LAB 4: ACTIVE BAND-PASS FILTER PROJECT

ELEC3509 A-L6

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INTODUCTION

The purpose of this lab is to create a filter using standardized filter blocks. This lab discusses second and fourth order filter circuits also the Chebyshev filter response in the context of a design problem. The design process used in this lab is very similar to the design process used for modern digital filters and transmission line filters.

THEORY AND DESIGN

- **Chebyshev Filter Design Requirements**

  1. Band-pass action
  2. Chebyshev response
  3. 3 dB passband ripple
  4. Fourth-order roll-off
  5. Lower cut-off frequency and upper cut-off
  6. Target passband gain = +0.0 dB to -3.0dB
  7. $\pm$8% error allowed in f_{-3dB}
  8. $\pm$1.0 dB error allowed in passband gain
  9. Supply voltages to be ±15 volts 10
  10. Op-Amps to be type TL082CD (No more than 6 Op-Amps total)
  11. Output voltage swing > ±10 volts

$$A = X\ mod\ 1031 = 127$$

$$B = X\ mod\ 1033 = 271$$

- **Lower Cut-off Frequency**

$$f_{-3dB\ Lower} = \frac{A^5}{5.534 * 10^9} - \frac{A^4}{2.11 * 10^6} + \frac{A^3}{2287} - \frac{A^2}{6.1} + 20.2A + 750 = 1449.64\ Hz$$

$$\delta = -\frac{B^2}{180000} + \frac{B}{173} + 0.5 = 1.66$$

- **Upper Cut-off Frequency**

$$f_{-3dB\ Upper} = f_{-3dB\ Lower}(1 + \delta) = 3856.04\ Hz$$

- **Bandwidth**

$$BW = 2\pi(f_{-3dB\,Upper} - f_{-3dBLower}) = 15119.87\,rad/s$$

- **Corner Frequency**

$$w_o = 2\pi\sqrt{f_{-3dB\,Upper} * f_{-3dB\,Lower}} = 14855.28\,rad/s$$

- **Quality Factor**

$$Q = \frac{w_o}{BW} = 0.983$$

- **Error allowed in $\boldsymbol{f_{-3dB}}$**

$$f_{-3dB\,Lower}\,Error = f_{-3dB\,Lower} * 8\% = 1449.64 * 8\% = \pm\,115.97\,Hz$$

$$f_{-3dB\,Upper}\,Error = f_{-3dB\,Upper} * 8\% = 3856.04 * 8\% = \pm\,308.48\,Hz$$

- **Ripple is $\boldsymbol{A_{max} = 3\,dB}$**

$$\epsilon = \sqrt{10^{\frac{A_{max}}{10}} - 1} = \sqrt{10^{\frac{3}{10}} - 1} = 0.998$$

- **Transfer Function**

The equation below is the general form for the second order 3 dB pass-band ripple Chebyshev filter.

$$H_2(S) = \frac{0.7079 * 0.7079}{S^2 + 0.6449S + 0.7079}$$

The equation below is the general form for the second order 3 dB pass-band ripple Chebyshev filter in terms of a, b, and c.

$$H_2(S) = \frac{a}{S^2 + bS + c}$$

By comparing both equation of the second order 3 dB pass-band ripple Chebyshev filter shown above, variables a, b, and c was determined as shown below

$$a = 0.7079^2 = 0.5011$$

$$b = 0.6449$$

$$c = 0.7079$$

The equation shown below is then below is then substituted into the second order filter to transform the second order filter equation to fourth order filter equation.

$$S \rightarrow \frac{S^2 + w_o^2}{BW} = \frac{Q[\left(\frac{S}{w_o}\right)^2 + 1]}{\left(\frac{S}{w_o}\right)} = \frac{S^2 + w_o^2}{BW * S};\ Q = \frac{w_o}{BW}$$

After substituting the equation above, we end up with the fourth order filter equation as shown below.

$$H_4(S) = \frac{aBW^2S^2}{S^4 + bBWS^3 + (2w_o^2 + cBW^2)S^2 + bBWw_o^2S + w_o^4}$$

After substituting the values of $a, b, c, BW,$ and w_o, we get the following equation for the fourth order filter equation as shown below.

$$H_4(S) = \frac{(114.56 * 10^6)S^2}{S^4 + (9750.80)S^3 + (603.19 * 10^6)S^2 + (2.15 * 10^{12})S + (4.8699 * 10^{16})}$$

The fourth order transfer function shown above consists of two second order transfer functions. In order to find those two second order transfer function $\left(H_A(S)\ \&\ H_B(S)\right)$, we will need to solve the following equations shown below.

$$H_{BP}(S) = \frac{aBW^2S^2}{\left(S^2 + \frac{w_o w_{01}}{q_1}S + (w_o w_{01})^2\right)\left(S^2 + \frac{w_o w_{02}}{q_2}S + (w_o w_{02})^2\right)}$$

$$q^2 = \frac{Q}{b}\left(\left(\frac{2Q}{b} + \frac{c}{2bQ}\right) + \sqrt{\left(\frac{2Q}{b} + \frac{c}{2bQ}\right)^2 - 1}\right) = 10.78$$

$$\therefore q = 3.28$$

$$w_{02} = \frac{aq}{2Q} + \frac{1}{2}\sqrt{\frac{b}{Q^2} - \frac{1}{q^2}} = 1.4759$$

$$w_{01} = \frac{1}{w_{02}} = 0.6776$$

$$H_A(S) = \frac{10703.27S}{S^2 + \frac{14855.28 * 0.6776}{3.28}S + (14855.28 * 0.6776)^2} = \frac{10703.27S}{S^2 + 3068.88S + 10.132 * 10^7}$$

$$H_B(S) = \frac{10703.27S}{S^2 + \frac{14855.28 * 1.4759}{3.28}S + (14855.28 * 1.4759)^2} = \frac{10703.27S}{S^2 + 6684.42S + 48.070 * 10^7}$$

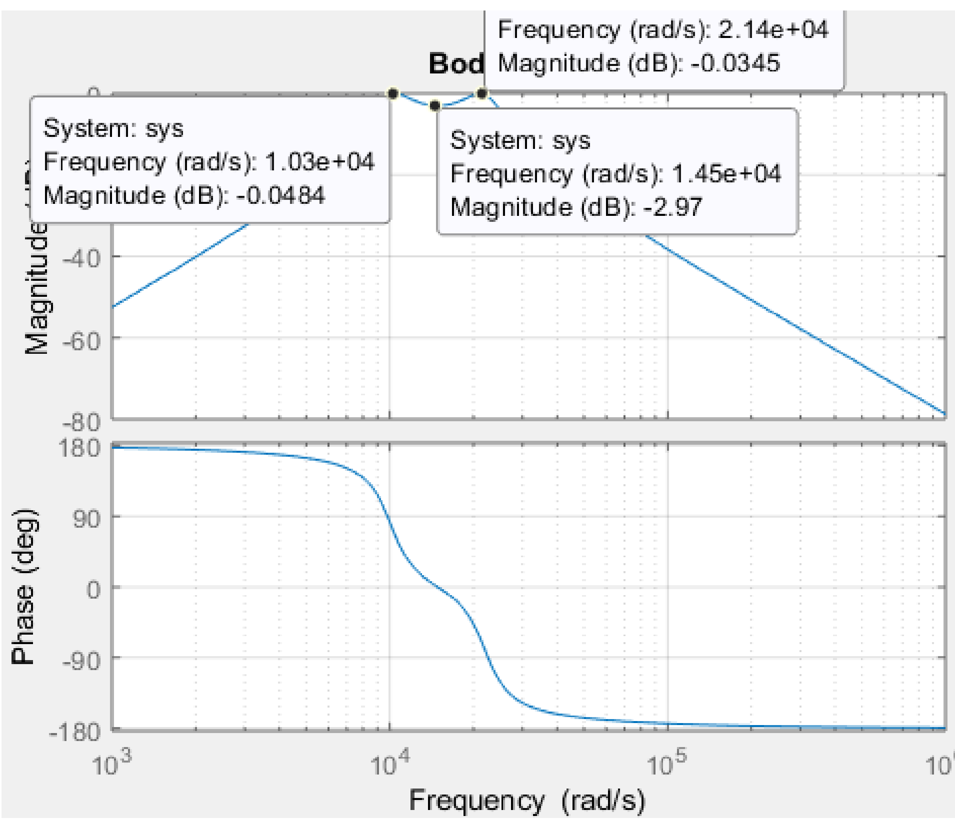
$$\therefore H_4(S) = \frac{10703.27S}{S^2 + 3068.88S + 10.132 * 10^7} * \frac{10703.27S}{S^2 + 6684.42S + 48.070 * 10^7}$$

- **MATLAB Simulation for The Overall Chebyshev Filter $H_4(S)$**

The code used to generate the plot for the overall Chebyshev filter is shown below.

```
Num = [114.56e6 0 0];
Dem= [1 9750.80 603.1e6 2.15e12 4.8699e16];
sys=tf(Num,Dem);
figure (1)
bode(sys)
grid on
```

The plot for the overall Chebyshev filter is shown below.



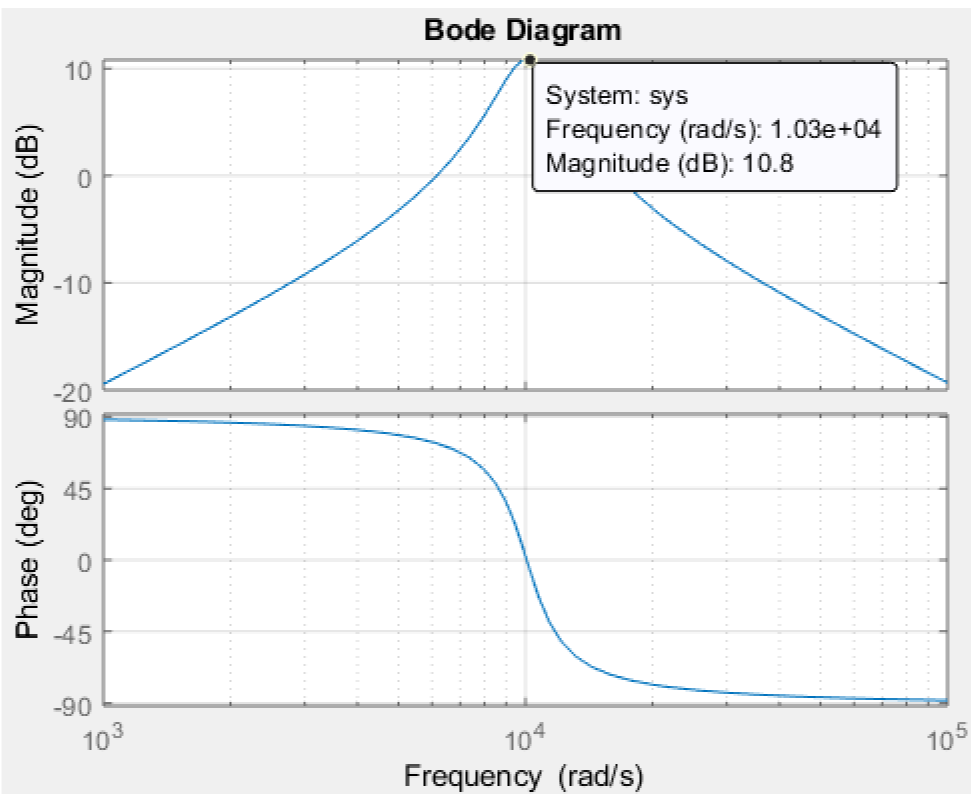
The plot shown above for the Chebyshev filter shows that the center frequency is at 14500 rad/s (2339.6 Hz) and gain is equal to -2.97 dB, $f_{-3dB\ Lower}$ is equal to 10300 rad/s (1639.3 Hz), and $f_{-3dB\ Upper}$ is equal to 21400 rad/s (3405.9 Hz).

- **<u>MATLAB Simulation for Stage 1 $H_A(S)$ filter</u>**

The code used to generate the plot for the $H_A(S)$ filter is shown below.

```
Num = [10703.27 0];
Dem= [1 3068.88 10.132e7];
sys=tf(Num,Dem);
figure (1)
bode(sys)
grid on
```

The plot for the $H_A(S)$ filter is shown below.



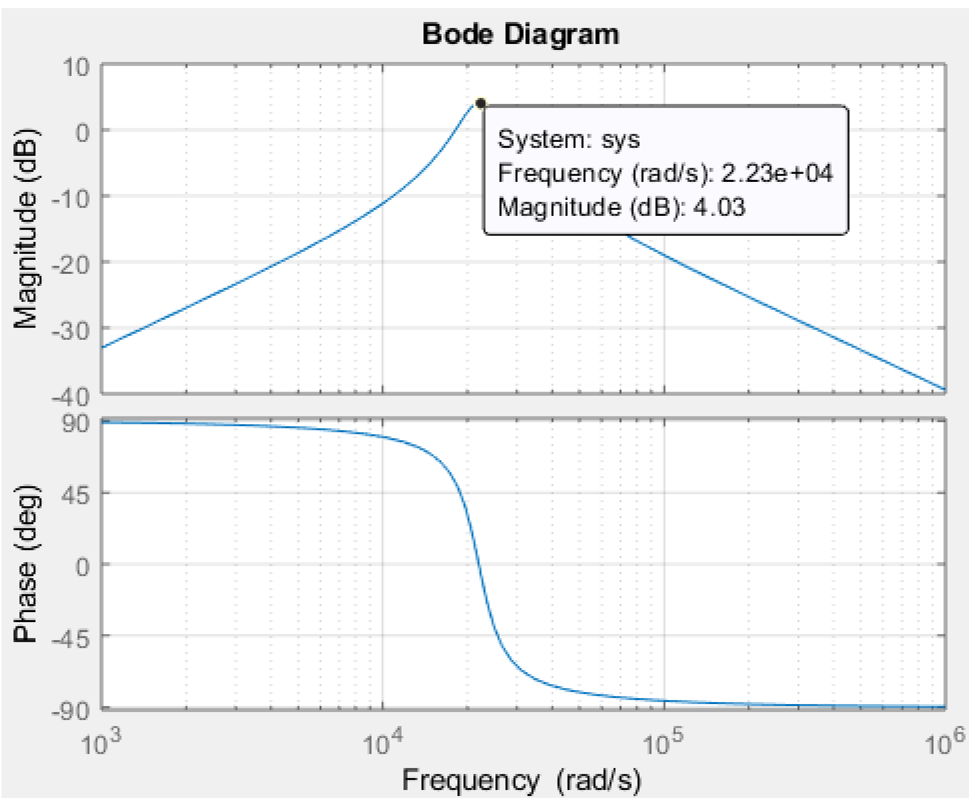
The plot shown above for the Chebyshev filter shows that the center frequency is at 10300 rad/s (1639.3 Hz) and gain is equal to 10.8 dB.

- **<u>MATLAB Simulation for Stage 2 $H_B(S)$ filter</u>**

The code used to generate the plot for the $H_B(S)$ filter is shown below.

```
Num = [10703.27 0];
Dem= [1 6684.42 48.070e7];
sys=tf(Num,Dem);
figure (1)
bode(sys)
grid on
```

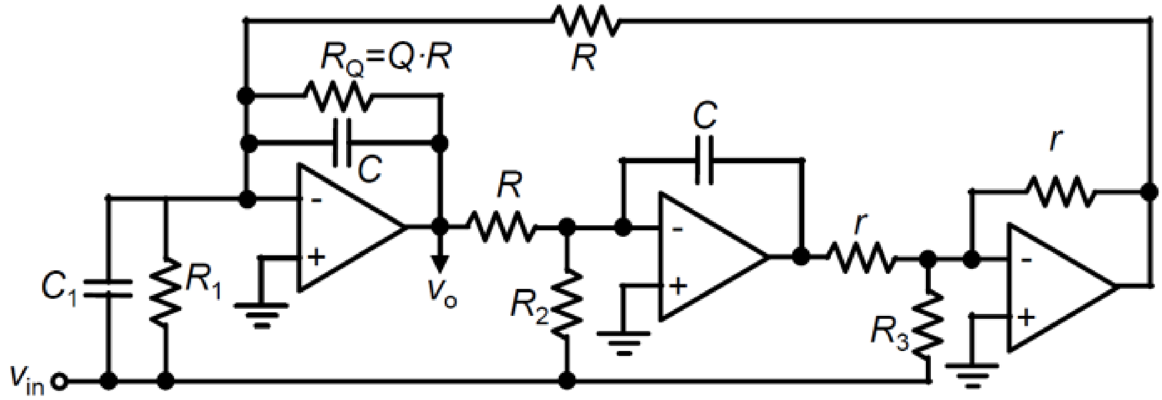
The plot for the $H_B(S)$ filter is shown below.



The plot shown above for the Chebyshev filter shows that the center frequency is at 22300 rad/s (3549.2 Hz) and gain is equal to 4.03 dB.

TOW-THOMAS FILTER

Shown below is the circuit for Tow-Thomas filter with feedforward.



The transfer function for Tow-Thomas (with Feedforward) is shown below.

$$H(S) = \frac{S^2\left(\frac{C_1}{C}\right) + S\left(\frac{1}{C}\right)\left(\frac{1}{R_1} - \frac{r}{R_3R}\right) + \frac{1}{C^2R_2R}}{S^2 + S\frac{w_o}{Q} + \left(\frac{1}{RC}\right)^2}$$

C, r can be fixed arbitrarily

For Bandpass: $C_1 = 0;\ R_2 = \infty$. Hence, the bandpass Tow-Thomas filter can be represented as shown below.

$$H(S) = \frac{\frac{S}{C}\left(\frac{1}{R_1} - \frac{r}{RR_3}\right)}{S^2 + S\frac{w_o}{Q} + \left(\frac{1}{RC}\right)^2}$$

- **<u>First Stage</u>**

$$H_A(S) = \frac{10703.27S}{S^2 + 3068.88S + 10.132 * 10^7}$$

  - <u>Center Frequency</u>

$$w_{oA} = \frac{1}{RC} = \sqrt{c} = \sqrt{10.132 * 10^7} = 10065.784\, rad/s$$

- Bandwidth

$$BW_A = \frac{w_{oA}}{Q_A} = b = 3068.88\ rad/s$$

- Quality Factor

$$Q_A = \frac{w_{oA}}{BW_A} = \frac{10065.784}{3068.88} = 3.280$$

- Theoretical Gain

$$A_{midA} = 10.8\ dB$$

- Capacitance Value

$$C_A = 22\ nF$$

- Resistance Values

$$R_1 = \frac{1}{w_{oA}C_A} = \frac{1}{(10065.784) * (22\ nF)} = 4515.75\ \Omega$$

$$R_{q1} = R_1 * Q_A = (4515.75\ \Omega) * (3.28) = 14811.65\ \Omega$$

$$Assume\ r_A = R_{q1}$$

$$R_{31} = \frac{r_A}{R_1 C_A a} = \frac{14811.65}{4515.78 * 22 * 10^{-9} * 10703.27} = 13929.46\ \Omega$$

- **Second Stage**

$$H_B(S) = \frac{10703.27S}{S^2 + 6684.42S + 48.070 * 10^7}$$

- Center Frequency

$$w_{oB} = \frac{1}{RC} = \sqrt{c} = \sqrt{48.07 * 10^7} = 21925\ rad/s$$

- Bandwidth

$$BW_B = \frac{w_{oB}}{Q_B} = b = 6684.42\ rad/s$$

- Quality Factor

$$Q_B = \frac{w_{oB}}{BW_B} = \frac{21925}{6684.42} = 3.280$$

- Theoretical Gain

$$A_{midB} = 4.03\ dB$$

- Capacitance Value

$$C_B = 33\ nF$$

- Resistance Values

$$R_2 = \frac{1}{w_{oB}C_B} = \frac{1}{(21925)(33\ nF)} = 1382\ \Omega$$

$$R_{q2} = R_2 * Q_B = (1382)(3.28) = 4533.91\ \Omega$$

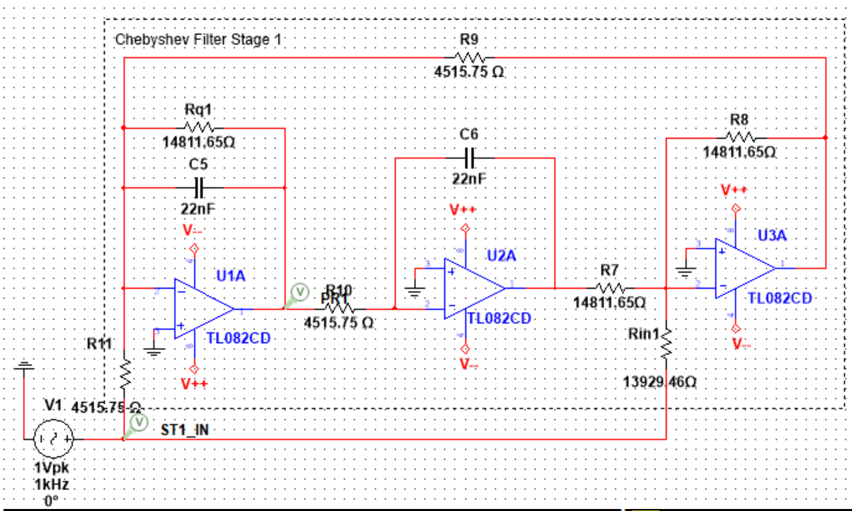
$$Assume\ r_B = R_{q2}$$

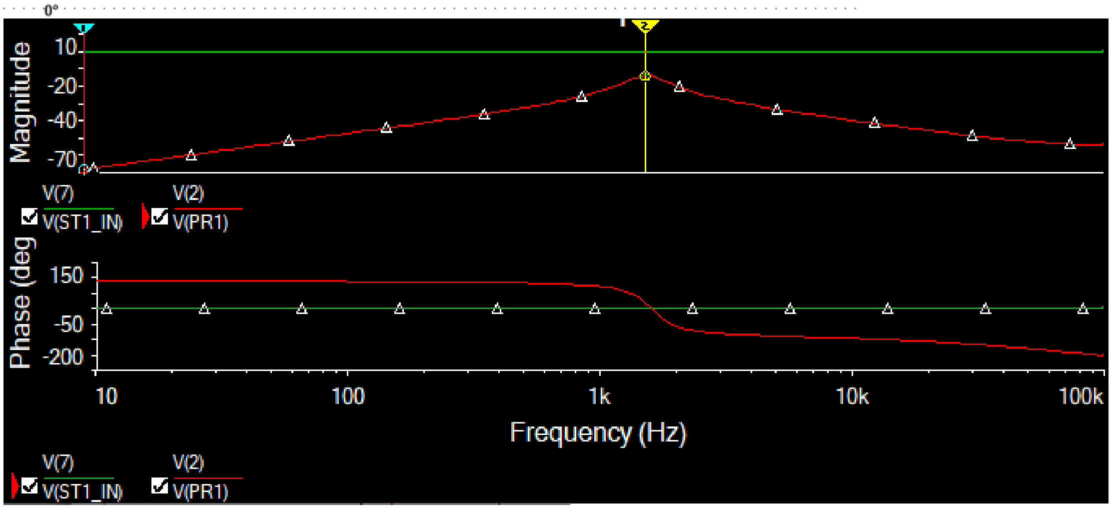
$$R_{32} = \frac{r_B}{R_2 C_B a} = \frac{4533.91}{1382 * 33 * 10^{-9} * 10703.27} = 9288.26\ \Omega$$

TOW-THOMAS SIMULATION

- **<u>First Stage $H_A(S)$</u>**

  - **<u>Simulation using Theoritical Values</u>**



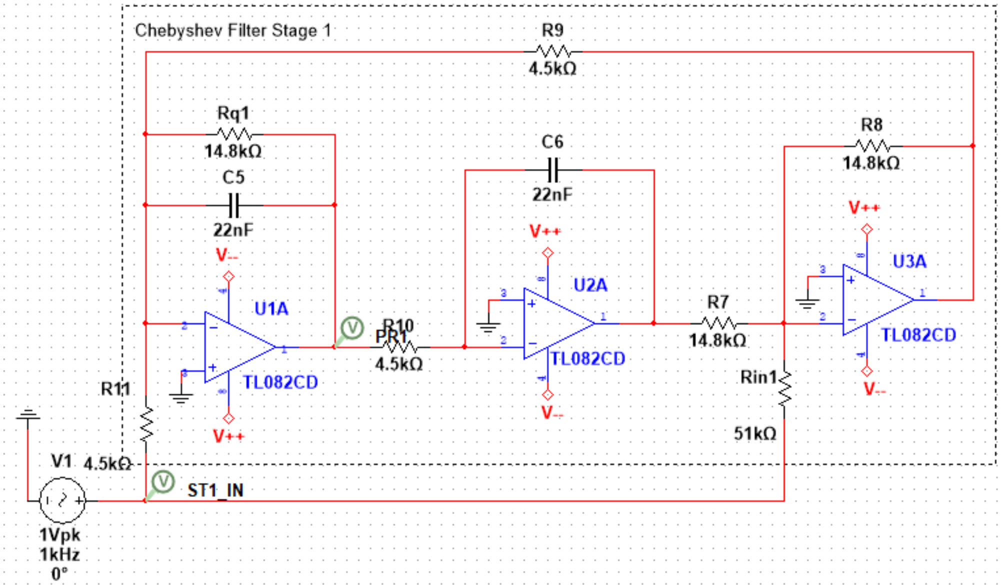


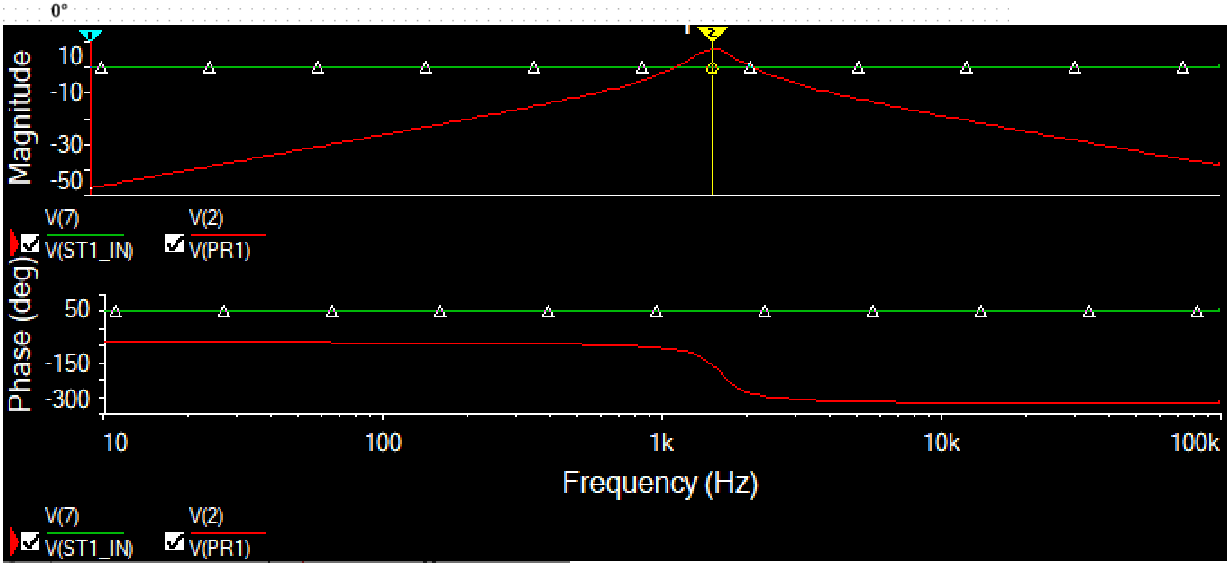
Cursor

	V(7) V(ST1_IN)	V(2) V(PR1)
x1	10.0000	10.0000
y1	0.0000	-68.0584
x2	1.5884k	1.5884k
y2	0.0000	-13.6086
dx	1.5784k	1.5784k
dy	0.0000	54.4498
dy/dx	0.0000	34.4970m
1/dx	633.5573µ	633.5573µ

Center frequency is at 1588.4 Hz (9980.2rad/s), and Gain is -13.6086 dB.

- **Simulation using Standard Values**





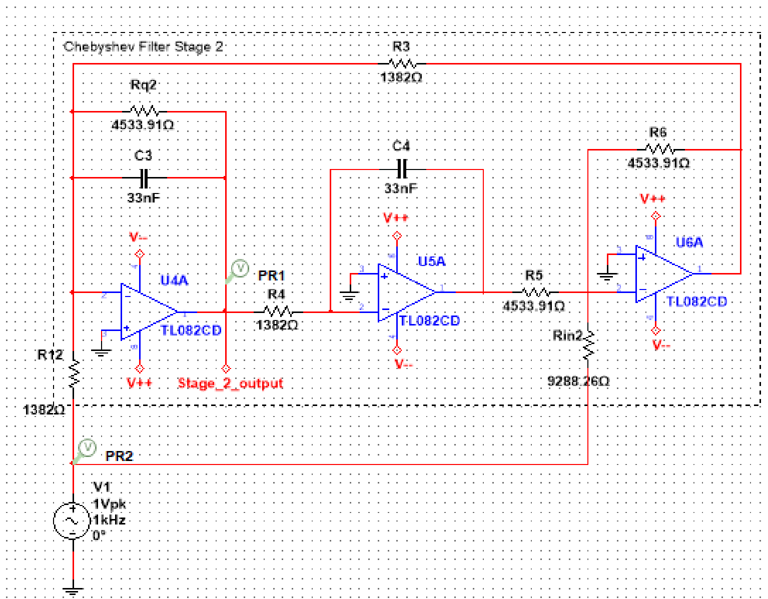
Cursor

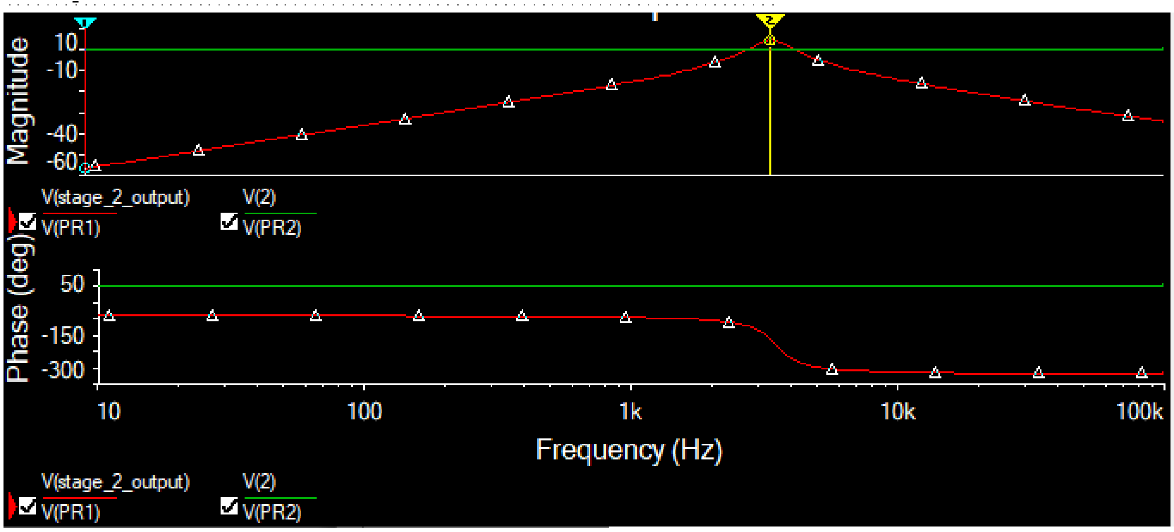
	V(7) V(ST1_IN)	V(2) V(PR1)
x1	10.0000	10.0000
y1	0.0000	-47.0964
x2	1.5884k	1.5884k
y2	0.0000	7.3817
dx	1.5784k	1.5784k
dy	0.0000	54.4780
dy/dx	0.0000	34.5149m
1/dx	633.5573µ	633.5573µ

Center frequency is at 1588.4 Hz (9980.2 rad/s), and Gain is 7.3817 dB.

- **Second Stage $H_B(S)$**

  - **Simulation using Theoritical Values**



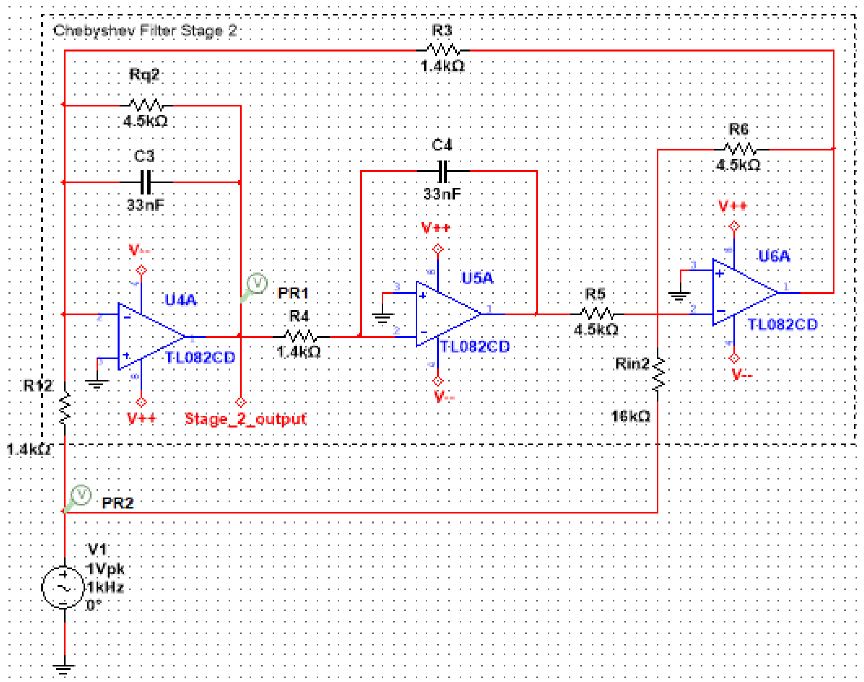


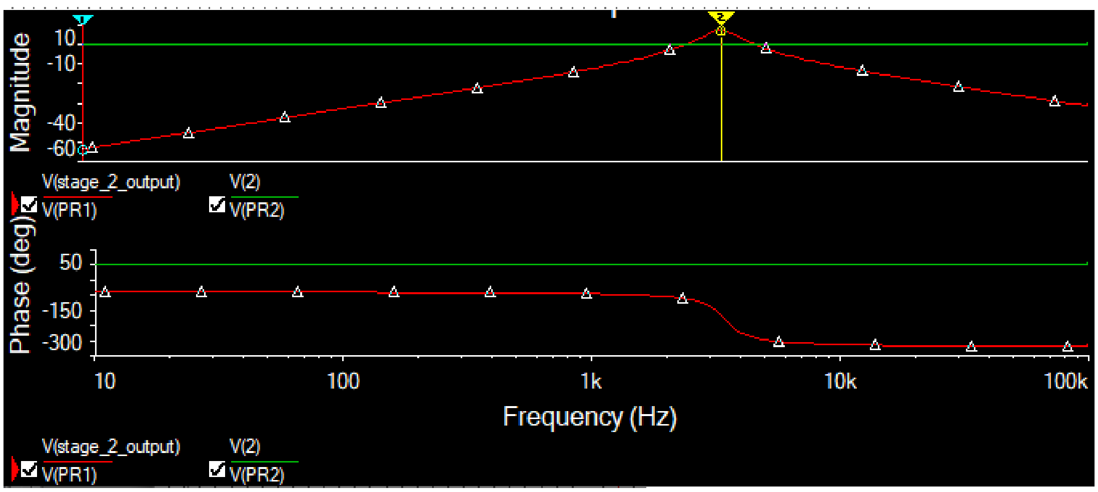
Cursor

	V(stage_2_output) V(PR1)	V(2) V(PR2)
x1	10.0000	10.0000
y1	-56.6634	0.0000
x2	3.4600k	3.4600k
y2	4.6319	0.0000
dx	3.4500k	3.4500k
dy	61.2953	0.0000
dy/dx	17.7668m	0.0000
1/dx	289.8558µ	289.8558µ

Center frequency is at 3460 Hz (21739.8 rad/s), and Gain is 4.6319 dB.

➢ **Simulation using Standard Values**





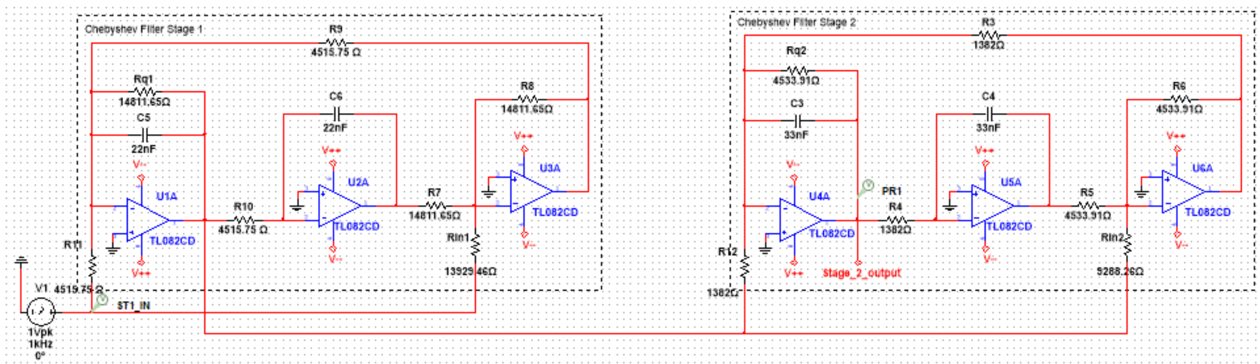
Cursor

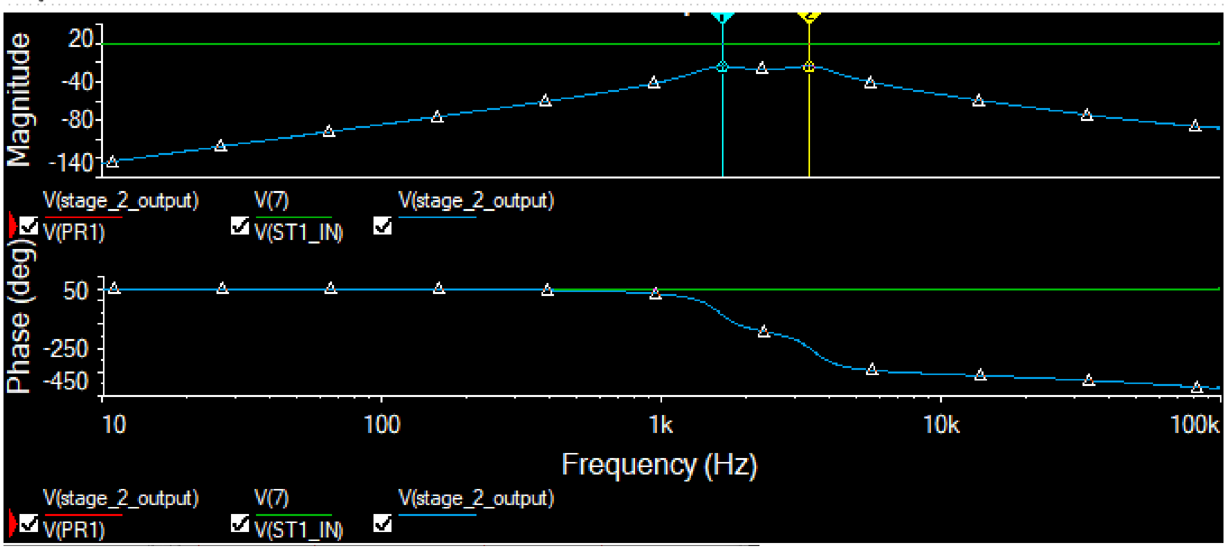
	V(stage_2_output) V(PR1)	V(2) V(PR2)
x1	10.0000	10.0000
y1	-53.6028	0.0000
x2	3.4600k	3.4600k
y2	7.3935	0.0000
dx	3.4500k	3.4500k
dy	60.9963	0.0000
dy/dx	17.6801m	0.0000
1/dx	289.8558µ	289.8558µ

Center frequency is at 3460 Hz (21739.8 rad/s), and Gain is 7.3935 dB.

- **Full Chebyshev Filter $H_4(S)$**

   - **Simulation using Theoritical Values**

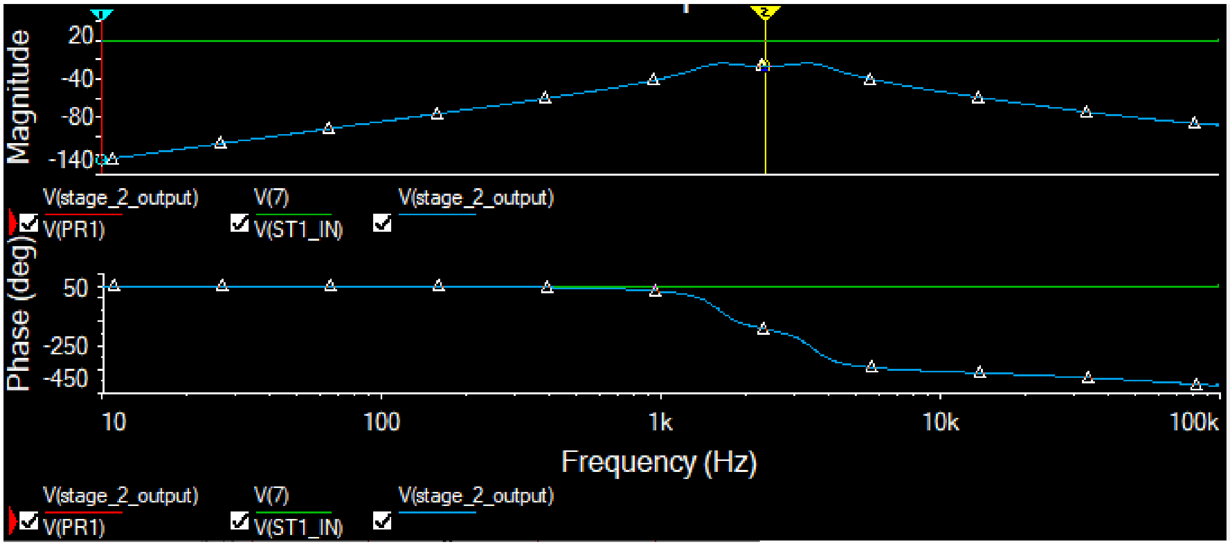




Cursor

	V(stage_2_output) V(PR1)	V(7) V(ST1_IN)	V(stage_2_output)
x1	1.6571k	1.6571k	1.6571k
y1	-23.9947	0.0000	-23.9947
x2	3.3809k	3.3809k	3.3809k
y2	-23.9130	0.0000	-23.9130
dx	1.7238k	1.7238k	1.7238k
dy	81.7287m	0.0000	81.7287m
dy/dx	47.4126µ	0.0000	47.4126µ
1/dx	580.1217µ	580.1217µ	580.1217µ

The Full Chebyshev filter has a lower -3db frequency equals to 1657.1 Hz (10411.8 rad/s), and upper -3dB frequency equals to 3380.9 Hz (21242.8 rad/s).

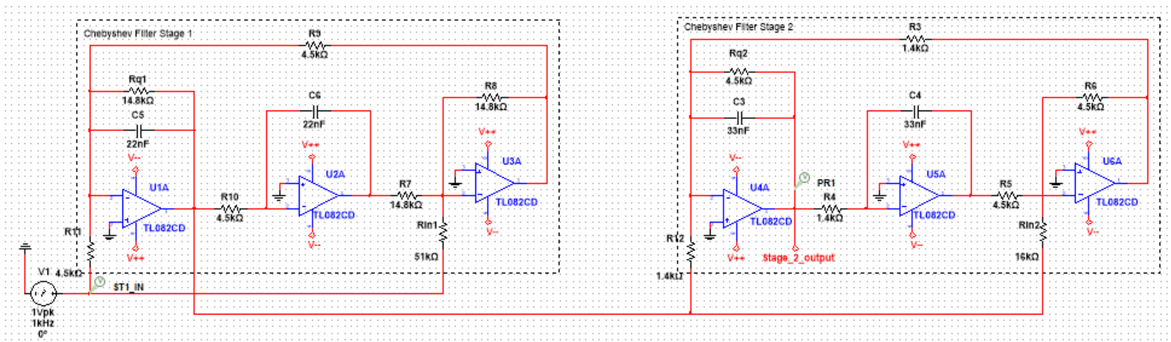


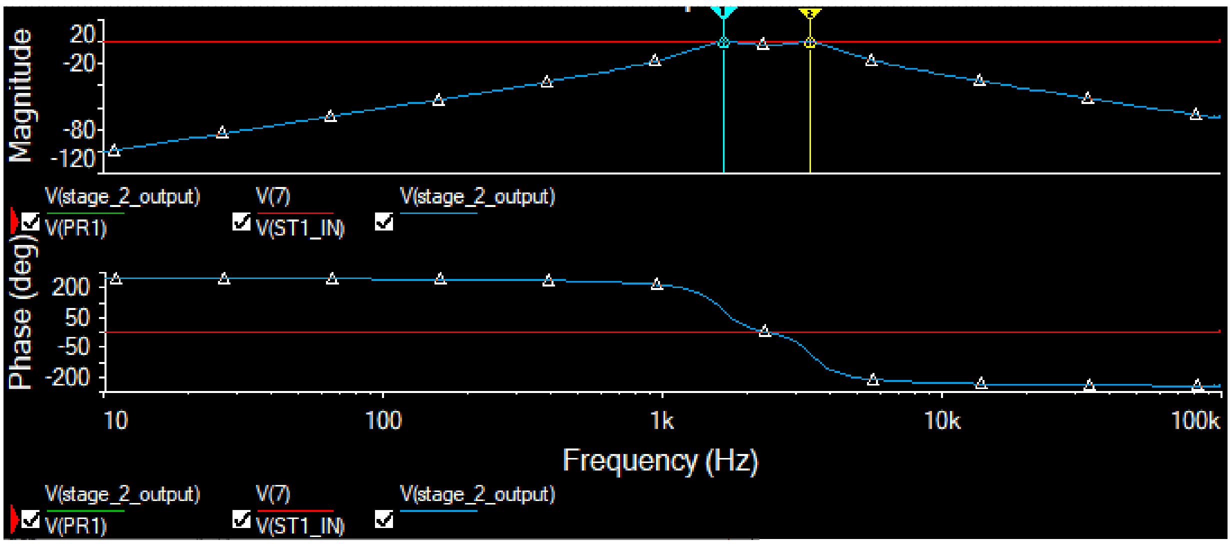
Cursor

	V(stage_2_output) V(PR1)	V(7) V(ST1_IN)	V(stage_2_output)
x1	10.0000	10.0000	10.0000
y1	-124.7218	0.0000	-124.7218
x2	2.3670k	2.3670k	2.3670k
y2	-27.0113	0.0000	-27.0113
dx	2.3570k	2.3570k	2.3570k
dy	97.7104	0.0000	97.7104
dy/dx	41.4559m	0.0000	41.4559m
1/dx	424.2728µ	424.2728µ	424.2728µ

The Full Chebyshev filter has a gain of -27.0113 dB and center frequency equal to 2367 Hz (14872.3).

- **Simulation using Standard Values**

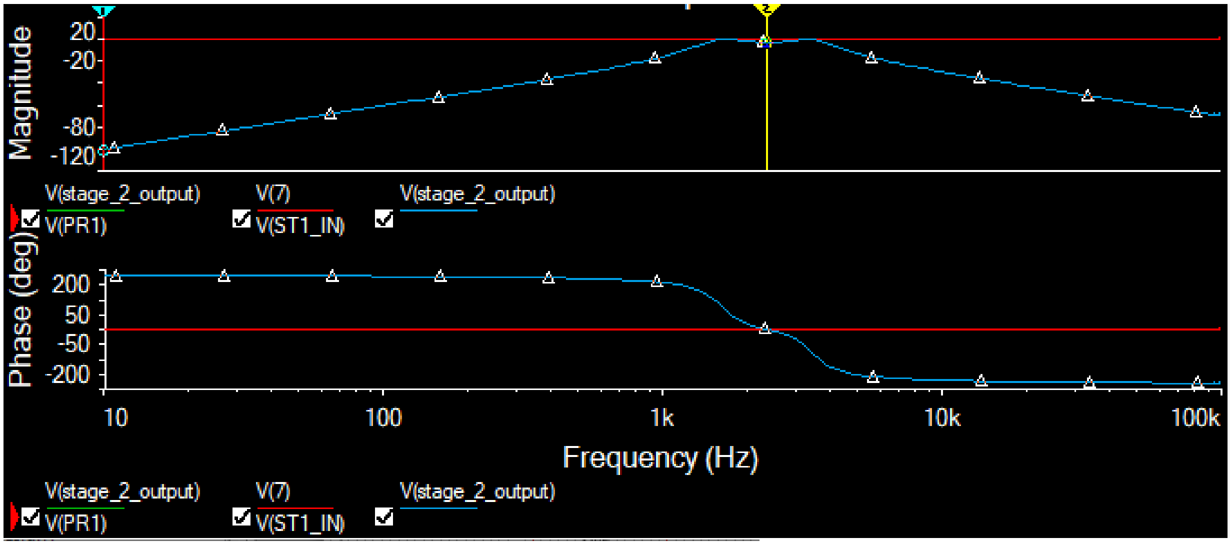




Cursor

	V(stage_2_output) V(PR1)	V(7) V(ST1_IN)	V(stage_2_output)
x1	1.6563k	1.6563k	1.6563k
y1	149.9241m	0.0000	149.9241m
x2	3.3711k	3.3711k	3.3711k
y2	-72.3726m	0.0000	-72.3726m
dx	1.7149k	1.7149k	1.7149k
dy	-222.2967m	0.0000	-222.2967m
dy/dx	-129.6296µ	0.0000	-129.6296µ
1/dx	583.1380µ	583.1380µ	583.1380µ

The Full Chebyshev filter has a lower -3db frequency equals to 1656.3 Hz (10406.8 rad/s), and upper -3dB frequency equals to 3371.1 Hz (21181.2 rad/s).



Cursor

	V(stage_2_output) / V(PR1)	V(7) / V(ST1_IN)	V(stage_2_output)
x1	10.0000	10.0000	10.0000
y1	-100.6991	0.0000	-100.6991
x2	2.3670k	2.3670k	2.3670k
y2	-2.7443	0.0000	-2.7443
dx	2.3570k	2.3570k	2.3570k
dy	97.9548	0.0000	97.9548
dy/dx	41.5596m	0.0000	41.5596m
1/dx	424.2728µ	424.2728µ	424.2728µ

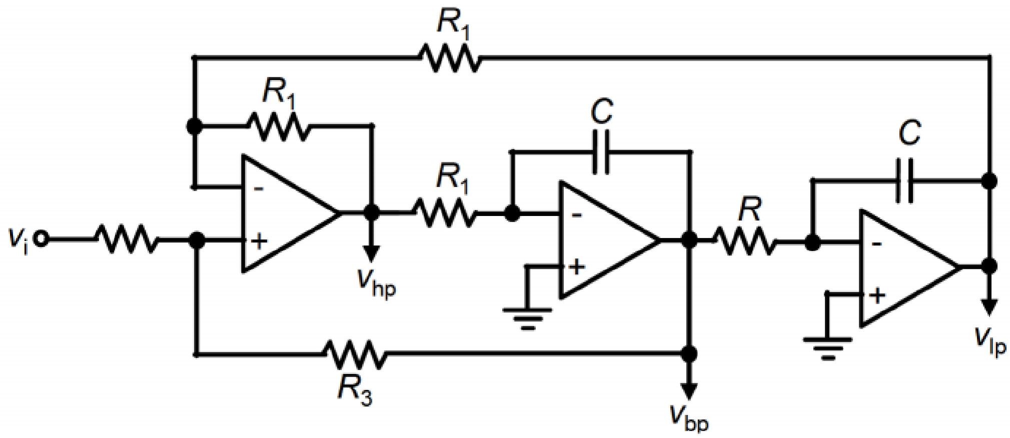
The Full Chebyshev filter has a gain of -2.7443 dB and center frequency equal to 2367 Hz (14872.3 rad/s).

The table below show the theoretical and standard values for the different resistors used in the simulation.

Resistor	Theoretical Value (Ω)	Standard Value (Ω)
R_1	4515.75	4500
R_{q1}	14811.65	14800
r_A	14811.65	14800
R_{31}	13929.46	51000
R_2	1382	1400
R_{q2}	4533.91	4500
r_B	4533.91	4500
R_{32}	9288.26	16000

KHN FILTER

Shown below is the circuit for KHN filter.



The transfer function for KHN filter is shown below.

$$H_{\boldsymbol{BP}} = \frac{S\left(\frac{R_3}{R_3 + R_2}\right)\left(\frac{R_1}{R_1} + 1\right)\left(\frac{1}{R_1 C}\right)}{S^2 + \left(\frac{R_1}{R_1} + 1\right)\left(\frac{R_2}{R_3 + R_2}\right)\left(\frac{1}{R_1 C}\right)S + \left(\frac{1}{RR_1 C^2}\right)^2}$$

$$Q = \frac{R_2 + R_3}{2R_2}$$

$$C = \frac{1}{RR_1 c^2}$$

$$w_o = \sqrt{\frac{1}{RR_1 C^2}}$$

$$BW = \left(\frac{R_1}{R_1} + 1\right)\left(\frac{R_2}{R_3 + R_2}\right)\left(\frac{1}{R_1 C}\right)$$

$$a = \left(\frac{R_3}{R_2 + R_3}\right)\left(\frac{1}{R_1 C}\right)\left(\frac{R_1}{R_1} + 1\right)$$

$$H_{LP}(S) = \frac{a}{S^2 + bS + c}$$

$$H_{BP}(S) = \frac{aBW^2 S^2}{S^4 + bBWS^3 + (2w_o^2 + cBW^2)S^2 + bBWw_o^2 S + w_o^4}$$

- **<u>First Stage</u>**

$$H_C(S) = \frac{10703.27S}{S^2 + 3068.88S + 10.132 * 10^7}$$

- <u>Center Frequency</u>

$$w_{oC} = \frac{1}{RC} = \sqrt{c} = \sqrt{10.132 * 10^7} = 10065.784\ rad/s$$

- <u>Bandwidth</u>

$$BW_C = \frac{w_{oC}}{Q_A} = b = 3068.88\ rad/s$$

- <u>Quality Factor</u>

$$Q_C = \frac{w_{oC}}{BW_C} = \frac{10065.784}{3068.88} = 3.280$$

- <u>Capacitance Value</u>

$$C_C = 22\ nF$$

- <u>Resistance Values</u>

$$R = \frac{1}{w_{oC}C_C} = \frac{1}{(10065.784) * (22\ nF)} = 4515.75\ \Omega$$

$$R_{q1} = R_1 * Q_A = (4515.75\ \Omega) * (3.28) = 14811.65\ \Omega$$

$$Assume\ R_2 = 7\ k\Omega, R_1 = R$$

$$a = \left(\frac{R_3}{R_2 + R_3}\right)\left(\frac{1}{R_1 C}\right)\left(\frac{R_1}{R_1} + 1\right) = 10703.27$$

$$\left(\frac{R_3}{R_2 + R_3}\right) = \frac{10703.27}{\left(\frac{1}{R_1 C}\right)\left(\frac{R_1}{R_1} + 1\right)} = 1.0633$$

$$R_3 = 1.0633R_3 + 1.0633R_2 = \frac{1.0633}{1 - 1.0633}R_2 = 1.0633R_2 = 7443.1\ \Omega$$

- **<u>Second Stage</u>**

$$H_D(S) = \frac{10703.27S}{S^2 + 6684.42S + 48.070 * 10^7}$$

- <u>Center Frequency</u>

$$w_{oD} = \frac{1}{RC} = \sqrt{c} = \sqrt{48.07 * 10^7} = 21925\ rad/s$$

- Bandwidth

$$BW_D = \frac{w_{oD}}{Q_D} = b = 6684.42\ rad/s$$

- Quality Factor

$$Q_D = \frac{w_{oD}}{BW_D} = \frac{21925}{6684.42} = 3.280$$

- Capacitance Value

$$C_D = 33\ nF$$

- Resistance Values

$$R = \frac{1}{w_{oB}C_B} = \frac{1}{(21925)(33\ nF)} = 1382\ \Omega$$

$$Assume\ R_2 = 25\ k\Omega, R_1 = R$$

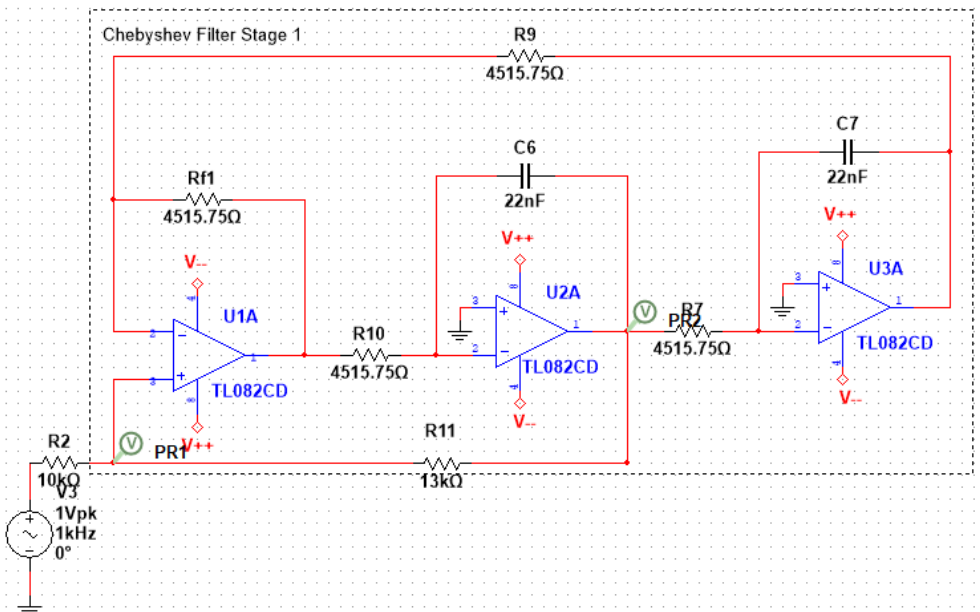
$$a = \left(\frac{R_3}{R_2 + R_3}\right)\left(\frac{1}{R_1 C}\right)\left(\frac{R_1}{R_1} + 1\right) = 10703.27$$

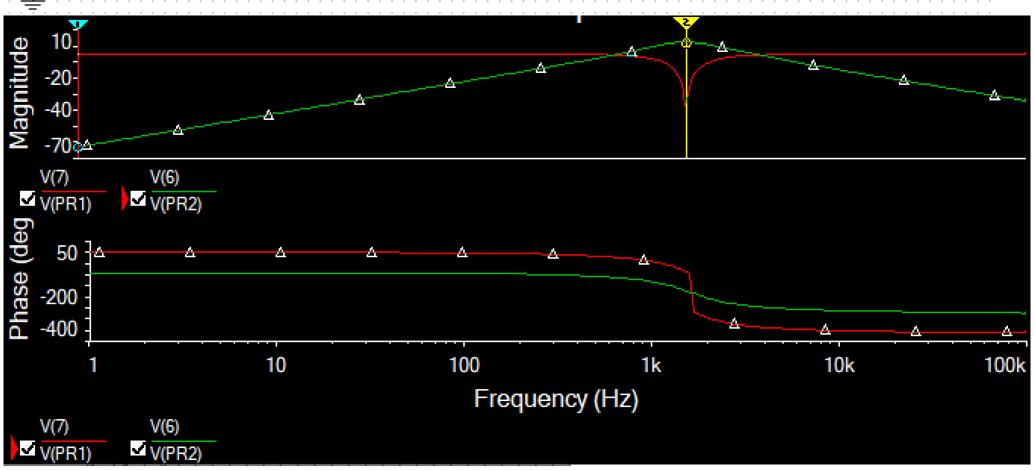
$$\left(\frac{R_3}{R_2 + R_3}\right) = \frac{10703.27}{\left(\frac{1}{R_1 C}\right)\left(\frac{R_1}{R_1} + 1\right)} = 0.48813$$

$$R_3 = 0.48813R_3 + 0.48813R_2 = \frac{0.48813}{1 - 0.48813}R_2 = 0.48813R_2 = 12203.33\ \Omega$$

KHN SIMULATION

- **First Stage**



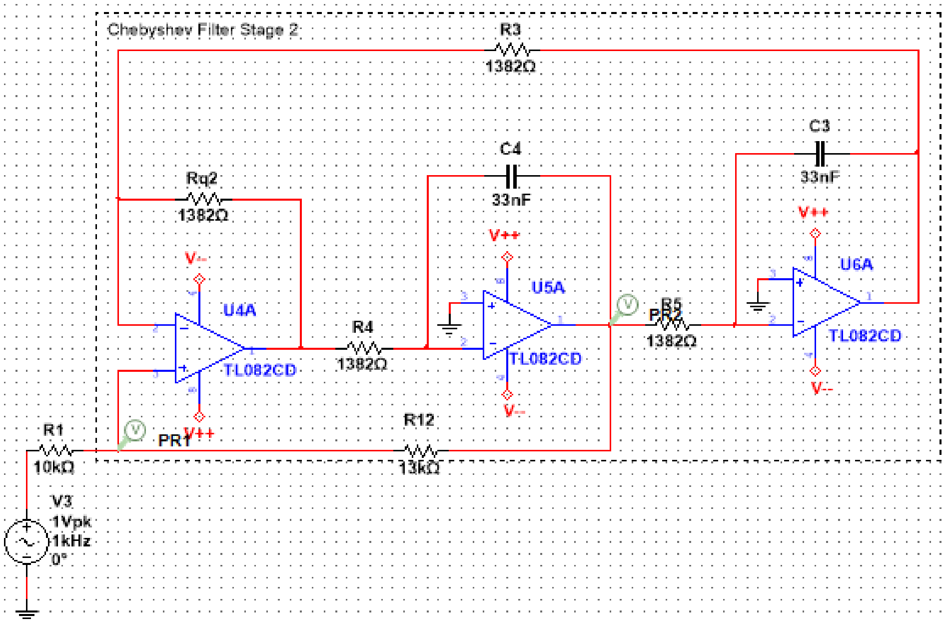


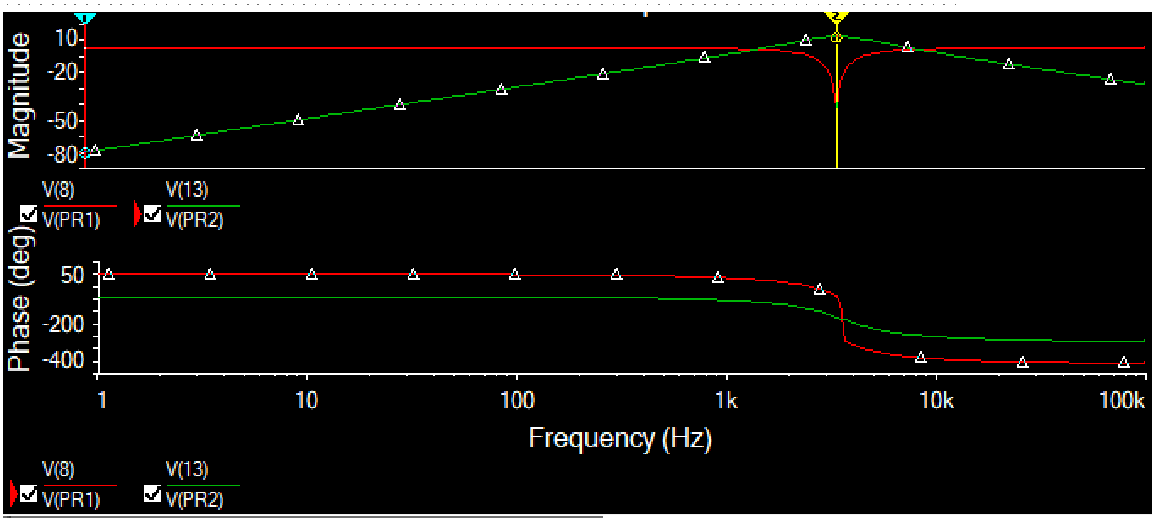
Cursor

	V(7) V(PR1)	V(6) V(PR2)
x1	1.0000	1.0000
y1	-4.9557	-63.0243
x2	1.6060k	1.6060k
y2	-34.3377	2.2885
dx	1.6050k	1.6050k
dy	-29.3820	65.3129
dy/dx	-18.3067m	40.6938m
1/dx	623.0586µ	623.0586µ

Center frequency is at 1606 Hz (10090.8 rad/s), and Gain is 2.2885 dB

- **Second Stage**



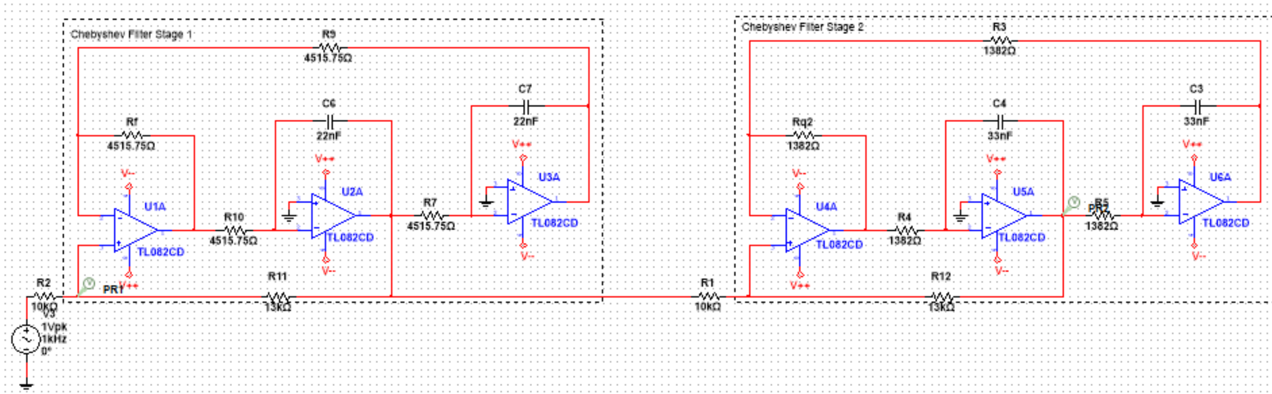


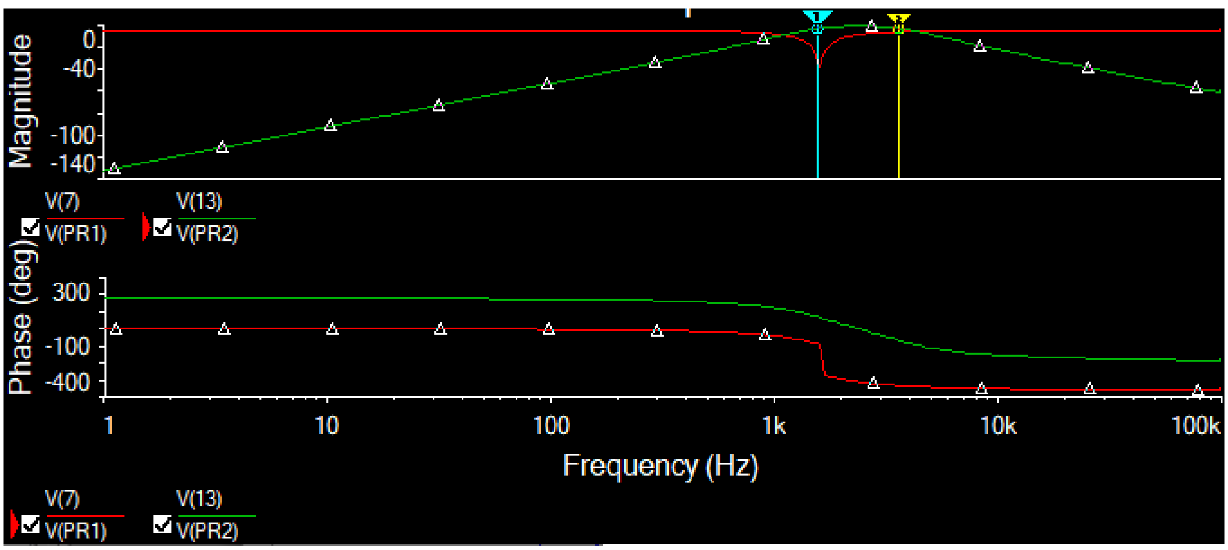
Cursor

	V(8) V(PR1)	V(13) V(PR2)
x1	1.0000	1.0000
y1	-4.9557	-69.7808
x2	3.4727k	3.4727k
y2	-41.6390	2.3260
dx	3.4717k	3.4717k
dy	-36.6832	72.1067
dy/dx	-10.5663m	20.7697m
1/dx	288.0416µ	288.0416µ

Center frequency is at 3471.7 Hz (21809.5 rad/s), and Gain is 2.326 dB

- **Overall KHN Filter**

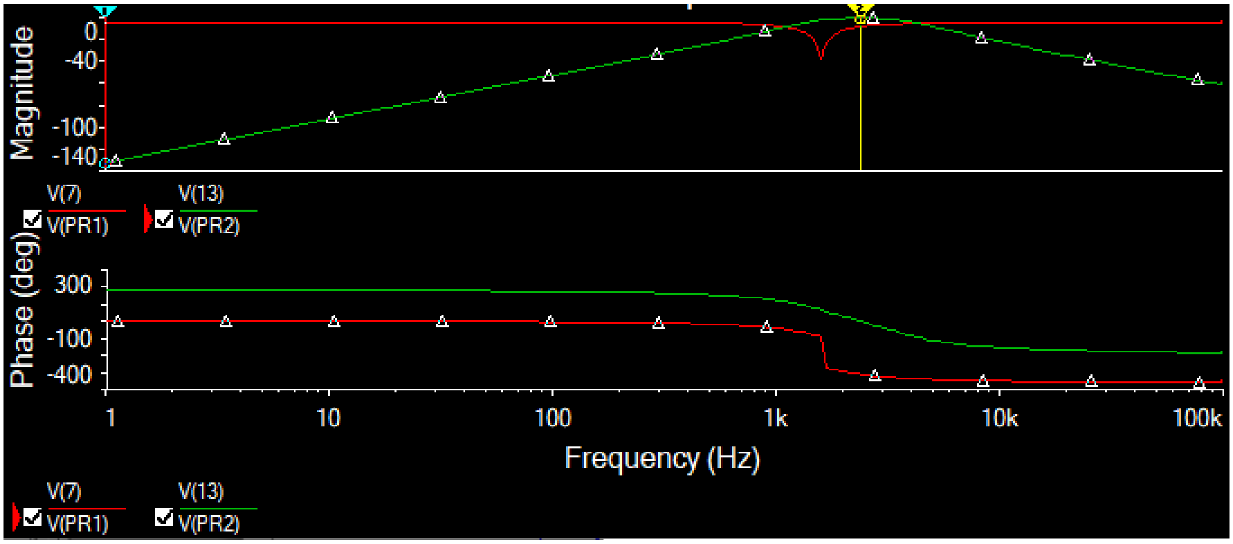




Cursor

	V(7) V(PR1)	V(13) V(PR2)
x1	1.5647k	1.5647k
y1	-33.3567	-2.5887
x2	3.6066k	3.6066k
y2	-5.8450	-2.6704
dx	2.0419k	2.0419k
dy	27.5116	-81.6770m
dy/dx	13.4738m	-40.0013μ
1/dx	489.7499μ	489.7499μ

The overall filter has a lower -3db frequency equals to 1564.7 Hz (9831.3 rad/s), and upper -3dB frequency equals to 3606.6 Hz (22660.9 rad/s).



Cursor

	V(7) V(PR1)	V(13) V(PR2)
x1	1.0000	1.0000
y1	-4.9557	-132.8051
x2	2.3968k	2.3968k
y2	-8.1609	-711.1806m
dx	2.3958k	2.3958k
dy	-3.2052	132.0939
dy/dx	-1.3378m	55.1359m
1/dx	417.3992µ	417.3992µ

The overall filter has a gain of -0.711 dB and center frequency equal to 2369.8 Hz (14889.9 rad/s).

RESULTS

The table below shows the theoretical, simulated, and simulated standard values for the

$A_{midA}, and\ w_{oA}$ for the stage 1 $H_A(S)$ filter circuit.

	Prelab	Matlab	Simulated TT	Simulated Standard TT	Simulated KHN
A_{midA}	10.8 dB	10.8 dB	-13.6086 dB	7.3817 dB	2.2885 Db
w_{oA}	10065.784 rad/s	10300 rad/s	9980.2 rad/s	9980.2 rad/s	10090.8 rad/s

The table below shows the theoretical, simulated, and simulated standard values for the

$A_{midB}, and\ w_{oB}$ for the stage 2 $H_B(S)$ filter circuit.

	Prelab	Matlab	Simulated TT	Simulated Standard TT	Simulated KHN
A_{midB}	4.03 dB	4.03 dB	4.6319 dB	7.3935 dB	2.326 dB
w_{oB}	21925 rad/s	22300 rad/s	21739.8 rad/s	21739.8 rad/s	21809.5 rad/s

The table below shows the theoretical, simulated, and simulated standard values for the

$A_{mid}, f_{high}, f_{low}, BW,$ and w_o for the $H_4(S)$ overall filter circuit.

	Prelab	Matlab	Simulated TT	Simulated Standard TT	Simulated KHN
A_{mid}	-2.97 dB	-2.97 Db	-27.0113 dB	-2.7443 dB	-0.711 dB
f_{high}	3856.04 Hz	3405.9 Hz	3380.9 Hz	3371.1 Hz	3606 Hz
f_{low}	1449.64 Hz	1639.3 Hz	1657.1 Hz	1656.3 Hz	1564.7 Hz
BW	15119.87 rad/s	11099.88 rad/s	10830.95 rad/s	10774.41 rad/s	12825.87 rad/s
w_o	14855.28 rad/s	14846.53 rad/s	14872.03 rad/s	14846.88 rad/s	14924.79 rad/s

ANALYSIS

In the overall filter circuits, The Simulated Standard Tow-Thomas, Matlab, and Simulated KHN achieved a suitable gain of -2.7443dB, -2.97 dB, and -0.711 dB, while the Simulated Tow-Thomas using the theoretical values achieved a non-acceptable gain of -27 dB so I had to change some resistor values in the Simulated Standard Tow-Thomas simulation until I got an acceptable gain. All simulations using Matlab, Theoretical Simulation of TT, Simulated Standard TT, and Simulated KHN achieved an upper and lower 3-db frequency within the range specified in the prelab which is from 1449.64 Hz to 3856.04 Hz. Also, all simulations using Matlab, Theoretical Simulation of TT, Simulated Standard TT, and Simulated KHN achieved a bandwidth and center frequency which is relatively close to each other.

For the first and second stage filter circuit, the Matlab, Simulated TT, Simulated Standard TT, and Simulated KHN achieved a center frequency which is relatively close to the prelab's center frequency which is 10065.784 rad/s and 21925 rad/s respectively.

For the first stage filter circuit the Matlab, Simulated TT, Simulated Standard TT, and Simulated KHN achieved a gain of 10.8 dB, -13.61 dB, 7.382 dB, 2.229 dB, Matlab simulation was the only simulation to be close to the prelab's value while the rest of the simulations had a value which was relatively different to that of the prelab..

For the second stage filter circuit the Matlab, Simulated TT, Simulated Standard TT, and Simulated KHN achieved a gain of 4.03 dB, 4.63 dB, 7.39 dB, 2.33 dB which are all unacceptable except for the gain produced by Matlab and the Simulated KHN which are close to the prelab's value 4.03 dB.

CONCLUSION

In conclusion, the purpose of this lab was successfully achieved, also I can conclude that the Tow-Thomas filter is better and easier to build compared to the KHN filter to construct a Chebyshev filters.