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ECE 334

Final Project

12/10/22

Design:

1. Qmin = $\log(f_{min})$ = log(22.5) = 1.352 Hz
   Qmax = $\log(f_{max})$ = log(22050) = 4.343 Hz
   ΔQ = (Qmax - Qmin) / N => (4.343 - 1.352) / (8) = 0.373875 Hz

   f_{min} = 22.5 Hz * (2π) = 141.372 rad/sec
   f_{max} = 22050 * (2π) = 138544.236 rad/sec
   f_1 => $\log(f_1)$ = 1.725875 => 10^(1.725875) = 53.196 Hz * (2π) = 334.237 rad/s
   f_2 => $\log(f_2)$ = 2.09975 => 10^(2.09975) = 125.820 Hz * (2π) = 790.550 rad/s
   f_3 => $\log(f_3)$ = 2.473625 => 10^(2.473625) = 297.595 Hz * (2π) = 1869.845 rad/s
   f_4 => $\log(f_4)$ = 2.8475 => 10^(2.8475) = 703.882 Hz * (2π) = 4422.621 rad/s
   f_5 => $\log(f_5)$ = 3.221375 => 10^(3.221375) = 1664.850 Hz * (2π) = 10460.561 rad/s
   f_6 => $\log(f_6)$ = 3.59525 => 10^(3.59525) = 3937.767 Hz * (2π) = 24741.720 rad/s
   f_7 => $\log(f_7)$ = 3.969125 => 10^(3.969125) = 9313.759 Hz * (2π) = 58520.074 rad/s

Filter	Ω_l (radians/second)	Ω_h (radians/second)
$h_1[n]$	141.372	334.237
$h_2[n]$	334.237	790.550
$h_3[n]$	790.550	1869.845
$h_4[n]$	1869.845	4422.621
$h_5[n]$	4422.621	10460.561
$h_6[n]$	10460.561	24741.720
$h_7[n]$	24741.720	58520.074
$h_8[n]$	58520.074	138544.236

2. Using a sampling rate of fs = 44100 Hz:
   Sampling Interval T = 1/44100
   Divide each term by T:

Filter	w_l (radians/sample)	w_h (radians/sample)
$h_1[n]$	0.00321 $\cong$ 0	0.00758
$h_2[n]$	0.00758	0.01793
$h_3[n]$	0.01793	0.04240
$h_4[n]$	0.04240	0.1003
$h_5[n]$	0.1003	0.2372
$h_6[n]$	0.2372	0.5610
$h_7[n]$	0.5610	1.3270
$h_8[n]$	1.3270	3.14159 $\cong \pi$

3.

Filter	Gain (V/V)	Gain (dB)	Windowing Function
$h_1[n]$	15	23.522	Barlett
$h_2[n]$	20	26.021	Blackman
$h_3[n]$	8	18.062	Hamming
$h_4[n]$	30	29.542	Hanning
$h_5[n]$	2	6.021	Rectangular
$h_6[n]$	5	13.979	Barlett
$h_7[n]$	25	27.959	Blackman
$h_8[n]$	1	0	Hamming

Implementation and Analysis:

Figure 1:

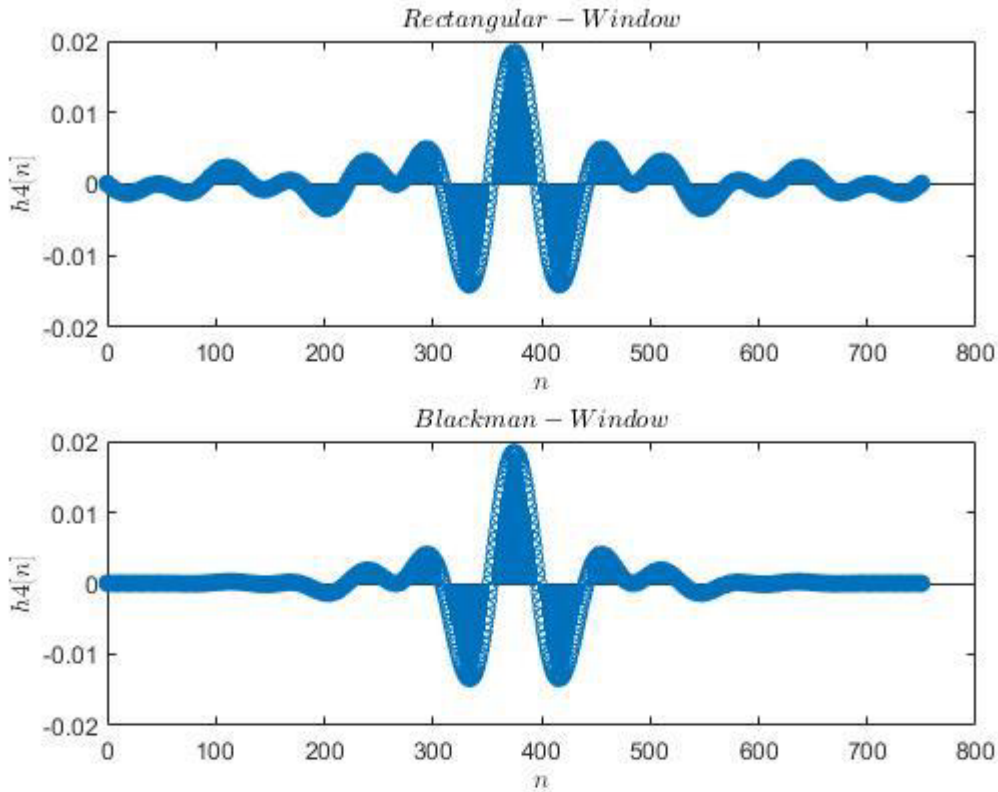
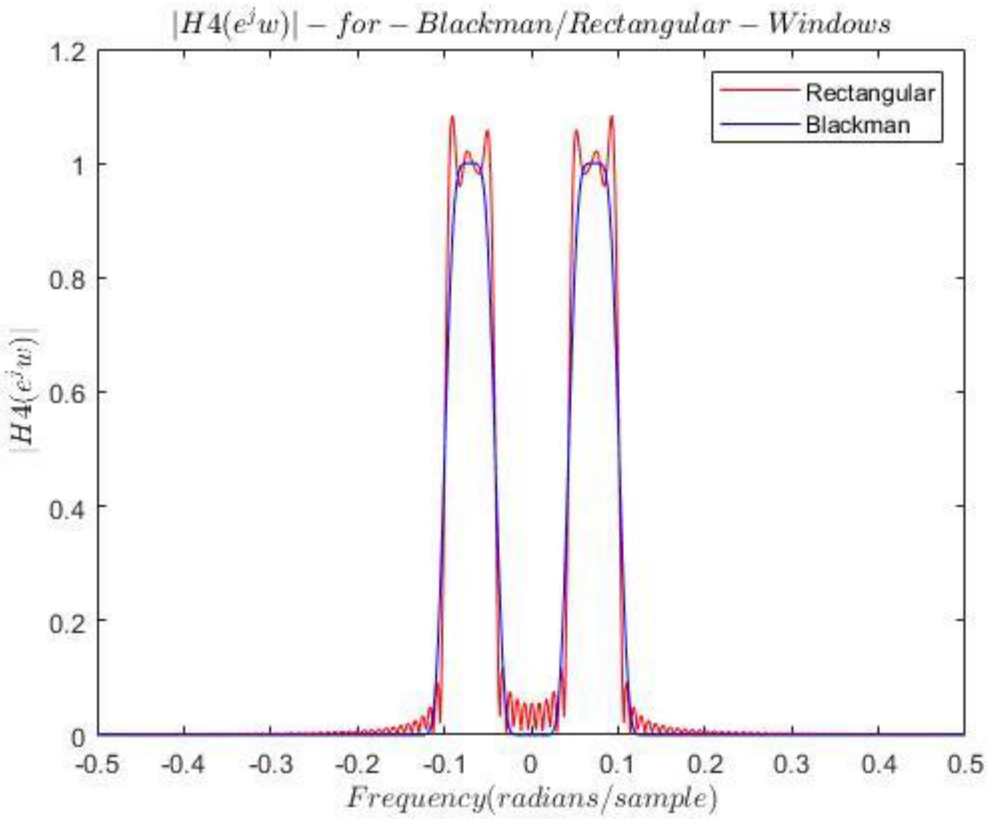


Figure 2:



$|H4(e^jw)| - for - Blackman/Rectangular - Windows$
Rectangular
Blackman
1.2
1
0.8
0.6
0.4
0.2
0
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
$Frequency(radians/sample)$
$|H4(e^jw)|$

Figure 3:

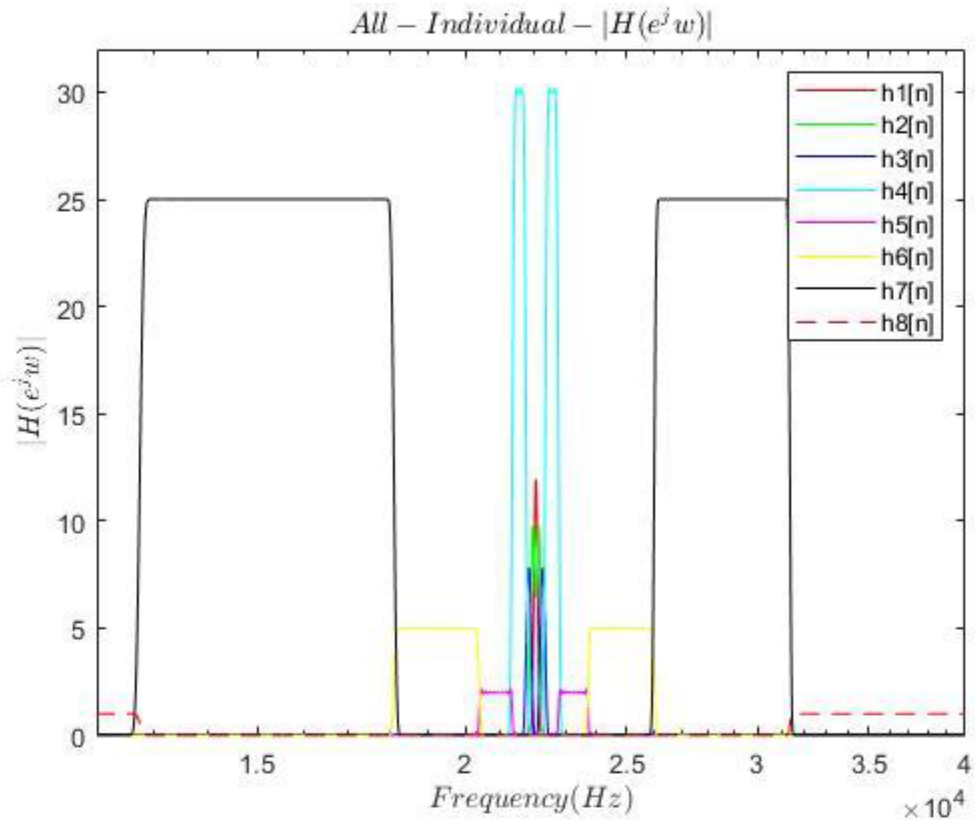

$All - Individual - |H(e^jw)|$
30
25
20
15
10
5
0
1.5
2
2.5
3
3.5
4
$\times 10^4$
$Frequency(Hz)$
$|H(e^jw)|$
h1[n]
h2[n]
h3[n]
h4[n]
h5[n]
h6[n]
h7[n]
h8[n]

Figure 4:

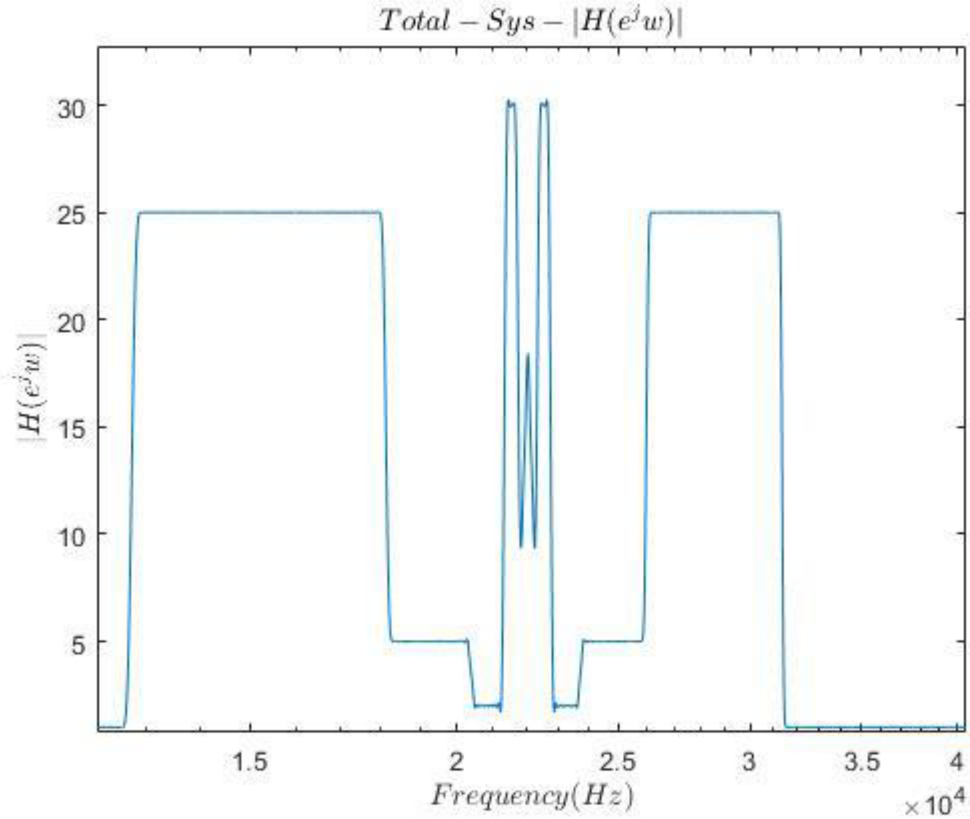

$Total - Sys - |H(e^j w)|$
30
25
20
15
10
5
$|H(e^j w)|$
1.5
2
2.5
3
3.5
4
$Frequency(Hz)$
$\times 10^4$

Figure 5:

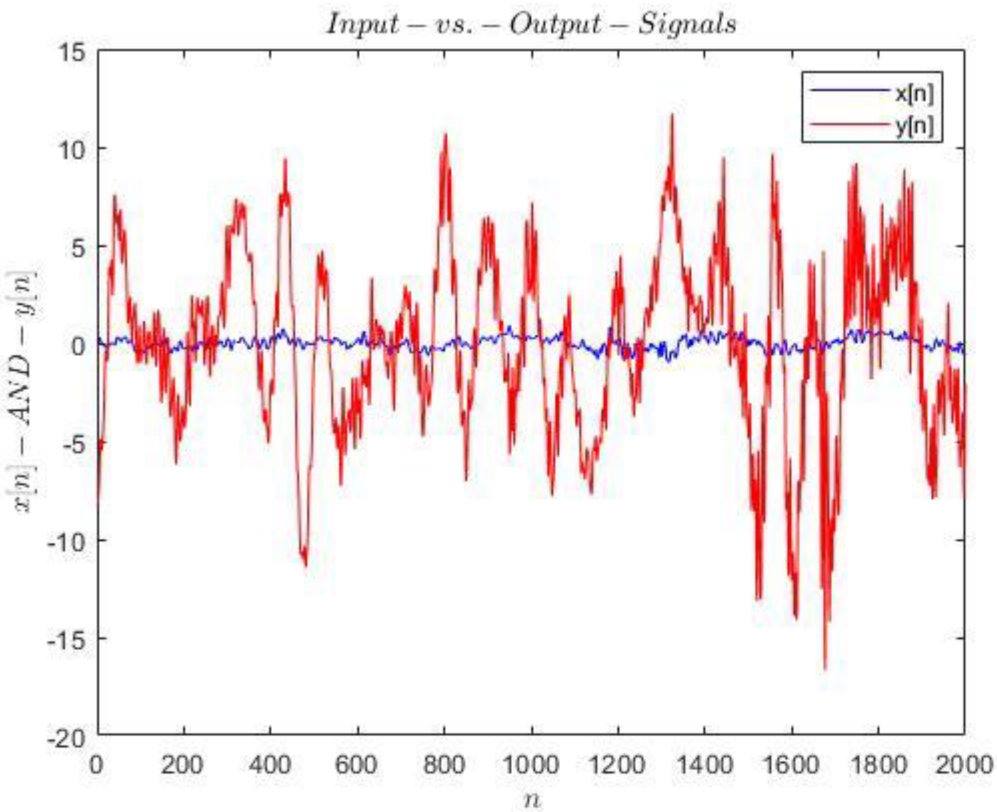
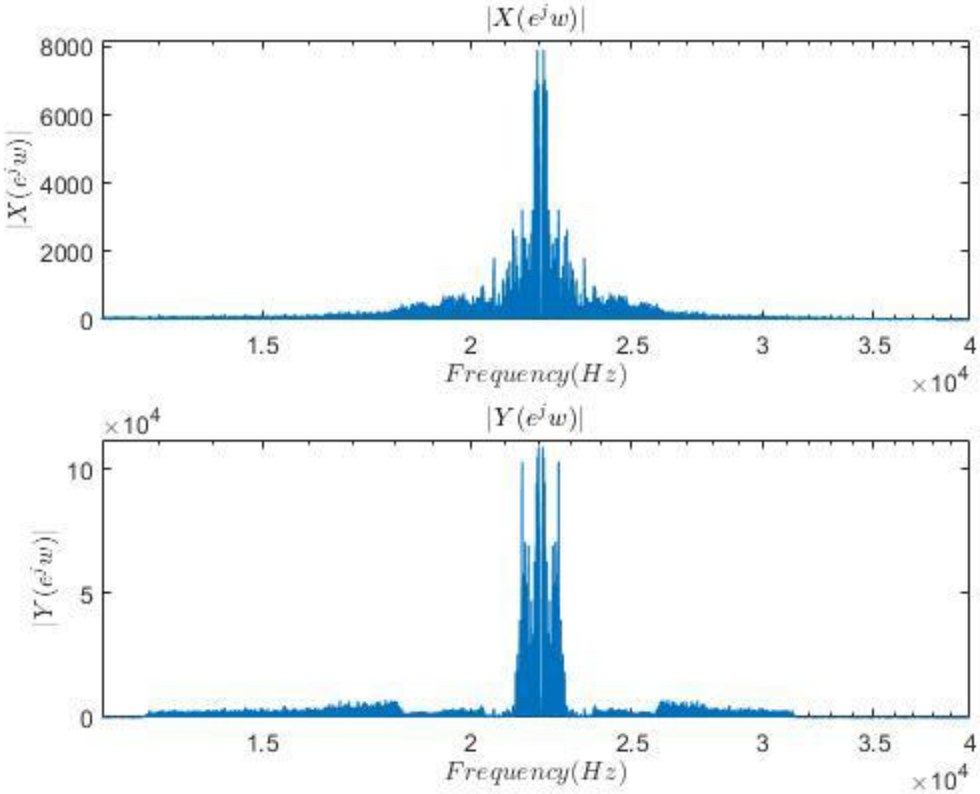
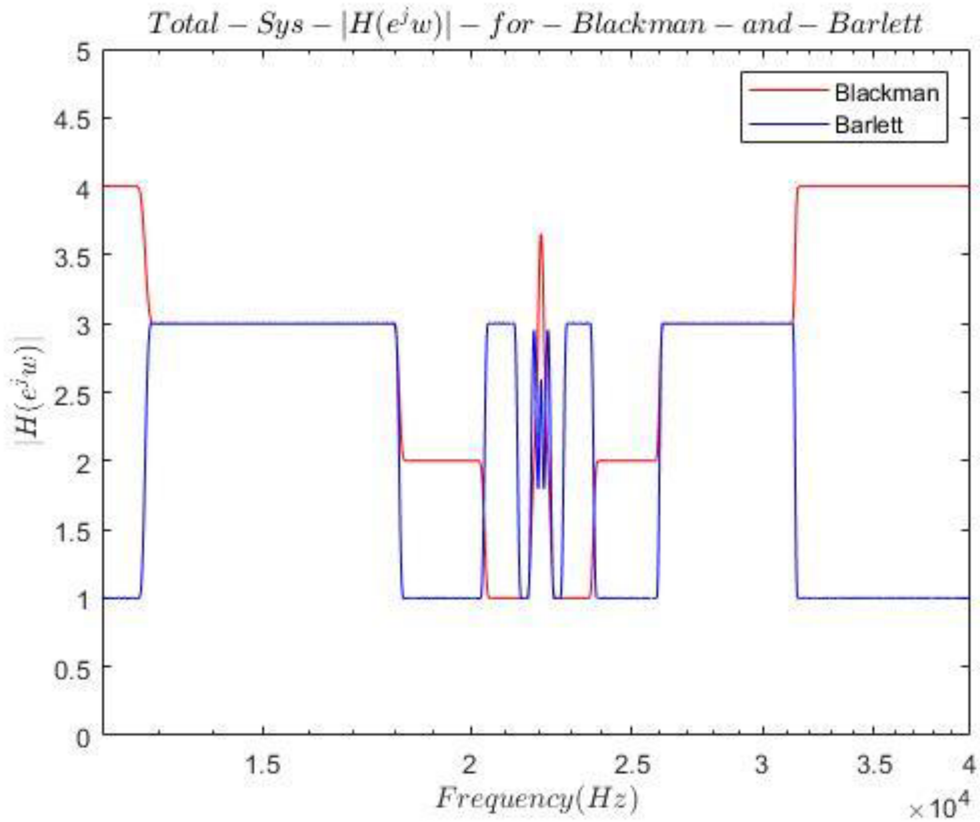

$Input - vs. - Output - Signals$
x[n]
y[n]
15
10
5
0
-5
-10
-15
-20
0
200
400
600
800
1000
1200
1400
1600
1800
2000
n
$x[n] - AND - y[n]$

Figure 6:



$|X(e^jw)|$
8000
6000
4000
2000
0
$|X(e^jw)|$
1.5
2
2.5
3
3.5
4
$Frequency(Hz)$
$\times 10^4$
$|Y(e^jw)|$
$\times 10^4$
10
5
0
$|Y(e^jw)|$
1.5
2
2.5
3
3.5
4
$Frequency(Hz)$
$\times 10^4$

Figure 7:



Results and DIscussion:

1. Although they made the signal sound much more distorted once filtered, I chose a variety of gains and windowing functions just to see how they affected the input signal. I wanted to tangibly realize the impact present in the disparities between each filter's respective frequency response.
2. Both the rectangular and Blackman windows have the same three peaks/valleys near the center of the window. However, the rectangular window differs in that it has many smaller peaks and valleys extending outward from these shared central peaks/valleys, whereas the Blackman window only has 2 to 3 more smaller peaks on both sides before the impulse response comes to a constant around 0.
3. The filter magnitude response of an ideal bandpass filter resembles a square pulse that features a certain frequency range where frequencies are passed, but otherwise rejected if outside this range. The rectangular filter's magnitude response appears akin to an ideal bandpass, but differs due to the consistent and small amounts of noise in the pass and stop bands. The Blackman filter's magnitude response is much more smooth than the rectangular magnitude response and much closer to an ideal bandpass' magnitude

response; however, the passband of the Blackman is not a perfectly square pulse and curves slightly near the edges.

4. The bandpass filters occupy equal frequency bands on a logarithmic scale, where the impulse responses representing higher digital frequencies that are harder to hear with the human ear are wider on the scale. The gains of each filter clearly match the results displayed on the graph. Something else notable about the graph is that it is kind of hard to see the effects of each type of filter with how wide some of the responses are, but upon zooming in, these effects are clearly visible and within expectation.
5. The total system magnitude response of Figure 4 closely resembles the sum of each response present in Figure 3, except for that parts of individual magnitude responses have been cut off where there has been an overlap. Thus the total response more resembles a set of piecewise functions summed together.
6. As many of the windows with regard to magnitude responses of each filter resemble square pulses that are actually composed of sinc functions, the phase responses will resemble sawtooth waveforms, except for the largest sinc peak in the middle(representing the "pulse"), which is a linear line that causes the largest change in phase. Except for this sinc peak(s), the phase will simply oscillate between two values.
7. In Figure 5, the major difference between x[n] and y[n] is in the contrast in magnitude between the two signals. Except for a small portion of the graph, the peaks and valleys of y[n] are much larger than x[n], which makes sense due to the few very large gains I selected. y[n] features the largest peaks and valleys around n = 1300 to n = 1700, which is close in location to where the highest peaks of the total system frequency response occur. The shape of x[n] also closely resembles y[n] throughout the graph despite the difference in magnitude.
8. Yes, the output signal indicates that my chosen gains have been properly applied within their respective frequency bands. For example, I chose my largest gain of 30 for h_4[n], which is centered on 22000 Hz, where the largest frequency response also occurs. In fact, all of the individual frequency responses are centered around this frequency, and since many of the shorter-in-width responses are condensed near this frequency, the most frequencies are passed around this particular frequency.
9. Yes, the total system magnitude responses generated in Figure 7 appear to have the expected shape based upon the specified gains. For example, the Blackman window's first and last gain values are 4, and its magnitude response's gain reaches 4 around 7500 and about 3.6 around 22000 Hz, the latter of which the window is centered around. Both windows involve parabola(s) followed by square pulses extending outward. The Blackman window features only one parabola centered around 22000 Hz, whereas the Barlett window features three parabolas. Furthermore, the Barlett window seems to feature very tiny amounts of noise throughout the response. This approach may be useful for other applications with regards to image and signal processing as it allows those working in those fields to test and select the window that minimizes data loss.

10. I believe since we all have different preferences for “good-sounding” music, especially across other global and cultural backgrounds., tuning will greatly vary across these backgrounds and even between myself and my classmates. Although I might like a more “bass and electronic” Weezer song, someone else could like a more “high-pitched opera” Weezer song. These differences in preferences and customs in music are reflected in the many differences in how audio equalizers are tuned.

MATLAB Code:

```
%given parameters
fs = 44100;
N = 8;
M = 751;
wl = 0;
wu = pi;

fmin = 22.5;
fmax = 22050;

%TASK 1
%create each impluse response
[h1,n] = bpw(wl, 0.00758, M, 'bart');
[h2,n] = bpw(0.00758, 0.01793, M, 'blac');
[h3,n] = bpw(0.01793, 0.04240, M, 'hamm');
[h4,n] = bpw(0.04240, 0.1003, M, 'hann');
[h5,n] = bpw(0.1003, 0.2372, M, 'rect');
[h6,n] = bpw(0.2372, 0.5610, M, 'bart');
[h7,n] = bpw(0.5610, 1.3270, M, 'blac');
[h8,n] = bpw(1.3270, wu, M, 'hamm');

%choose a gain for each filter
G1 = 15;
G2 = 20;
G3 = 8;
G4 = 30;
G5 = 2;
G6 = 5;
G7 = 25;
G8 = 1;
```

```
%multiply each impulse response computed
ht = (h1.*G1) + (h2.*G2) + (h3.*G3) + (h4.*G4) + (h5.*G5) + (h6.*G6) + (h7.*G7) + (h8.*G8);

%TASK 2
%read in audio file
[x, fs] = audioread('Undone_Clip.wav');
x = x(:, 1);
%sound(x, fs);

%convolve the audio file w/ the total impulse response
y = conv(x, ht);
%sound(conv_result, fs);

%TASK 3
%recreate h4[n] using both a rect and blac filter
[h4_rect,n] = bpw(0.04240, 0.1003, M, 'rect');
[h4_blac,n] = bpw(0.04240, 0.1003, M, 'blac');

figure(1);
subplot(2,1,1);
stem(n, h4_rect);
xlabel('$$n$$', 'Interpreter','latex');
ylabel('$$h4[n]$$', 'Interpreter', 'latex');
title('$$Rectangular-Window$$', 'Interpreter','latex');

subplot(2,1,2);
stem(n, h4_blac);
xlabel('$$n$$', 'Interpreter','latex');
ylabel('$$h4[n]$$', 'Interpreter', 'latex');
title('$$Blackman-Window$$', 'Interpreter','latex');

%TASK 4
%plot magnitude of freqeuncy responses on same plot
H4_rect = abs(fftshift(fft(h4_rect, 4096)));
H4_blac = abs(fftshift(fft(h4_blac, 4096)));
w = linspace(-pi, pi, 4096);

figure(2);
plot(w, H4_rect, 'r');
hold on;
plot(w, H4_blac, 'b');
```

```
axis([-0.5 0.5 0 1.2]);
xlabel('$$Frequency(radians/sample)$$', 'Interpreter','latex');
ylabel('$$|H4(e^jw)|$$', 'Interpreter', 'latex');
title('$$|H4(e^jw)|-for-Blackman/Rectangular-Windows$$', 'Interpreter','latex');
legend('Rectangular', 'Blackman');

%TASK 5
%plot magnitude of freq response for each individual filter

%%%%% DIDN'T USE- AS GENERATED WEIRD FREQ RESPONSE PLOTS %%%%%%%
%re-create freq response as a function of Hz instead of digital freq
% [h1_f,n] = bpw(wl, 53.202, M, 'bart');
% [h2_f,n] = bpw(53.202, 125.846, M, 'blac');
% [h3_f,n] = bpw(125.846, 297.594, M, 'hamm');
% [h4_f,n] = bpw(297.594, 703.979, M, 'hann');
% [h5_f,n] = bpw(703.979, 1664.843, M, 'rect');
% [h6_f,n] = bpw(1664.843, 3937.509, M, 'bart');
% [h7_f,n] = bpw(3937.509, 9313.859, M, 'blac');
% [h8_f,n] = bpw(9313.859, wu, M, 'hamm');

%%%%%%%%%%%%%%%%%%%%%%%%%%

%using gain values selected above
h1 = h1.*G1;
h2 = h2.*G2;
h3 = h3.*G3;
h4 = h4.*G4;
h5 = h5.*G5;
h6 = h6.*G6;
h7 = h7.*G7;
h8 = h8.*G8;

H1 = abs(fftshift(fft(h1, 4096)));
H2 = abs(fftshift(fft(h2, 4096)));
H3 = abs(fftshift(fft(h3, 4096)));
H4 = abs(fftshift(fft(h4, 4096)));
H5 = abs(fftshift(fft(h5, 4096)));
H6 = abs(fftshift(fft(h6, 4096)));
H7 = abs(fftshift(fft(h7, 4096)));
H8 = abs(fftshift(fft(h8, 4096)));

%plot as a function of Hz rather than digital freq
```

```
f = linspace(0, 44100, 4096);


figure(3);
semilogx(f, H1, 'r');
hold on;
semilogx(f, H2, 'g');
hold on;
semilogx(f, H3, 'b');
hold on;
semilogx(f, H4, 'c');
hold on;
semilogx(f, H5, 'm');
hold on;
semilogx(f, H6, 'y');
hold on;
semilogx(f, H7, 'k');
hold on;
semilogx(f, H8, 'r--');

axis([12000 40000 0 32]);
xlabel('$$Frequency(Hz)$$', 'Interpreter','latex');
ylabel('$$|H(e^jw)|$$', 'Interpreter', 'latex');
title('$$All-Individual-|H(e^jw)|$$', 'Interpreter','latex');
legend('h1[n]', 'h2[n]' , 'h3[n]', 'h4[n]', 'h5[n]', 'h6[n]' , 'h7[n]', 'h8[n]');

%TASK 6
%repeat previous task for total sys response

HT = abs(fftshift(fft(ht, 4096)));
figure(4);

semilogx(f, HT);
axis([12000 40000 0 32]);
xlabel('$$Frequency(Hz)$$', 'Interpreter','latex');
ylabel('$$|H(e^jw)|$$', 'Interpreter', 'latex');
title('$$Total-Sys-|H(e^jw)|$$', 'Interpreter','latex');

%TASK 7
%plot 2000 samples of input and output sequence

figure(5);
```

```
plot(x(1001:3000), 'b');
hold on;
plot(y(1001:3000), 'r');

xlabel('$$n$$', 'Interpreter','latex');
ylabel('$$x[n]-AND-y[n]$$', 'Interpreter', 'latex');
title('$$Input-vs.-Output-Signals$$', 'Interpreter','latex');
legend('x[n]', 'y[n]');

%TASK 8
%plot freq spectrum of input and output

%do not specify N for the fft
Y = abs(fftshift(fft(y)));
X = abs(fftshift(fft(x)));

%transpose X and Y to fix plotting issue
X = X.';
Y = Y.';

%plot as a function of Hz- match # of samples
f2_X = linspace(0, 44100, 537146);
f2_Y = linspace(0, 44100, 537896);

figure(6);

subplot(2,1,1);
semilogx(f2_X, X);
axis([12000 40000 0 8200]);
xlabel('$$Frequency(Hz)$$', 'Interpreter','latex');
ylabel('$$|X(e^jw)|$$', 'Interpreter', 'latex');
title('$$|X(e^jw)|$$', 'Interpreter','latex');

subplot(2,1,2);
semilogx(f2_Y, Y);
axis([12000 40000 0 112000]);
xlabel('$$Frequency(Hz)$$', 'Interpreter','latex');
ylabel('$$|Y(e^jw)|$$', 'Interpreter', 'latex');
title('$$|Y(e^jw)|$$', 'Interpreter','latex');

%TASK 9
```

```
%recreate equalizer h[n] w/ Blackman Window
[h1_blac,n] = bpw(wl, 0.00758, M, 'blac');
[h2_blac,n] = bpw(0.00758, 0.01793, M, 'blac');
[h3_blac,n] = bpw(0.01793, 0.04240, M, 'blac');
[h4_blac,n] = bpw(0.04240, 0.1003, M, 'blac');
[h5_blac,n] = bpw(0.1003, 0.2372, M, 'blac');
[h6_blac,n] = bpw(0.2372, 0.5610, M, 'blac');
[h7_blac,n] = bpw(0.5610, 1.3270, M, 'blac');
[h8_blac,n] = bpw(1.3270, wu, M, 'blac');

%use given gains
G1 = 4;
G2 = 3;
G3 = 2;
G4 = 1;
G5 = 1;
G6 = 2;
G7 = 3;
G8 = 4;

%multiply each impulse response computed
ht_blac = (h1_blac.*G1) + (h2_blac.*G2) + (h3_blac.*G3) + (h4_blac.*G4) + (h5_blac.*G5) +
(h6_blac.*G6) + (h7_blac.*G7) + (h8_blac.*G8);

%recreate equalizer h[n] w/ Barlett Window
[h1_bart,n] = bpw(wl, 0.00758, M, 'bart');
[h2_bart,n] = bpw(0.00758, 0.01793, M, 'bart');
[h3_bart,n] = bpw(0.01793, 0.04240, M, 'bart');
[h4_bart,n] = bpw(0.04240, 0.1003, M, 'bart');
[h5_bart,n] = bpw(0.1003, 0.2372, M, 'bart');
[h6_bart,n] = bpw(0.2372, 0.5610, M, 'bart');
[h7_bart,n] = bpw(0.5610, 1.3270, M, 'bart');
[h8_bart,n] = bpw(1.3270, wu, M, 'bart');

%use given gains
G1 = 3;
G2 = 1;
G3 = 3;
G4 = 1;
G5 = 3;
G6 = 1;
G7 = 3;
```

```
G8 = 1;

%multiply each impulse response computed
ht_bart = (h1_bart.*G1) + (h2_bart.*G2) + (h3_bart.*G3) + (h4_bart.*G4) + (h5_bart.*G5) +
(h6_bart.*G6) + (h7_bart.*G7) + (h8_bart.*G8);

%Plot total magnitude response of both equalizers
HT_blac = abs(fftshift(fft(ht_blac, 4096)));
HT_bart = abs(fftshift(fft(ht_bart, 4096)));

figure(7);

semilogx(f, HT_blac, 'r');
hold on;
semilogx(f, HT_bart, 'b');

axis([12000 40000 0 5]);
xlabel('$$Frequency(Hz)$$', 'Interpreter','latex');
ylabel('$$|H(e^jw)|$$', 'Interpreter', 'latex');
title('$$Total-Sys-|H(e^jw)|-for-Blackman-and-Barlett$$', 'Interpreter','latex');
legend('Blackman', 'Barlett');


function [h,n] = bpw(wl, wu, len, win)
% [h] = bpw(wl, wu, len, win);
%
% Creates a causal FIR bandpass impulse response using the windowing method
%
% wl Lower Cutoff (Radians): wl = [0,pi]
% wu Upper Cutoff (Radians): wh = [0,pi], wh>wl
% len Length of h (should be odd)
% win 'bart', 'blac', 'hamm' 'hann' or 'rect'
% ==> (Bartlett, Blackman, Hamming, Hanning, Rectangular)
%
% h Created Impulse Response
% n Causal time index vector from [0:len-1];
%
%
% Author: Bradley M. Ratliff, Ph.D.
% University of Dayton
% 4/22/2016
```

```
%If length is even, make it odd.
if mod(len,2) == 0
len = len + 1;
end

%Create n vector
M = len-1;
n = [-M/2:M/2];
n2 = n+M/2;

%Create Impulse Response Using Rectangular Window
h = (wu/pi)*sinc((wu*n)/pi) - (wl/pi)*sinc((wl*n)/pi);

%Apply Appropriate Window.
if win == 'bart'
wn = 0.54 - 0.46*cos((2*pi*n2)/M);
elseif win == 'blac'
wn = 0.42 - 0.5*cos(2*pi*n2/M) + 0.08*cos(4*pi*n2/M);
elseif win == 'hamm'
wn = 0.54 - 0.46*cos((2*pi*n2)/M);
elseif win == 'hann'
wn = 0.5 - 0.5*cos((2*pi*n2)/M);
elseif win == 'rect'
wn = 0*n2+1;
else
disp('Not a valid window type! ==> Rect Window Used.');
wn = 0*n2+1;
end
h = h.*wn;
n = n2;
end
```