3: Active 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 design a circuit that uses an operational amplifier.

4. 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)
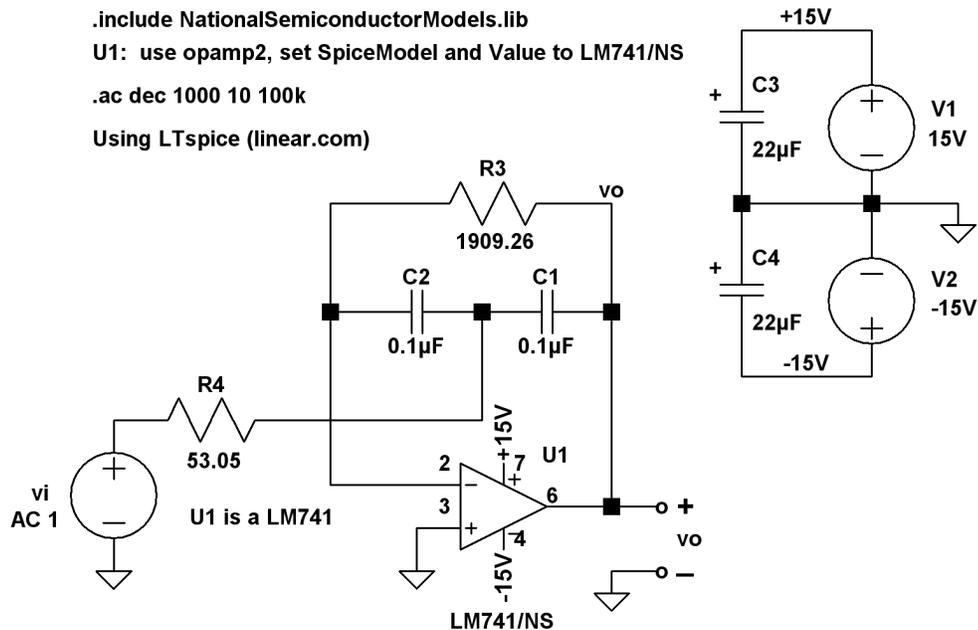Consider the circuit of Figure 1.

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

Design this active bandpass filter to meet the following specifications (exact values will be given in class):

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

These equations will be useful during your work. Let $R_3 = R$, $R_4 = \frac{R}{m} > 500\Omega$, and $C_1 = C_2 = C$. Then

$$T(s) = \frac{V_o(s)}{V_i(s)} = \frac{\left(-\frac{m}{RC}\right)s}{\frac{m}{(RC)^2}+\left(\frac{2}{RC}\right)s+s^2}$$

$$\omega_0 = \frac{\sqrt{m}}{RC}$$

$$Q = \frac{\sqrt{m}}{2}$$

and

$$T_0(j\omega_0) = \frac{m}{2}\angle 180°= T_p\angle 180°.$$

The pre-lab must include the following:

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!

2. Bode plots (magnitude and phase) for the circuit response using available 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 (see table below). You are allowed to "build" one of the listed values if that part is not available in the lab. Do not use electrolytic capacitors.

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

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

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	
	0.33nF	22pF	0.1uF
	0.47nF	47pF	0.15uF
10pF	0.56nF	100pF	0.22uF
20pF	0.68nF	470pF	0.33uF
30pF	1nF	0.001uF	0.47uF
47pF	2.2nF	0.022uF	0.68uF
56pF	2.7nF	0.047uF	1uF
68pF	3.3nF	0.01uF	2.2uF
100pF	3.9nF	0.1uF	4.7uF
220pF	4.7nF		10uF
330pF	6.8nF		
680pF	10nF		
1nF	15nF		
4.7nF	22nF		
10nF	33nF		
47nF	39nF		
100nF	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

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 $10/T_p$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.

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 for a square wave input of f_0 Hz. The input square wave must be symmetric about zero volts. Observe that the circuit tends to exaggerate the content of the center frequency. The output waveform should be symmetric about zero volts (WHY?) and not

clipped. Display both the input and output waveforms on the scope. Get a hardcopy printout and place in your notebook.

Exercise

1. 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

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

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.

2. Compare and contrast the active bandpass filter with the passive bandpass filter of the previous laboratory. What are the chief advantages and drawbacks of each circuit? Be specific and justify your conclusions based on engineering science.

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