2: Passive Bandpass Filter Design

ECE 3200 Electronics II
updated 25 January 2021

References

1. A. S. Sedra and K. C. Smith, *Microelectronic Circuits*, 7th ed., Oxford University Press, 2015.

2. W. H. Middendorf and R. H. Engelmann, *Design of Devices and Systems*, Marcel Dekker, 3rd ed., 1998. This is the current text for the ECE Senior Design Sequence. In that class you will explore design methods to turn *specifications* (what the device is supposed to do) to *parameters* (information to build the device that meets the specs, e.g. schematics and component values).

Objectives

1. To generate a design based on a set of specifications.

2. To demonstrate the measurement and application of Bode plots in circuit design and analysis.

3. To improve and further develop an ability to effectively communicate technical information via a written report.

Pre-Laboratory Assignment
(ONE PRE-LAB ASSIGNMENT PER GROUP — WORK TOGETHER)

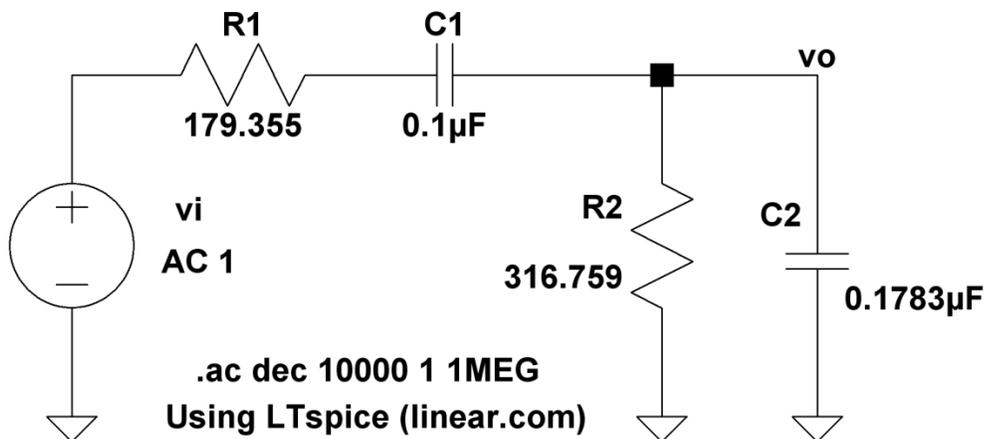Consider the circuit of Figure 1.

Figure 1. Passive Bandpass Filter
(values give a center frequency of $f_0 = 5\text{kHz}$ and are for illustrative purposes only)

Design this bandpass filter to meet the following specifications (exact values will be given in class); that is, select parameters R_1, R_2, C_1, and C_2.

- Center frequency of f_0
- Quality factor of Q
- Gain at center frequency T_p

These equations will be useful during your work:

$$T(s) = \frac{V_o(s)}{V_i(s)} = \frac{s R_2 C_1}{1 + s(R_1 C_1 + R_2 C_2 + R_2 C_1) + s^2 (R_1 R_2 C_1 C_2)}$$

$$\omega_0 = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}$$

$$T_p = \frac{R_2 C_1}{R_1 C_1 + R_2 C_2 + R_2 C_1}.$$

If

$$f_R = \sqrt{\frac{R_2}{R_1}}$$

and

$$f_C = \sqrt{\frac{C_2}{C_1}}$$

then

$$Q^{-1} = f_R f_C + \frac{1}{f_R f_C} + \frac{f_R}{f_C}$$

$$T_p = Q \frac{f_R}{f_C}$$

and

$$\omega_0 = \frac{1}{R_2 C_1} \frac{f_R}{f_C} = \frac{1}{R_2 C_2} f_R f_C.$$

Note that

$$T(j\omega) = \frac{j\omega \left(\omega_0 \frac{T_p}{Q} \right)}{(\omega_0^2 - \omega^2) + j\omega \left(\frac{\omega_0}{Q} \right)}.$$

The pre-lab **must** include the following (see note below):

1. Bode plots (magnitude and phase) for the response using your *ideal* component values (i.e. without regard to available values). Show that these results meet all of the specifications EXACTLY with zero error.

2. Bode plots (magnitude and phase) for the circuit response using *available standard* component values. Demonstrate that these values provide an acceptable level of performance. It is **YOUR** job to **MEET** the specifications as closely as possible. This may require several iterations of choosing component values. You **MUST** use available resistor and capacitor values in your final design. Do not use electrolytic capacitors.

Available standard capacitor values
(avoid using small capacitance values, say less than 220pF)

Hilitchi Monolithic Multilayer Ceramic Capacitor Assortment Kit HCC525	Hilitchi Mylar Polyester Film Capacitor Assortment Kit HPFC-700	CERAMIC DISC CAPACITOR COMPONENT KIT	Hilitchi Monolithic Multilayer Ceramic Capacitor Assortment Kit HDR-550
OCR Ceramic Capacitor Assortment Kit	0.22nF	10pF	0.1uF
	0.33nF	22pF	0.15uF
10pF	0.47nF	47pF	0.22uF
20pF	0.56nF	100pF	0.33uF
30pF	0.68nF	470pF	0.47uF
47pF	1nF	0.001uF	0.68uF
56pF	2.2nF	0.022uF	1uF
68pF	2.7nF	0.047uF	2.2uF
100pF	3.3nF	0.01uF	4.7uF
220pF	3.9nF	0.1uF	10uF
330pF	4.7nF		
680pF	6.8nF		
1nF	10nF		
4.7nF	15nF		
10nF	22nF		
47nF	33nF		
100nF	39nF		
	47nF		
	68nF		
	82nF		
	100nF		
	150nF		
	220nF		
	470nF		

Available standard resistor values
10Ω, 47Ω, 100Ω, 150Ω, 220Ω, 270Ω, 330Ω, 390Ω, 470Ω, 680Ω, 1kΩ, 1.2kΩ, 1.5kΩ, 2kΩ, 2.2kΩ, 2.7kΩ, 3.3kΩ, 4.7kΩ, 5.1kΩ, 5.6kΩ, 10kΩ, 15kΩ, 20kΩ, 22kΩ, 33kΩ, 47kΩ, 100kΩ, 470kΩ, 1MΩ, 10MΩ

NOTE: Use LTspice to produce the Bode plots. Use a frequency range from $0.1f_0$ to $10f_0$.

Place a copy of your pre-lab in your lab notebook, including the Bode plots.
Make sure that your pre-lab assignment meets the guidelines as outlined in section1.6.

Procedures

1. Construct the circuit using components which are within 10% of the design values. Measure your capacitor values. YOU ARE NOT ALLOWED TO USE RESISTOR OR CAPACITOR SUBSTITUTION BOXES.

2. CENTER FREQUENCY MEASUREMENT. With the input set to a 2 V peak-to-peak sine wave, display the output waveform on the scope. Adjust the input frequency until the output amplitude peaks. Note that this is the actual center frequency of your circuit, f_0. Compare to the design value. Discuss any serious discrepancies with the instructor. Your lab notebook entry should look something like:

   Procedure Part 2 Center frequency measurement

   Adjusted signal generator to peak output.
   Peak-to-Peak voltage of input via scope: xxx.x V
   Peak-to-Peak voltage of output via scope: xxx.x V

   Measured frequency via scope: f0=xxx.x Hz
   Design Value: xxx.x Hz
   Percent error: x.x %

   The center frequency is off only x.x %. This is due to....

3. FREQUENCY RESPONSE MEASUREMENT. Using a sine wave input, measure and plot the magnitude and phase of your circuit transfer function as the input frequency is varied. The test frequency should range from $0.1f_0$ to $10f_0$. The test frequencies should be geometrically equally spaced over the interval (Let the first test frequency be $f_0/10$. Then each successive frequency is k times the previous, where $k = 100^{\left(\frac{1}{N}\right)}$. Choose the number of data points N as an even number to insure that f_0 is one of the test frequencies. Choose N at least 10). You may wish to take additional measurements as well. Use the scope's dual channel capability to simultaneously display the input and output sine waves. For each frequency:

   a. Record the amplitudes of both. The ratio is $|T(j\omega)|$. Calculate the gain in decibels. DO NOT ASSUME THAT THE SIGNAL GENERATOR OUTPUT VOLTAGE DOES NOT CHANGE WITH FREQUENCY!

   b. Find $\angle T(j\omega)$ by using the scope cursors to measure the time difference between peaks of the input and output waves. Record this time difference in units of scope divisions as well as seconds. The phase angle in radians is $\omega\Delta t$ (also record the angle in degrees, 360 fΔt). BE SURE TO NOTE WHETHER THE OUTPUT IS LEADING OR LAGGING THE INPUT. The phase angle is positive for the output leading the input and negative for the output lagging the input.

As you take your data compare your results to those obtained in the pre-lab. PLOT YOUR DATA ON YOUR PRE-LAB MAGNITUDE AND PHASE PLOTS. Resolve any serious discrepancies.

MEASURE (AGAIN?) THE MAGNITUDE AND PHASE AT f_0, $3f_0$, and $5f_0$. Compare this data with your pre-lab results to insure its accuracy. You will need this data to complete the lab exercises.

4. CIRCUIT BANDWIDTH AND Q MEASUREMENT. Find and record the two frequencies at which $|T(j\omega)|$ is 3dB down from its peak. Use this to estimate the circuit bandwidth BW and hence the circuit Q = f_0/BW. Compare to the design value.

5. GAIN COMPARISON. Compare the gain T_p at f_0 to the design value.

6. Discuss any serious discrepancies with the instructor. Remember that it is YOUR job to meet the specifications.

7. SQUARE WAVE RESPONSE MEASUREMENT. Once your circuit is operating within specs, display the response of your circuit to a square wave input at f_0 Hz. The input square wave must be symmetric about zero volts. The output waveform should be symmetric about zero volts (WHY?). Display both the input and output waveforms on the scope. Get a hardcopy printout and place in your notebook.

Exercise
Conduct a theoretical analysis of the circuit response to the f_0 square wave. Proceed as follows. Express the input waveform as a Fourier series. Use the first three non-zero terms for your analysis, i.e.

$$v_i(t) = \frac{4V_p}{\pi}\left[\sin(2\pi f_0 t) + \frac{1}{3}\sin(2\pi 3 f_0 t) + \frac{1}{5}\sin(2\pi 5 f_0 t)\right].$$

Find the circuit response to each of these three sinusoids by using your experimental gain and phase plots, i.e. $|T(j\omega)|$ and $\angle T(j\omega)$ at f_0, $3f_0$, and $5f_0$. Denote the gains as T_1, T_2, and T_3, respectively, and the angles as Θ_1, Θ_2, and Θ_3, respectively. Thus the output voltage is approximately

$$v_o(t) = \frac{4V_p}{\pi}\left[T_1\sin(2\pi f_0 t + \Theta_1) + T_2\frac{1}{3}\sin(2\pi 3 f_0 t + \Theta_2) + T_3\frac{1}{5}\sin(2\pi 5 f_0 t + \Theta_3)\right].$$

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Plot both equations for $v_i(t)$ and $v_o(t)$ using a computer tool of your choice. Compare the results to those observed in the laboratory. Also plot each individual sinusoid in the equations for $v_i(t)$ and $v_o(t)$ to show the relative contribution of each to the waveforms.

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