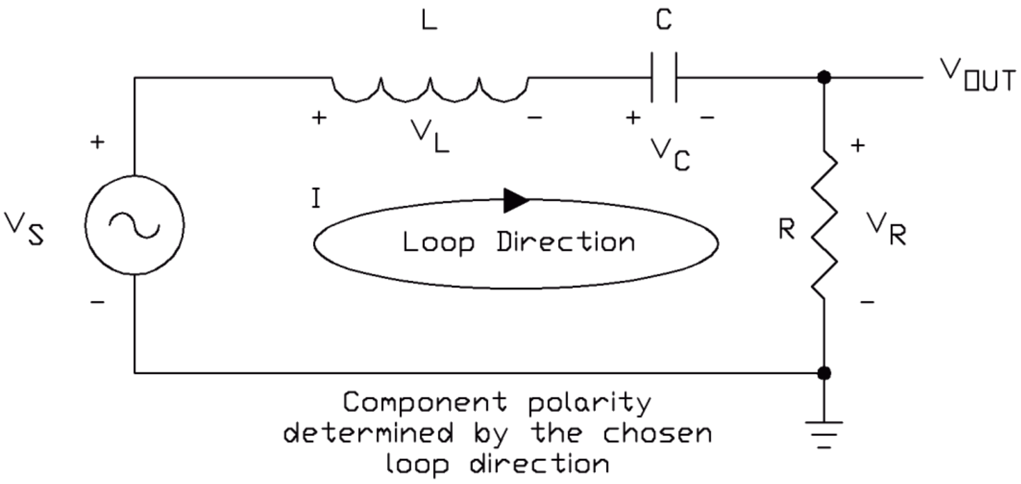

Figure 2
Series RLC Bandpass Filter

Because this is an AC circuit, all of the voltages and currents are phasors and are shown in bold face. Using KVL

$$\mathbf{V_S} = \mathbf{V_L} + \mathbf{V_C} + \mathbf{V_R} \quad \text{EQ 1}$$

where

$\mathbf{V_S}$ = supply voltage phasor

$\mathbf{V_L} = \mathbf{IX_L}$ inductor voltage drop phasor

$\mathbf{V_C} = \mathbf{IX_C}$ capacitor voltage drop phasor

$\mathbf{V_R} = \mathbf{I}R$ resistor voltage drop phasor

The inductive reactance $\mathbf{X_L} = j\omega L = j2\pi fL$

The capacitive reactance $\mathbf{X_C} = \frac{1}{j\omega C} = \frac{-j}{\omega C} = \frac{-j}{2\pi fC}$

From EQ 1

$$\mathbf{V_S} = \mathbf{I}\left(R + j\omega L - \frac{j}{\omega C}\right) = \mathbf{IZ}$$

Then the complex impedance of the circuit, **Z,** is

$$\mathbf{Z} = \mathrm{R}+\mathrm{j}\left(\omega L-\frac{1}{\omega C}\right)$$

At a particular frequency, when

$$\omega\mathrm{L}=\frac{1}{\omega\mathrm{C}}=2\pi\mathrm{fL}=\frac{1}{2\pi\mathrm{fC}}$$

$$\mathrm{f}=\mathrm{f}_0=\frac{1}{2\pi\sqrt{\mathrm{LC}}} \quad \text{EQ 2}$$

The frequency, f_0, is called the resonant frequency. At resonance the impedance **Z** = R and is at a minimum. Since at resonance there is no impedance between V_S and V_R, $V_S = V_R$. At frequency f_0 the current is

$$|\mathrm{I}|=\frac{\mathrm{V_S}}{\mathrm{R}}$$

and reaches a maximum value for a given voltage V_S.

The resonance condition at f_0 shown using phasors is illustrated in Figure 3.

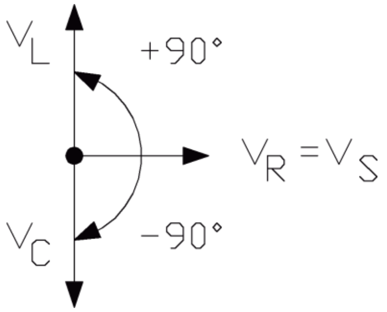

Figure 3
Phasor Diagram at Resonance

As can be seen , at resonance, current is a maximum, power factor is unity, impedance is equal to resistance, $|V_L| = |V_C|$ and each is equal to the quality factor times $|V_S|$. At lower frequencies the circuit is capacitive since $\mathbf{X_C}$>$\mathbf{X_L}$, and at higher frequencies it is more inductive since $\mathbf{X_L}$>$\mathbf{X_C}$**.**

If $2\pi f_1 = \omega_L$ and $2\pi f_2 = \omega_U$ then f_1 and f_2 are called the half power frequencies where the current is 0.707 times the maximum current at resonance. These frequencies can be calculated as follows:

$$f_1=\frac{1}{2\pi}\left\{\left(-\frac{R}{2L}+\sqrt{\left(\frac{R}{2L}\right)^2+\frac{1}{LC}}\right)\right\}\ \text{Hz}\quad \text{EQ 3}$$

$$f_2=\frac{1}{2\pi}\left\{\left(+\frac{R}{2L}+\sqrt{\left(\frac{R}{2L}\right)^2+\frac{1}{LC}}\right)\right\}\ \text{Hz}\quad \text{EQ 4}$$

The bandwidth β is defined as $\beta = f_2 - f_1$ or

$$\beta=\frac{R}{2\pi L}\ \text{Hz}\quad \text{EQ 5}$$

and represents the band of frequencies between f_1 and f_2 in which the current is high. The quality factor is defined as the ratio of the resonant frequency to the bandwidth.

$$Q=\frac{f_0}{\beta}=\frac{1}{R}\sqrt{\frac{L}{C}}=\frac{2\pi f_0 L}{R}=\frac{1}{2\pi f_0 CR}$$

At resonance, $|V_L| = |V_C| = QV_S$

Equipment:

- Digital Multimeter (DMM Keysight 34461A)
- Tektronix TBS 1064 Oscilloscope
- Tektronix AFG 1022 Function Generator
- 100 Ohm Resistor, 0.22µF Capacitor, 50mH Inductor
- Breadboard

Procedure:

- Construct the circuit shown below in Figure 4. Use the Tektronix AFG 1022 Function Generator output 1 for V_S and connect the Tektronix TBS 1064 Oscilloscope CH 1 and 2 as shown. This figure must appear in your report. Calculate the resonant frequency, f_0, using EQ 2. This calculation must appear in your report. Set the function generator frequency to the resonant frequency that you calculated and set the amplitude to 5 volts.

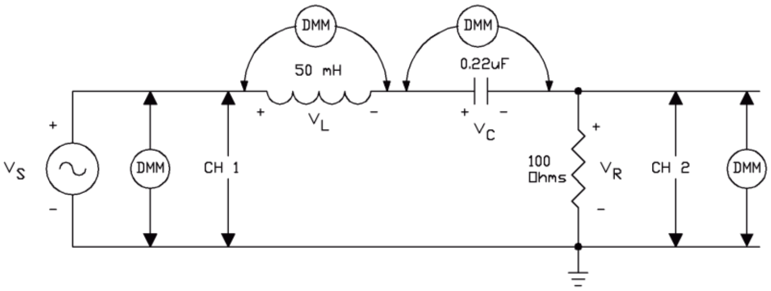

Figure 4
Test Setup

Due to component tolerances the values for the inductor and capacitor may not be exactly the same as those used in your calculations but the actual resonant frequency should be very close to what you calculated. To determine the actual resonant frequency connect the DMM to read the AC voltage across the 100 ohm resistor and note the voltage reading. Then increase the function generator frequency by 30 Hz. Did the DMM voltage increase or decrease? Based on the DMM voltage increasing or decreasing do <u>one</u> of the following:

- If the DMM voltage increased the function generataor frequency is too low. Increase the function generator frequency by 10 Hz and again note the DMM voltage. Continue increasing the frequency by 10 Hz until the DMM voltage begins to decrease. At that point decrease the frequency by 10 Hz. This is now the actual resonant frequency, f_0. At this frequency the CH 1 and CH 2 oscilloscope waveforms should be exactly in phase.
- If the DMM voltage decreased the function generator frequency is too high. Decrease the function generator frequency by 10 Hz and again note the DMM voltage. Continue decreasing the frequency by 10 Hz until the DMM voltage begins to decrease. At that point increase the frequency by 10 Hz. This is now the actual resonant frequency, f_0. At this frequency the CH 1 and CH 2 oscilloscope waveforms should be exactly in phase.

Only one DMM will be used to measure the voltages across the inductor, (V_L), the capacitor, (V_C), the function generator output voltage, (V_S), and the 100 ohm resistor voltage, (V_R). Since these are AC measurements the polarity does not matter. In the Lab 8 Exercise (the lowpass filter exercise) we measured the function generator output voltage at 100 Hz and assumed it was the same for all frequencies. This was a good assumption since the input impedance to the lowpass filter was high at all frequencies compared to the output impedance of the function generator. In this exercise the impedance looking into the filter (from the generator side) is low and varies with frequency. This creates a voltage drop across the function generator's internal 50 ohm output impedance and causes the function generator output voltage, V_S, to change with frequency (especially around the resonant frequency where the loop current is high).

Starting at the actual resonant frequency, record the frequency, V_S, V_L, V_C and V_R in an Excel spreadsheet. Also note whether the current (CH 2) leads or lags the input voltage (CH 1).

Increase the frequency by 20 Hz and again record the frequency, V_S, V_L, V_C, V_R and the lead/lag information. Continue to increase the frequency by 20 Hz steps (recording data at each frequency) until the value of V_R/V_S has decreased to less than 0.707 times the value it had at the actual resonant frequency. At that point you can increase the frequency steps to 100 Hz (recording data at each frequency) until you reach 3000 Hz. Reset the frequency to the actual resonant frequency. Decrease the frequency by 20 Hz and again record the frequency, V_S, V_L, V_C, V_R and the lead/lag information. Continue to decrease the frequency by 20 Hz steps (recording data at each frequency) until the value of V_R/V_S has decreased to less than 0.707 times the value it had at the actual resonant frequency. At that point you can increase the frequency steps to 100 Hz (recording data at each frequency) until you reach 700 Hz. The data in your Excel spreadsheet should look like that shown in Table 1 and <u>must be included in your report</u>.

Frequency Hz	V_S Volts (RMS)	V_L Volts (RMS)	V_C Volts (RMS)	V_R Volts (RMS)	Lead or Lag	Gain V_R/V_S

Table 1
Excel Spreadsheet Format

You don't have to put the data in order of increasing frequency. Just enter the frequency and the data – Excel will figure it out.

Create an Excel graph using frequency as the horizontal axis and the filter gain, V_R/V_S, on the vertical axis. Use linear axis. Your graph should look similar to Figure 1.The graph must have a title and each axis must be properly annotated. The graph <u>must be included in your report.</u> The voltage, V_R, is representative of the current in the circuit. <u>From the graph</u> determine the resonant frequency, f_0, the upper and lower cutoff frequencies, f_1 and f_2, and the bandwidth, β. <u>These frequencies must be marked on your graph.</u>

Using either LTspice or PSpice simulate the circuit shown in Figure 4. Set the spice voltage source amplitude to 3.5355V ($5/\sqrt{2}$) so the spice voltage, V_R, will be in RMS units. Sweep the frequency from 700 Hz to 3000 Hz. Use the cursors to determine the resonant frequency, the cutoff frequencies, the bandwidth and the maximum output voltage, V_R. The <u>simulation circuit</u>

and the simulation graph must be included in your report. These frequencies and output voltage, V_R must be marked on your graph.

In Table 2 compare the resonant frequency, f_0, the cutoff frequencies, f_1 and f_2, the bandwidth, β, and the maximum output voltage, V_R, between your calculated values (from equations 2, 3, 4 and 5), your measured values and the simulated values. All calculations must be shown for the calculated values in Table 2. Table 2 must be included in your report.

	Resonant Frequency f_0 Hz	Lower Cutoff Frequency f_1 Hz	Upper Cutoff Frequency f_2 Hz	Bandwidth β Hz	Maximum Output Voltage V_R Volts RMS at f_0
Calculated					
Measured					
Simulated					

Table 2
Comparison Between Calculated, Measured and Simulated Values

Extra Credit (+20%)

You will probably notice some differences between your measured , simulated and calculated data. If you can “explain” these differencs I will consider adding up to 20% to your lab grade. By “explain” I don’t mean “the component tolerances affected the readings” or “the test equipment was out of calibration” or “I made a mistake when I took the data”.
I want hard facts with some calculations! Component tolerances, equipment calibration and operator errors are not what I am looking for.

Help:
If you need help calculating values in the report don’t wait until you hand it in and I correct it. Send me an email before you hand the report in and I will try and help you.