CHAPTER 10

Design of FIR Filters

Tutorial Problems

1. (a) Solution:
   The relative specifications are:

$$A_{\mathrm{p}} = 20\log_{10}\left(\frac{1+\delta_{\mathrm{p}}}{1-\delta_{\mathrm{p}}}\right) = 0.1737\mathrm{dB}$$

$$A_{\mathrm{s}} = 20\log_{10}\left(\frac{1+\delta_{\mathrm{p}}}{\delta_{\mathrm{s}}}\right) = 60.0864\mathrm{dB}$$

   The analog filter specifications are:

$$\epsilon = \sqrt{10^{(-0.1A_{\mathrm{p}})}-1} = 0.2020$$

$$A = 10^{(0.05A_{\mathrm{s}})} = 1010$$

   (b) Solution:
   The relative specifications are:

$$A_{\mathrm{p}} = 20\log_{10}(\sqrt{1+\epsilon^2}) = 0.2633\mathrm{dB}$$

$$A_{\mathrm{s}} = 20\log_{10} A = 46.0206\mathrm{dB}$$

   The absolute specifications are:

$$A_{\mathrm{p}} = 20\log_{10}\left(\frac{1+\delta_{\mathrm{p}}}{1-\delta_{\mathrm{p}}}\right) \implies \delta_{\mathrm{p}} = 0.0152$$

$$A_{\mathrm{s}} = 20\log_{10}\left(\frac{1+\delta_{\mathrm{p}}}{\delta_{\mathrm{s}}}\right) \implies \delta_{\mathrm{s}} = 2.4395\times 10^{-4}$$

2. Proof:

$$h[n] = 2h_e[n]u[n] - h_e[0]\delta[n] \tag{10.14}$$

$$H_I(\mathrm{e}^{\mathrm{j}\omega}) = -\frac{1}{2\pi}\int_{-\pi}^{\pi} H_R(\mathrm{e}^{\mathrm{j}\theta}) \cot\left(\frac{\omega-\theta}{2}\right) \mathrm{d}\theta \tag{10.16}$$

First, we have

$$\frac{1}{2}\cot(\frac{x}{2}) = \frac{1}{x} + \sum_{n=1}^{\infty} \frac{1}{x+2n\pi} - \frac{1}{2n\pi}$$

$$\mathrm{DTFT}(u[n]) = U(\mathrm{e}^{\mathrm{j}\omega}) = \frac{1}{1-\mathrm{e}^{-\mathrm{j}\omega}} + \sum_{k=-\infty}^{\infty} \pi\delta(\omega - 2\pi k)$$

Hence,

$$H(\mathrm{e}^{\mathrm{j}\omega}) = 2 \times \frac{1}{2\pi}\int_{-\pi}^{\pi} H_R(\mathrm{e}^{\mathrm{j}\theta}) U(\mathrm{e}^{\mathrm{j}(\omega-\theta)}) \mathrm{d}\theta - h[0]$$

where

$$\begin{aligned} U(\mathrm{e}^{\mathrm{j}\omega}) &= \sum_{k=-\infty}^{\infty} \pi\delta(\omega - 2\pi k) + \frac{1}{1-\mathrm{e}^{\mathrm{j}\omega}} \\ &= \sum_{k=-\infty}^{\infty} \pi\delta(\omega - 2\pi k) + \frac{1}{2} - \frac{\mathrm{j}}{2}\cot(\frac{\omega}{2}) \end{aligned}$$

$$\begin{aligned} X(\mathrm{e}^{\mathrm{j}\omega}) &= X_R(\mathrm{e}^{\mathrm{j}\omega}) + \mathrm{j}X_I(\mathrm{e}^{\mathrm{j}\omega}) \\ &= X_R(\mathrm{e}^{\mathrm{j}\omega}) + \frac{1}{2\pi}\int_{-\pi}^{\pi} X_R(\mathrm{e}^{\mathrm{j}\theta})\mathrm{d}\theta - \frac{1}{2\pi}\int_{-\pi}^{\pi} X_R(\mathrm{e}^{\mathrm{j}\theta})\mathrm{d}\theta \\ &\quad - \frac{\mathrm{j}}{2\pi}\int_{-\pi}^{\pi} X_R(\mathrm{e}^{\mathrm{j}\theta}) \cot\left(\frac{\omega-\theta}{2}\right) \mathrm{d}\theta \end{aligned}$$

Hence, we proved that

$$H_I(\mathrm{e}^{\mathrm{j}\omega}) = -\frac{1}{2\pi}\int_{-\pi}^{\pi} H_R(\mathrm{e}^{\mathrm{j}\theta}) \cot\left(\frac{\omega-\theta}{2}\right) \mathrm{d}\theta$$

3. (a) Proof:

$$H(\mathrm{e}^{\mathrm{j}\omega}) = \sum_{k=1}^{(M+1)/2} b[k]\cos[\omega(k-\frac{1}{2})]\cdot \mathrm{e}^{-\mathrm{j}\omega M/2} \triangleq A(\mathrm{e}^{\mathrm{j}\omega})\cdot \mathrm{e}^{-\mathrm{j}\omega M/2} \tag{10.29}$$

$$b[k] = 2h[(M+1)/2-k], \quad k=1,2,\ldots,(M+1)/2 \tag{10.30}$$

$$\begin{aligned}
H(\mathrm{e}^{\mathrm{j}\omega}) &= \sum_{k=0}^{M} h[k]\cdot \mathrm{e}^{-\mathrm{j}k\omega} = \sum_{k=0}^{\frac{M-1}{2}} h[k]\mathrm{e}^{-\mathrm{j}k\omega} + \sum_{k=\frac{M+1}{2}}^{M} h[k]\mathrm{e}^{-\mathrm{j}k\omega} \\
&= \sum_{k=0}^{\frac{M-1}{2}} \left(h[k]\mathrm{e}^{-\mathrm{j}k\omega} + h[k+\frac{M+1}{2}]\mathrm{e}^{-\mathrm{j}(\frac{M+1}{2}+k)\omega}\right) \\
&= \sum_{k=0}^{\frac{M-1}{2}} \left(h[k]\mathrm{e}^{\mathrm{j}\omega(\frac{M}{2}-k)} + h[k+\frac{M+1}{2}]\mathrm{e}^{-\mathrm{j}(\frac{1}{2}+k)\omega}\right)\cdot \mathrm{e}^{-\mathrm{j}\omega M/2} \\
&= \sum_{k=0}^{\frac{M-1}{2}} \left(h[k]\mathrm{e}^{\mathrm{j}\omega(\frac{M}{2}-k)} + h[\frac{M-1}{2}-k]\mathrm{e}^{-\mathrm{j}(\frac{1}{2}+k)\omega}\right)\cdot \mathrm{e}^{-\mathrm{j}\omega M/2} \\
&= \sum_{k=0}^{\frac{M-1}{2}} \left(h[\frac{M-1}{2}-k]\mathrm{e}^{\mathrm{j}\omega(\frac{1}{2}+k)} + h[\frac{M-1}{2}-k]\mathrm{e}^{-\mathrm{j}(\frac{1}{2}+k)\omega}\right)\cdot \mathrm{e}^{-\mathrm{j}\omega M/2} \\
&= \left(\sum_{k=0}^{\frac{M-1}{2}} 2h[\frac{M-1}{2}-k]\cos\omega(k+\frac{1}{2})\right)\cdot \mathrm{e}^{-\mathrm{j}\omega M/2} \\
&= \left(\sum_{k=1}^{\frac{M+1}{2}} 2h[\frac{M+1}{2}-k]\cos\omega(k-\frac{1}{2})\right)\cdot \mathrm{e}^{-\mathrm{j}\omega M/2}
\end{aligned}$$

(b) Proof:

$$A(\mathrm{e}^{\mathrm{j}\omega}) = \cos(\frac{\omega}{2})\sum_{k=0}^{(M-1)/2} \tilde{b}[k]\cos\omega k \tag{10.31}$$

$$b[k] = \begin{cases} \frac{1}{2}(\tilde{b}[1]+2\tilde{b}[0]), & k=1 \\ \frac{1}{2}(\tilde{b}[k]+\tilde{b}[k-1]), & 2\le k\le (M-1)/2 \\ \frac{1}{2}\tilde{b}[(M-1)/2], & k=(M+1)/2 \end{cases} \tag{10.32}$$

$$
\begin{aligned}
A(e^{j\omega}) &= \cos(\frac{\omega}{2}) \sum_{k=0}^{(M-1)/2} \tilde{b}[k] \cos \omega k \\
&= \frac{1}{2} \sum_{k=0}^{(M-1)/2} \tilde{b}[k] \left[\cos \omega(k+\frac{1}{2}) + \cos \omega(k-\frac{1}{2}) \right] \\
&= \sum_{k=0}^{(M-1)/2} \left(\frac{1}{2}\tilde{b}[k] \cos \omega(k+\frac{1}{2}) + \frac{1}{2}\tilde{b}[k] \cos \omega(k-\frac{1}{2}) \right) \\
&= (\tilde{b}[0] + \frac{1}{2}\tilde{b}[1]) \cos \frac{\omega}{2} + \sum_{k=2}^{(M-1)/2} \frac{1}{2}(\tilde{b}[k] + \tilde{b}[k-1]) \cos \omega(k-\frac{1}{2}) \\
&\quad + \frac{1}{2}\tilde{b}[(M-1)/2] \cos \frac{M}{2}\omega
\end{aligned}
$$

4. (a) Solution:

The DTFT of $h[n]$ is:

$$
\begin{aligned}
H(e^{j\omega}) &= \sum_{n=-\infty}^{\infty} h[n] e^{-j\omega n} = \sum_{n=0}^{3} e^{-j\omega n} = 1 + e^{-j\omega} + e^{-2j\omega} + e^{-3j\omega} \\
&= (1 + \cos\omega + \cos 2\omega + \cos 3\omega) - j(\sin\omega + \sin 2\omega + \sin 3\omega)
\end{aligned}
$$

Hence, the magnitude response is:

$$
|H(e^{j\omega})| = \sqrt{(1 + \cos\omega + \cos 2\omega + \cos 3\omega)^2 + (\sin\omega + \sin 2\omega + \sin 3\omega)^2}
$$

(b) Solution:

$$
\begin{aligned}
A(e^{j\omega}) &= \sum_{k=1}^{2} b[k] \cos[\omega(k - \frac{1}{2})], \quad b[k] = 2h[2-k] \\
A(e^{j\omega}) &= b[1] \cos \frac{1}{2}\omega + b[2] \cos \frac{3}{2}\omega = 2 \cos \frac{1}{2}\omega + 2 \cos \frac{3}{2}\omega
\end{aligned}
$$

(c) Solution:

$$
\angle H(e^{j\omega}) = -\tan^{-1} \frac{\sin\omega + \sin 2\omega + \sin 3\omega}{1 + \cos\omega + \cos 2\omega + \cos 3\omega}
$$

(d) Solution:

$$
\Psi(e^{j\omega}) = -\omega M/2 = -\frac{3}{2}\omega
$$

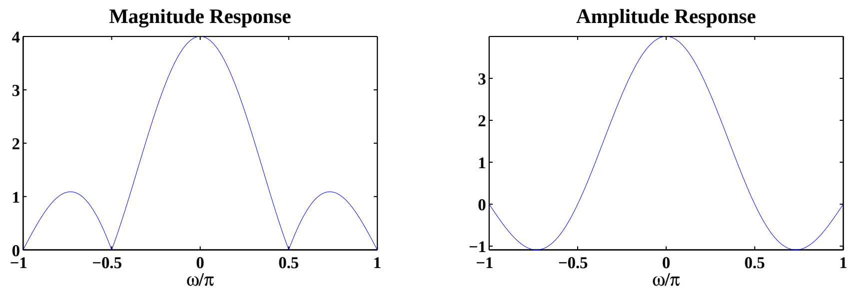


FIGURE 10.1: Plots of magnitude and amplitude responses.

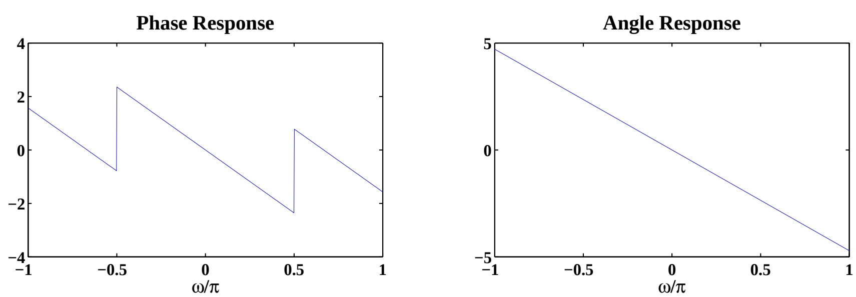


FIGURE 10.2: Plots of phase and angle responses.

5. Proof:
   Part I: Prove expression for $A\big(e^{j\omega}\big)$ for $M = 6$ type-III linear-phase FIR filter.
   We have

$$h[n] = -h[M-n], \quad 0 \le n \le M, \quad M = 6, \quad h[3] = 0$$

$$\begin{aligned}
H\big(e^{j\omega}\big) &= \sum_{k=0}^{6} h[k] \cdot e^{-jk\omega} = \sum_{k=0}^{3} h[k]e^{-j\omega k} - h[3]e^{-j\omega 3} + \sum_{k=3}^{6} h[k]e^{-jk\omega} \\
&= \sum_{k=0}^{3} \Big(h[k]e^{-j\omega k} + h[k+3]e^{-j\omega(k+3)}\Big) \\
&= \sum_{k=0}^{3} \Big(h[k]e^{-j\omega(k-3)} + h[k+3]e^{-j\omega k}\Big) \cdot e^{-j\omega 3} \\
&= \sum_{k=0}^{3} \Big(h[3-k]e^{j\omega k} - h[6-k-3]e^{-j\omega k}\Big) \cdot e^{-j\omega 3} \\
&= \sum_{k=0}^{3} (h[3-k] \cdot 2j\sin\omega k) \cdot e^{-j\omega 3} \\
&= \sum_{k=1}^{3} (h[3-k] \cdot 2\sin\omega k) \cdot je^{-j\omega 3} + 2h[3]\,j\sin(0\omega)e^{-j3\omega} \\
&= \left(\sum_{k=1}^{3} c[k] \cdot \sin\omega k\right) \cdot e^{j(\frac{\pi}{2} - 3\omega)}
\end{aligned}$$

Part II: Prove expression for $A\big(e^{j\omega}\big)$ for $M = 5$ type-IV linear-phase FIR filter.
We have

$$h[n] = -h[M-n], \quad M = 5$$

$$\begin{aligned}
A\big(e^{j\omega}\big) &= \sum_{k=0}^{5} h[k]\cdot e^{-j\omega k} = \sum_{k=0}^{2}\Big(h[k]e^{-j\omega k} + h[k+3]e^{-j\omega(k+3)}\Big) \\
&= \sum_{k=0}^{2}\Big(h[k]e^{-j\omega(k-\frac{5}{2})} + h[k+3]e^{-j\omega(k+\frac{1}{2})}\Big)\cdot e^{-j\omega\frac{5}{2}} \\
&= \sum_{k=1}^{3}\Big(h[3-k]e^{j\omega(k-\frac{1}{2})} + h[3-k]e^{-j\omega(k+\frac{1}{2})}\Big)\cdot e^{-j\omega\frac{5}{2}} \\
&= \sum_{k=1}^{3}\left(2h[3-k]\,j\sin[\omega(k-\frac{1}{2})]\right)\cdot e^{-j\omega\frac{5}{2}} \\
&= \left(\sum_{k=1}^{3} 2h[3-k]\sin[\omega(k-\frac{1}{2})]\right)\cdot je^{-j\omega\frac{5}{2}} \\
&= \left(\sum_{k=1}^{3} d[k]\sin[\omega(k-\frac{1}{2})]\right) e^{j(\frac{\pi}{2}-\frac{5}{2}\omega)}
\end{aligned}$$

6. (a) See plot below.

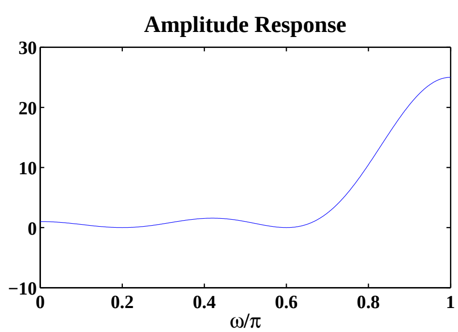


FIGURE 10.3: Plot of amplitude response from $h_1[n]$.

(b) See plot below.

(c) See plot below.

(d) See plot below.

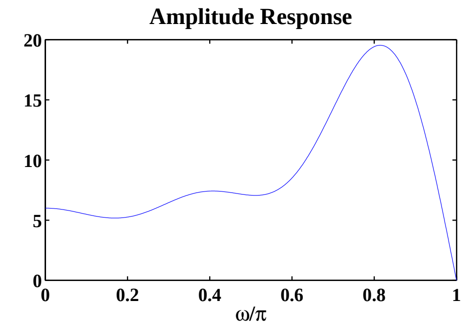


FIGURE 10.4: Plot of amplitude response from $h_2[n]$.

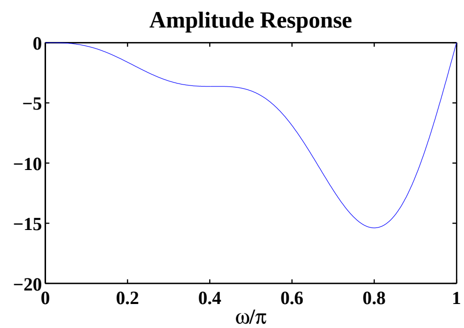


FIGURE 10.5: Plot of amplitude response from $h_3[n]$.

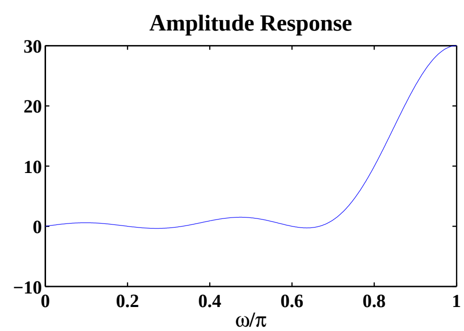


FIGURE 10.6: Plot of amplitude response from $h_4[n]$.

7. (a) See plot below.

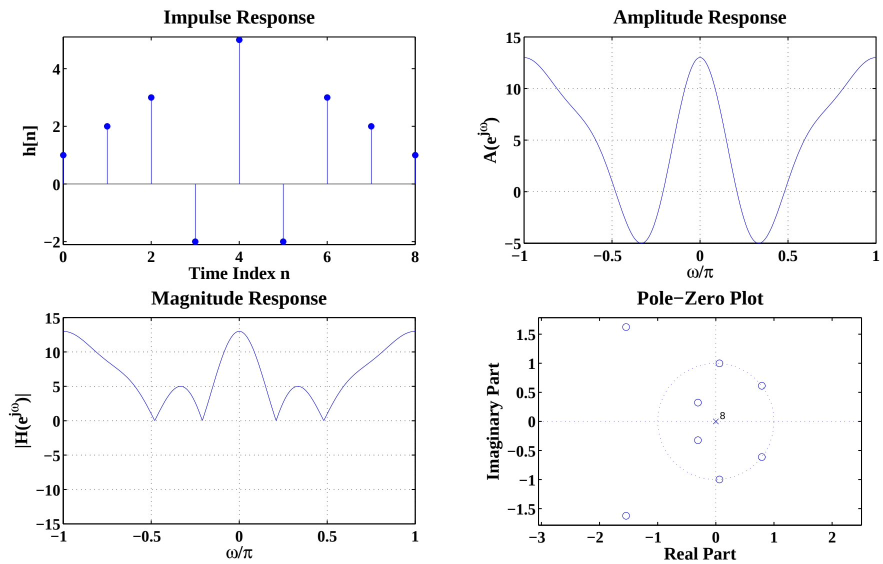


FIGURE 10.7: Plots of impulse response, amplitude response, magnitude response and pole-zero distribution in part (a).

(b) See plot below.

(c) See plot below.

(d) See plot below.

(e) tba.

MATLAB script:

```
% P1007: Reproduce Figures 10.4 and 10.5
close all; clc
%% Part a: Type-I
% hn = [1 2 3 -2 5 -2 3 2 1];
% w = linspace(-1,1,1000)*pi;

%% Part b: Type-II
% hn = [1 2 3 -2 -2 3 2 1];
% w = linspace(-2,2,1000)*pi;

%% Part c: Type-III
% hn = [1 2 3 -2 0 2 -3 -2 -1];
```

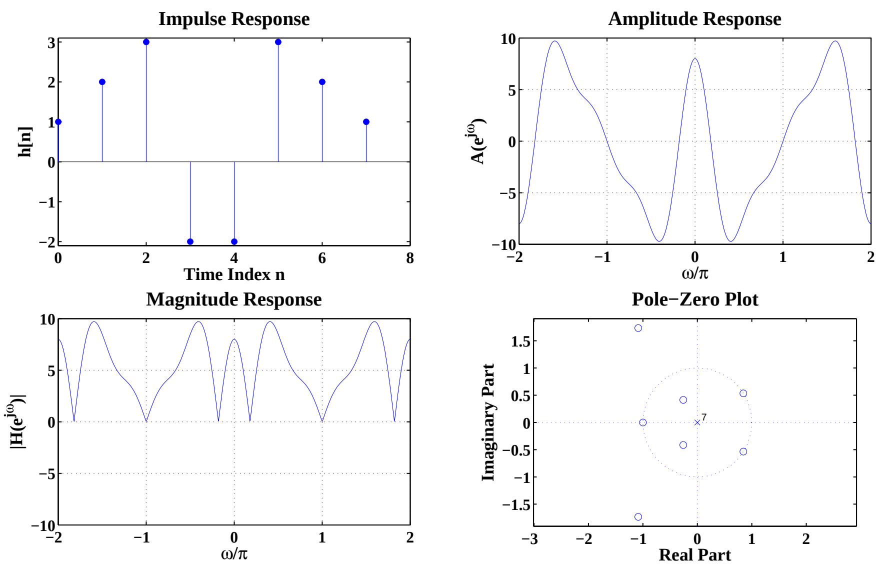


FIGURE 10.8: Plots of impulse response, amplitude response, magnitude response and pole-zero distribution in part (b).

```
% w = linspace(-1,1,1000)*pi;

%% Part d: Type-IV
hn = [1 2 3 -2 2 -3 -2 -1];
w = linspace(-2,2,1000)*pi;

H = freqz(hn,1,w);
Hmag = abs(H);
Hangle = angle(H);
n = 0:length(hn)-1;
[Hr w P L] = amplresp(hn,w);
% Plot:
hfa = figconfg('P1007a','small');
stem(n,hn,'filled');
ylim([min([hn 0])-.1 max(hn)+.1])
xlabel('Time Index n','fontsize',LFS)
ylabel('h[n]','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1007b','small');
```

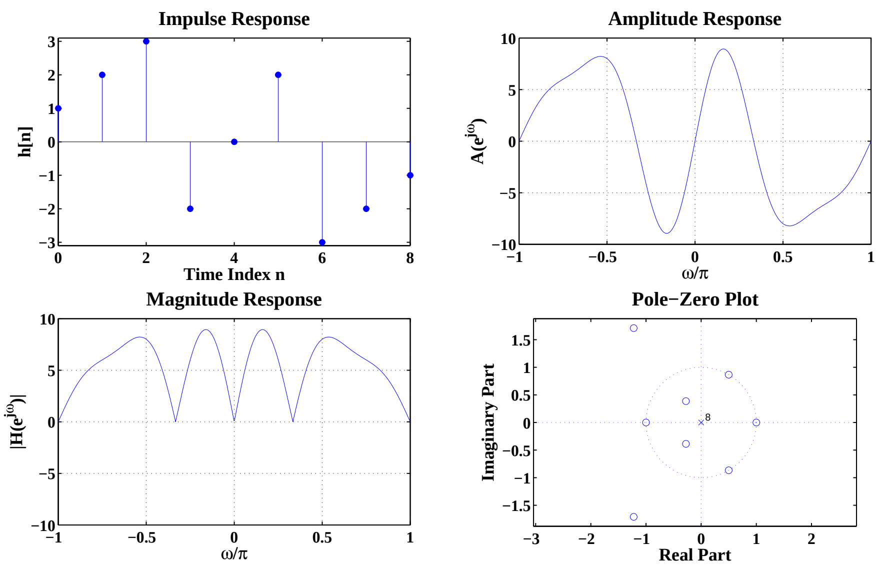


FIGURE 10.9: Plots of impulse response, amplitude response, magnitude response and pole-zero distribution in part (c).

```
zplane(hn,1)
xlabel('Real Part','fontsize',LFS)
ylabel('Imaginary Part','fontsize',LFS)
title('Pole-Zero Plot','fontsize',TFS)

hfc = figconfg('P1007c','small');
plot(w/pi,Hmag); grid on
yl = ylim;
ylim([-yl(2) yl(2)])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('|H(e^{j\omega})|','fontsize',LFS)
title('Magnitude Response','fontsize',TFS)

hfd = figconfg('P1007d','small');
plot(w/pi,Hr); grid on
xlabel('\omega/\pi','fontsize',LFS)
ylabel('A(e^{j\omega})','fontsize',LFS)
title('Amplitude Response','fontsize',TFS)
```

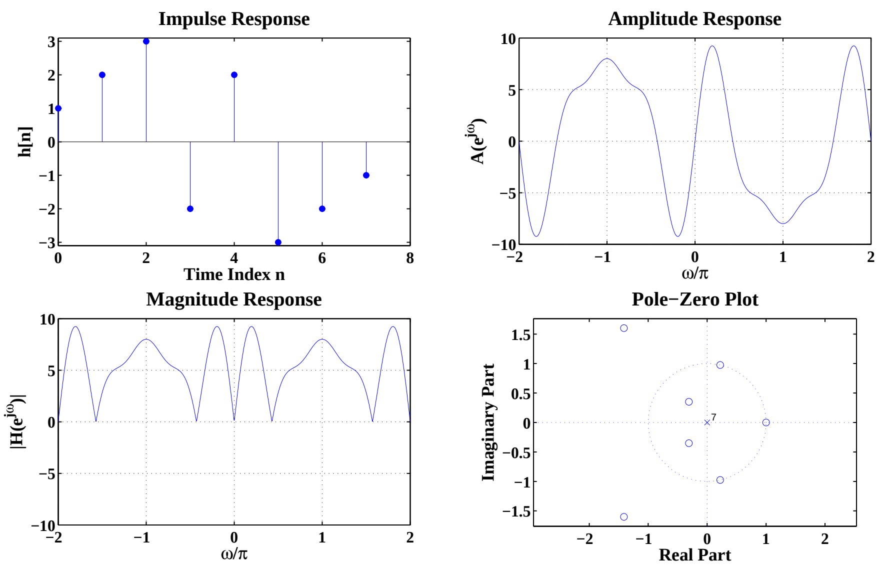


FIGURE 10.10: Plots of impulse response, amplitude response, magnitude response and pole-zero distribution in part (d).

8. (a) See plot below.

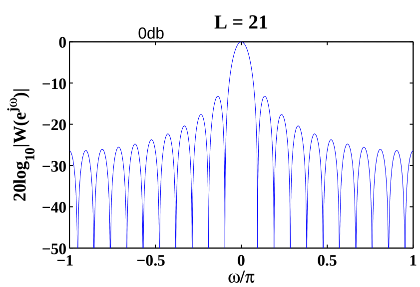


FIGURE 10.11: Plot of the log-magnitude response in dB over $-\pi \leq \omega \leq \pi$ when $L = 21$.

(b) See plot below.

(c) See plot below.

MATLAB script:

```
% P1008: Stude fixed window magnitude response
%        its peak of first side-lobe and transition bandwidth
```

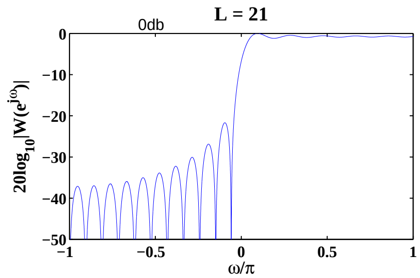


FIGURE 10.12: Plot of the accumulated amplitude response in dB over $-\pi \leq \omega \leq \pi$ when $L = 21$.

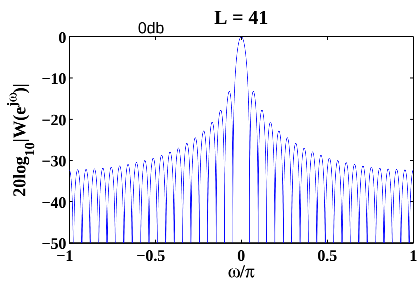


FIGURE 10.13: Plot of the log-magnitude response in dB over $-\pi \leq \omega \leq \pi$ when $L = 41$.

```
%         Rectangular Window
close all; clc
% L = 21; % Part a
L = 41; % Part b
hw = rectwin(L)';
Nw = 10000;
w = linspace(-1,1,Nw)*pi;
H = freqz(hw,1,w);
Hmag = abs(H);
Hmagdb = 20*log10(Hmag/max(Hmag));
[Ha w2 P2 L2] = amplresp(hw,w);
Hac = abs(cumsum(Ha));
Hacdb = 20*log10(Hac/max(Hac));

%% Find Peak Values:
[peakH peakHind] = findpeak(Hmagdb);
```

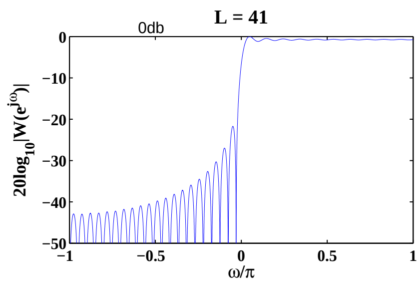


FIGURE 10.14: Plot of the accumulated amplitude response in dB over $-\pi \leq \omega \leq \pi$ when $L = 41$.

```
[peakHac peakHacind] = findpeak(Hacdb);
Lh = floor(length(peakH)/2);
sidlobeH = max(peakH(1:Lh));
sidlobeHac = max(peakHac(1:Lh));
bandwid = w(peakHacind(Lh+1)) - w(peakHacind(Lh));
bandwid/pi*L

%% Plot:
hfa = figconfg('P1008a','small');
plot(w/pi,Hmagdb);hold on
plot(w/pi,sidlobeH*ones(1,Nw),'--k')
text(w(Nw/5)/pi,sidlobeH,[num2str(sidlobeH,3),'db'],...
    'fontsize',LFS-2,'verticalalignment','bottom')
ylim([-50 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('20log_{10}|W(e^{j\omega})|','fontsize',LFS)
title(['L = ',num2str(L)],'fontsize',TFS)

hfb = figconfg('P1008b','small');
plot(w/pi,Hacdb); hold on
plot(w/pi,sidlobeHac*ones(1,Nw),'--k')
text(w(Nw/5)/pi,sidlobeHac,[num2str(sidlobeHac,3),'db'],...
    'fontsize',LFS-2,'verticalalignment','bottom')
ylim([-50 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('20log_{10}|W(e^{j\omega})|','fontsize',LFS)
title(['L = ',num2str(L)],'fontsize',TFS)
```

9.

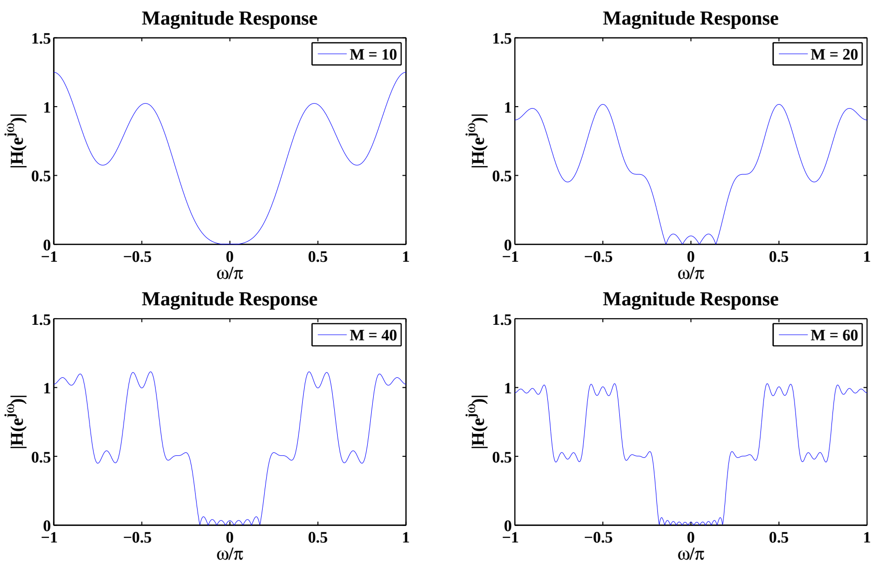


FIGURE 10.15: Amplitude plots of linear-phase FIR filter using the rectangular window of order $M = 10$, $M = 20$, $M = 40$ and $M = 60$.

MATLAB script:

```
% P1009: Design multiband filter using rectangular window
%        change window length for performance comparison
close all; clc
% M = 10;
% M = 20;
% M = 40;
M = 60;
h1 = 0.5*fir1(M,0.2,'high',rectwin(M+1));
h2 = 0.5*fir1(M,[0.4 0.6 0.8],'DC-0',rectwin(M+1));
h = h1 + h2;
w = linspace(-1,1,1000)*pi;
H = freqz(h,1,w);
%% Plot:
hfa = figconfg('P1008a','small');
plot(w/pi,abs(H));
ylim([0 1.5])
xlabel('\omega/\pi','fontsize',LFS)
```

```
ylabel('|H(e^{j\omega})|','fontsize',LFS)
title('Magnitude Response','fontsize',TFS)
legend(['M = ',num2str(M)],'location','northeast')
```

10. (a) See plot below.

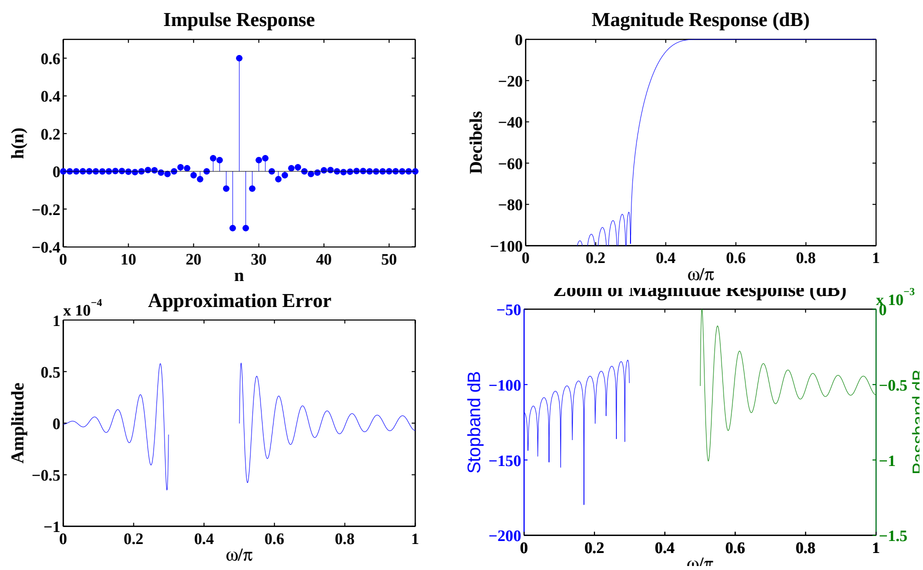


FIGURE 10.16: Impulse response, magnitude response, approximation error and zoom of magnitude response of the highpass FIR filter using fixed window design.

(b) See plot below.

MATLAB script:

```
% P1010: Design highpass filter using appropriate window
close all; clc
ws = 0.3*pi; wp = 0.5*pi;
As = 50; Ap = 0.001;
[deltap, deltas] = spec_convert(Ap,As,'rel','abs');
delta = min([deltap,deltas]);
A = -20*log10(delta);
[M,wn,beta,ftype] = kaiserord([0.3 0.5],[0 1],[deltas,deltap]);
%% Part (a)
wc = (ws+wp)/2;
% h = ideallp(pi,M) - ideallp(wc,M);
```

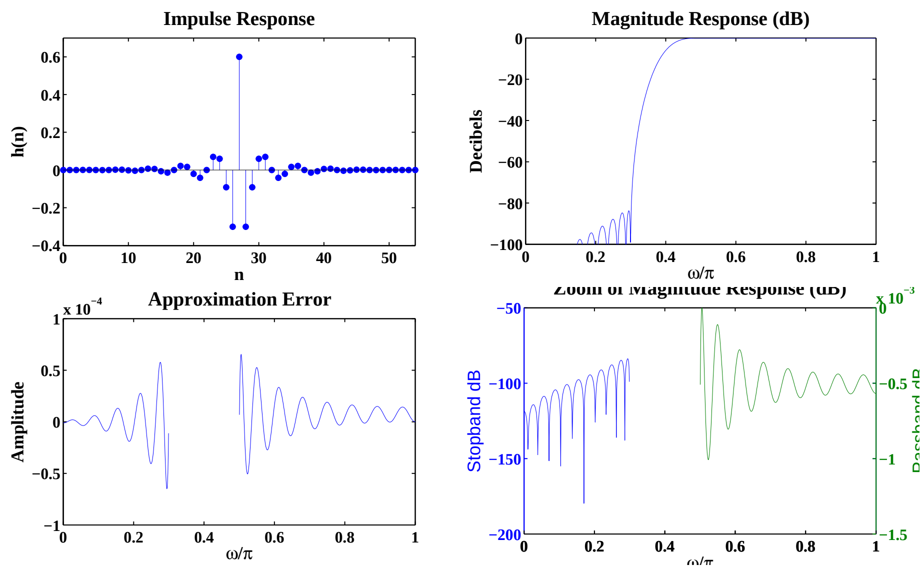


FIGURE 10.17: Impulse response, magnitude response, approximation error and zoom of magnitude response of the highpass FIR filter using fixed window design by fir1 function.

```
% h = h.*kaiser(M+1,beta);

%% Part (b)
h = fir1(M,wn,ftype,kaiser(M+1,beta));

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
[Ha w2 P2 L2] = amplresp(h(:)',w);
aerr = nan(1,length(w));
magz1 = nan(1,length(w));
magz2 = nan(1,length(w));
ind = w <= ws;
aperr(ind) = Ha(ind);
magz1(ind) = Hdb(ind);
ind = w >= wp;
aperr(ind) = Ha(ind) - 1;
magz2(ind) = Hdb(ind);
```

```
%% Plot:
hfa = figconfg('P1010a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1010b','small');
plot(w/pi,Hdb);
ylim([-100 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1010c','small');
plot(w/pi,aperr);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Approximation Error','fontsize',TFS)

hfd = figconfg('P1010d','small');
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
xlabel('\omega/\pi','fontsize',LFS)
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(1),'Ylabel'),'string','Stopband dB','fontsize',LFS)
set(get(AX(2),'Ylabel'),'string','Passband dB','fontsize',LFS)
```

11. (a) See plot below.
    (b) See plot below.
    (c) See plot below.

    MATLAB script:

```
% P1011: Study Frequency Sampling Technique of
%         different number of samples
close all; clc
% L = 20; % Part a
L = 400; % Part b & c
```

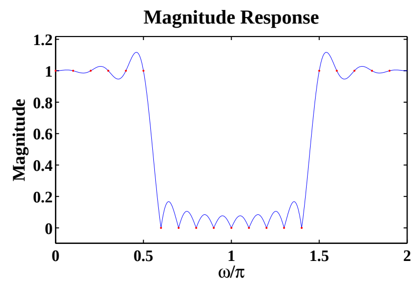


FIGURE 10.18: Magnitude response when $L = 20$ in part (a).

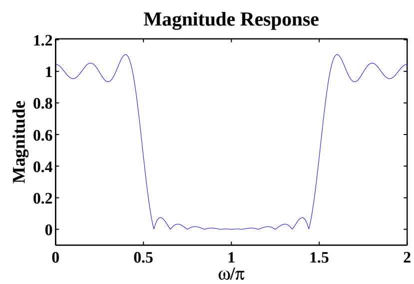


FIGURE 10.19: Magnitude response when $L = 400$ in part (b).

```
M = L - 1;
wc = pi/2;

Dw = 2*pi/L;
k1 = floor(wc/Dw);
Ad = [ones(1,k1+1),zeros(1,L-2*k1-1),ones(1,k1)];
alpha = M/2; Q = floor(alpha);
psid = -alpha*2*pi/L*[(0:Q),-(L-(Q+1:M))];
Hd = Ad.*exp(j*psid);
hd = real(ifft(Hd));
h = hd(L/2-9:L/2+10); % Part a & b
% h = hd(L/2-9:L/2+10).*hamming(20)'; % Part c

w = linspace(0,2,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);

%% Plot:
```

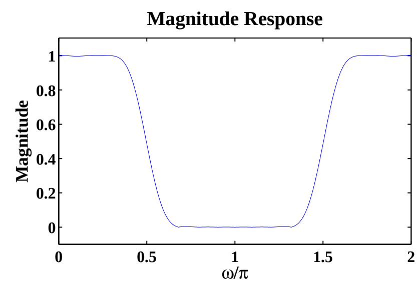


FIGURE 10.20: Magnitude response when $L = 400$ in part (c).

```
hf = figconfg('P1011','small');
plot(w/pi,Hmag);hold on
% plot((0:L-1)/L*2,Ad,'.r')
ylim([min(Hmag)-0.1 max(Hmag)+0.1])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Magnitude','fontsize',LFS)
title('Magnitude Response','fontsize',TFS)
```

12. (a) See plot below.

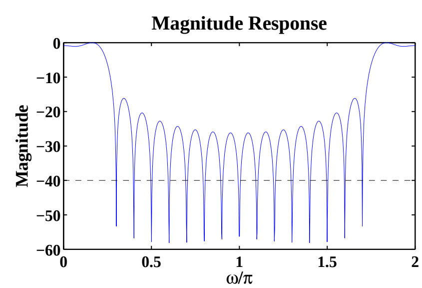


FIGURE 10.21: Magnitude response when $L = 20$ in part (a).

(b) See plot below.

(c) See plot below.

MATLAB script:

```
% P1012: Lowpass filter design by frequency sampling
close all; clc
% L = 20; % Part a
L = 40; % Part b & c
```

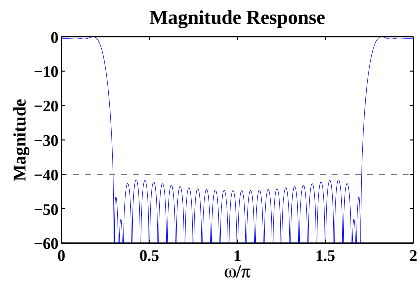


FIGURE 10.22: Magnitude response when $L = 40$ in part (b).

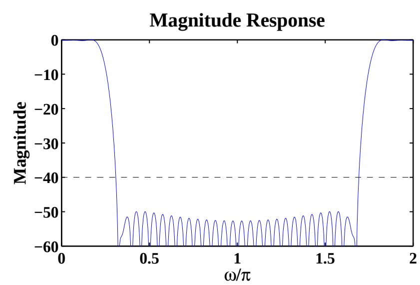


FIGURE 10.23: Magnitude response when $L = 40$ in part (c).

```
M = L - 1;
wp = 0.2*pi; ws = 0.3*pi; Ap = 0.2; As = 40;
wc = (wp+ws)/2;
Dw = 2*pi/L;
alpha = M/2; Q = floor(alpha);
psid = -alpha*2*pi/L*[(0:Q),-(L-(Q+1:M))];
T1 = 0.37897949;

%% Part a:
% k = floor(wc/Dw);
% Ad = [ones(1,k+1),zeros(1,L-2*k-1),ones(1,k)];
% Hd = Ad.*exp(j*psid);
% hd = real(ifft(Hd));
% h = hd.*rectwin(L)';

%% Part b:
% k1 = floor(wp/Dw); k2 = ceil(ws/Dw);
% Ad = [ones(1,k1+1),T1,zeros(1,L-2*k2+1),T1,ones(1,k1)];
```

```
% Hd = Ad.*exp(j*psid);
% hd = real(ifft(Hd));
% h = hd.*rectwin(L)';

%% Part c:
h = fir2(M,[0 wp/pi wc/pi ws/pi 1],[1 1 T1 0 0],rectwin(L));

w = linspace(0,2,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag/max(Hmag));

%% Plot:
hf = figconfg('P1012','small');
plot(w/pi,Hdb);hold on
plot(w/pi,-40*ones(1,length(w)),'--','color','k')
ylim([-60 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Magnitude','fontsize',LFS)
title('Magnitude Response','fontsize',TFS)
```

13. (a) Proof:

$$\cos[(n+1)\omega] = \cos n\omega \cos\omega - \sin n\omega \sin\omega$$
$$\cos[(n-1)\omega] = \cos n\omega \cos\omega + \sin n\omega \sin\omega$$

which implies that

$$\cos[(n+1)\omega] + \cos[(n-1)\omega] = 2\cos n\omega \cos\omega$$

that is

$$\cos[(n+1)\omega] = 2\cos(\omega)\cos(n\omega) - \cos[(n-1)\omega]$$

(b) Proof:
Define $\theta = \cos^{-1} x$, we have

$$\begin{aligned} T_{n+1}(x) = \cos[(n+1)\omega] &= 2\cos\theta\cos n\theta - \cos[(n-1)\theta] \\ &= 2x \cdot \cos(n\theta) - \cos(n-1)\theta \\ &= 2xT_n(x) - T_{n-1}(x) \end{aligned}$$

(c) Proof:

$$T_0(x) = 1, \quad T_1(x) = 1$$

$$n = 2, \quad T_2(x) = 2xT_1(x) - T_0(x) = 2x^2 - 1$$

$$n = 3, \quad T_3(x) = 2xT_2(x) - T_1(x) = 2x(2x^2 - 1) - x = 4x^3 - 3x$$

$$n = 4, \quad T_4(x) = 2xT_3(x) - T_2(x) = 2x(4x^3 - 3x) - (2x^2 - 1) = 8x^4 - 8x^2 + 1$$

$$n = 5, \quad T_5(x) = 2xT_4(x) - T_3(x) = 2x(8x^4 - 8x^2 + 1) - (4x^3 - 3x) = 16x^5 - 20x^3 + 5x$$

14. (a) See plot below.

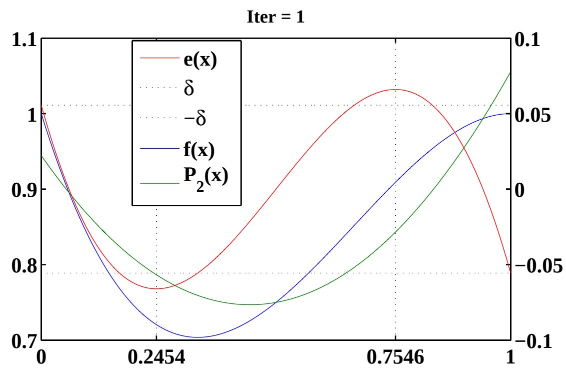


FIGURE 10.24: Graph of $f(x)$, the resulting $P_2(x)$, and $e(x)$.

(b) See plot below.

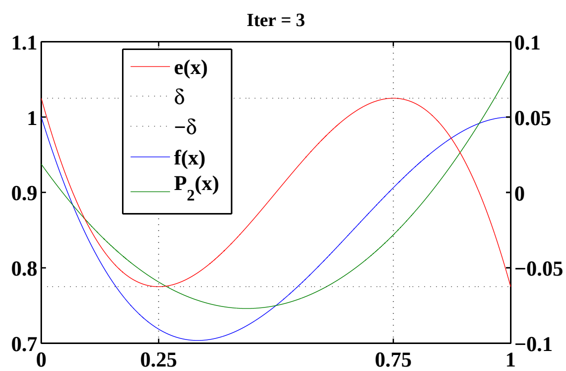


FIGURE 10.25: Graph of final $f(x)$, the resulting $P_2(x)$, and $e(x)$.

MATLAB script:

```
% P1014: Illustration of realization of alternation theorem
function [coeff] = main_1014
close all; clc
fx = @(x) 1-2*x+4*x.^2-2*x.^3;
x_init = [0 1/3 2/3 1];
x_loc = x_init;
ii = 0;
thresh_x = 1;
thresh_ex = 1;
while thresh_x > 1e-10 && thresh_ex > 1e-5
    ii = ii + 1;
    coeff = coeff_solver(x_loc);
    N = 10000;
    xp = linspace(0,1,N);
    a0 = coeff(1); a1 = coeff(2); a2 = coeff(3); delta = coeff(4);
    Px = @(x) a0+a1*x+a2*x.^2;
    ex = fx(xp)-Px(xp);

    hf = figconfg('P1014','small');
    % plot:
    [Ax hf1 hf2] = plotyy(xp,[fx(xp);Px(xp)],xp,...
        [ex;delta*ones(1,N);-delta*ones(1,N)]);
    set(hf2(2),'color','k','Linestyle',':')
    set(hf2(3),'color','k','Linestyle',':')
    legend('e(x)','\delta','-\delta','f(x)','P_2(x)','location','best')

    [extrema extrema_loc] = find_extrema(ex,xp);
    set(Ax(1),'Xtick',extrema_loc,'Xgrid','on')
    set(Ax(2),'Xtick',[],'Xgrid','on')
    title(['Iter = ',num2str(ii)],'fontsize',14)

    thresh_x = max(abs(x_loc-extrema_loc));
    [X Y] = meshgrid(abs(extrema),abs(extrema));
    thresh_ex = max(abs(X(:)-Y(:)));
    x_loc = extrema_loc;
    thresh_x, thresh_ex

end

end
```

```
%% Subfunctions:
function coeff = coeff_solver(x)
% Given guessed nodes, solve for coefficients a_k and delta
% Input:
%       x = [zeta_0 zeta_1 zeta_2 zeta_3];
% Output:
%       coeff = [a_0;a_1;a_2;delta];
x = x(:);
n = length(x);
A = [ones(n,1),x,x.^2];
B = [A,x.^3];
c = (-1).^(0:n-1);
A = [A,c(:)];
coeff = inv(A)*B*[1;-2;4;-2];
end

function [extrema extrema_loc] = find_extrema(fx,x)
% Find the locations of extrema of fx
% Inputs:
%        x: independent variable, value between 0 and 1
%        fx: dependent values
% Output:
%        extrema: values of x where fx is an extrema
fx = fx(:)';
a1 = [0,diff(fx)];
a2 = fliplr([0,diff(fliplr(fx))]);
a = abs(sign(a1) + sign(a2));
ind = find(a>0);
extrema_loc = x(ind);
extrema = fx(ind);
end
```

15. tba

16.

MATLAB script:

```
% P1016: Design highpass FIR filter using Parks-McClellan
close all; clc
```

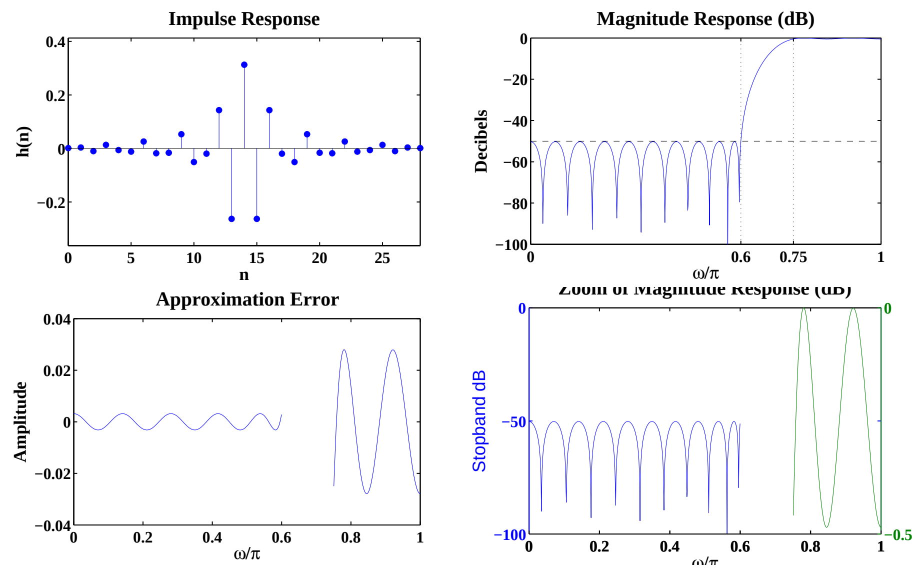


FIGURE 10.26: Graph of impulse response, magnitude response, approximation error and zoom magnitude response.

```
%% Specification:
ws = 0.6*pi; wp = 0.75*pi; As = 50; Ap = 0.5;
%% Passband and Stopband Ripple Calculation:
deltap = (10^(Ap/20)-1)/(10^(Ap/20)+1);
deltas = (1+deltap)/(10^(As/20));
%% Estimated Filter order using FIRPMORD function:
[M,fo,ao,W] = firpmord([ws,wp]/pi,[0,1],[deltas,deltap]);
M = M + 2
%% Filter Design using FIRPM function:
[h,delta] = firpm(M,fo,ao,W);
delta,
deltap,

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
[Ha w2 P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
magz1 = nan(1,length(w));
```

```
magz2 = nan(1,length(w));
ind = w <= ws;
aperr(ind) = Ha(ind);
magz1(ind) = Hdb(ind);
ind = w >= wp;
aperr(ind) = Ha(ind)-1;
magz2(ind) = Hdb(ind);
%% Plot:
hfa = figconfg('P1016a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1016b','small');
plot(w/pi,Hdb);hold on
plot(w/pi,-As*ones(1,length(w)),'--','color','k')
ylim([-100 0])
set(gca,'XTick',[0 ws wp pi]/pi,'Xgrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1016c','small');
plot(w/pi,aperr);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Approximation Error','fontsize',TFS)

hfd = figconfg('P1016d','small');
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
xlabel('\omega/\pi','fontsize',LFS)
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(2),'Ylabel'),'string','Passband dB','fontsize',LFS)
set(get(AX(1),'Ylabel'),'string','Stopband dB','fontsize',LFS)
set(AX(1),'Ytick',[-100 -50 0],'ylim',[-100 0])
```

17.

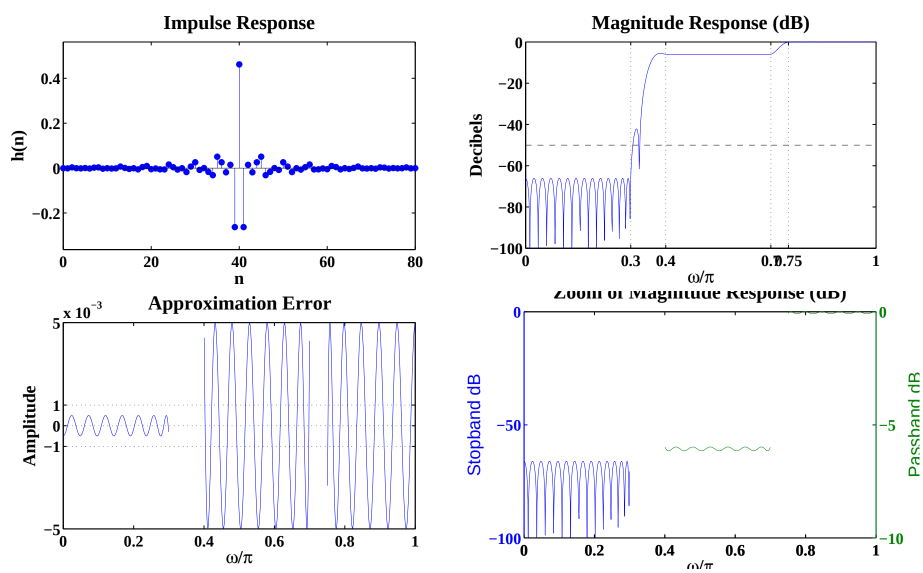


FIGURE 10.27: Graph of impulse response, magnitude response, approximation error and zoom magnitude response.

MATLAB script:

```
% P1017: Design multiband FIR filter using Parks-McClellan
close all; clc
%% Specification:
ws = 0.3*pi; wp1 = 0.4*pi; wp2 = 0.7*pi; wp3 = 0.75*pi;
deltas = 0.001; deltap1 = 0.005; deltap2 = 0.01;
%% Estimated Filter order using FIRPMORD function:
[M,fo,ao,W] = ...
firpmord([ws,wp1,wp2,wp3]/pi,[0,0.5,1],[deltas,deltap1,deltap2]);
M = M + 2
%% Filter Design using FIRPM function:
[h,delta] = firpm(M,fo,ao,W);
delta,
deltap1,

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
```

```
Hdb = 20*log10(Hmag./max(Hmag));
[Ha w2 P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
magz1 = nan(1,length(w));
magz2 = nan(1,length(w));
ind = w <= ws;
aperr(ind) = Ha(ind);
magz1(ind) = Hdb(ind);
ind = w >= wp1 & w <= wp2;
aperr(ind) = Ha(ind)-0.5;
magz2(ind) = Hdb(ind);
ind = w >= wp3;
aperr(ind) = Ha(ind)-1;
magz2(ind) = Hdb(ind);
%% Plot:
hfa = figconfg('P1017a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1017b','small');
plot(w/pi,Hdb);hold on
plot(w/pi,-As*ones(1,length(w)),'--','color','k')
ylim([-100 0])
set(gca,'XTick',[0 ws wp1 wp2 wp3 pi]/pi,'Xgrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1017c','small');
plot(w/pi,aperr);
set(gca,'Ytick',[-deltap1 -deltas 0 deltas deltap1],'Ygrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Approximation Error','fontsize',TFS)

hfd = figconfg('P1017d','small');
```

```
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
xlabel('\omega/\pi','fontsize',LFS)
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(2),'Ylabel'),'string','Passband dB','fontsize',LFS)
set(get(AX(1),'Ylabel'),'string','Stopband dB','fontsize',LFS)
set(AX(1),'Ytick',[-100 -50 0],'ylim',[-100 0])
```

18.

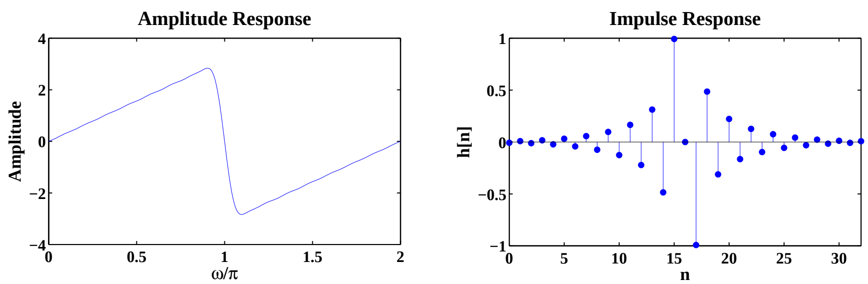


FIGURE 10.28: Graph of amplitude response and impulse response of the designed differentiator.

MATLAB script:

```
% P1018: Design a wideband type-III differentiator
%        using frequency sampling approach
close all; clc
M = 32;
L = M + 1;
Dw = 2*pi/L;
om = (0:L-1)*Dw;
ind = om >= pi;
om(ind) = om(ind) - 2*pi;
alpha = M/2;
H = j*om.*exp(-j*om*alpha);
hd = real(ifft(H));
h = hd.*hamming(L)';

w = linspace(0,2,1000)*pi;
[Ha wt P2 L2] = amplresp(h(:)',w);

%% Plot:
```

```
hfa = figconfg('P1018a','small');
plot(w/pi,Ha);hold on
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Amplitude Response','fontsize',TFS)

hfb = figconfg('P1018b','small');
stem(0:M,h,'filled')
xlim([0 M])
xlabel('n','fontsize',LFS)
ylabel('h[n]','fontsize',LFS)
title('Impulse Response','fontsize',TFS)
```

19.

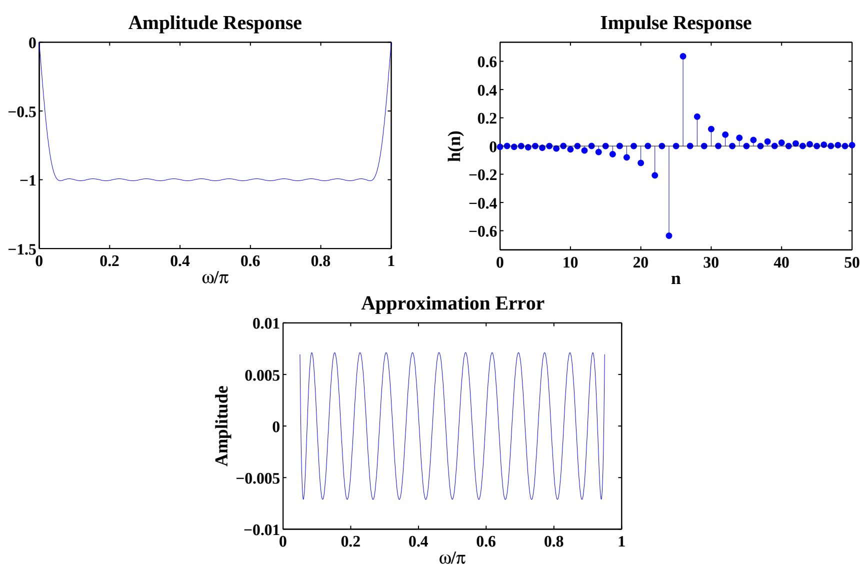


FIGURE 10.29: Graph of amplitude response, impulse response and the approximation error of the designed Hilbert transformer.

MATLAB script:

```
% P1019: Design Hilbert transformer using Parks-McClellan
close all; clc
L = 51; M = L-1;
w1 = 0.05*pi; w2 = 0.95*pi;
```

```
[h,delta] = firpm(M,[w1 w2]/pi,[1 1],'hilbert');

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
[Ha wa P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
ind = (w >= w1 & w <= w2);
aperr(ind) = Ha(ind)+1;

%% Plot:
hfa = figconfg('P1019a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1019b','small');
plot(w/pi,Ha);hold on
xlabel('\omega/\pi','fontsize',LFS)
title('Amplitude Response','fontsize',TFS)

hfc = figconfg('P1019c','small');
plot(w/pi,aperr);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Approximation Error','fontsize',TFS)
```

20. tba

Basic Problems

21. MATLAB function:

```
function [A,B] = spec_convert(C,D,typein,typeout)
% typein:  'abs' or 'rel' or 'ana'
% typeout: 'abs' or 'rel' or 'ana'
% C, D:     input specifications
% A, B:     output specifications
if strcmpi(typein,'abs')
    A = 20*log10((1+C)/(1-C));
    B = 20*log10((1+C)/D);
elseif strcmpi(typein,'ana')
    A = 20*log10(sqrt(1+C^2));
    B = 20*log10(D);
elseif strcmpi(typein,'rel')
    A = C;
    B = D;
end

if strcmpi(typeout,'ana')
    A = sqrt(10^(0.1*A)-1);
    B = 10^(0.05*B);
elseif strcmpi(typeout,'abs')
    A = 10^(A/20);
    A = (A-1)/(A+1);
    B = 10^(B/20);
    B = (A+1)/B;
end
```

22. (a) Proof:

$$H\left(e^{j\omega}\right) = \left(\sum_{k=1}^{M/2} c[k]\sin\omega k\right) je^{-j\omega M/2} \triangleq jA\left(e^{j\omega}\right)e^{-j\omega M/2} \tag{10.34}$$

$$c[k] = 2h[M/2-k], \quad k = 1, 2, \ldots, M/2 \tag{10.35}$$

Since $h[M/2] = 0$, we have

$$\begin{aligned}
H\left(e^{j\omega}\right) &= \sum_{k=0}^{M} h[k]\cdot e^{-jk\omega} = \sum_{k=0}^{M/2} h[k]e^{-jk\omega} + \sum_{k=M/2}^{M} h[k]e^{-jk\omega} \\
&= \sum_{k=0}^{M/2}\left(h[k]e^{-jk\omega} + h[k+M/2]e^{-j(k+M/2)\omega}\right) \\
&= \sum_{k=0}^{M/2}\left(h[k]e^{-j(k-M/2)\omega} + h[k+M/2]e^{-jk\omega}\right)\cdot e^{j\frac{M}{2}\omega} \\
&= \sum_{k=0}^{M/2}\left(h[M/2-k]e^{-j(M/2-k-M/2)\omega} - h[M-k-M/2]e^{-jk\omega}\right)\cdot e^{j\frac{M}{2}\omega} \\
&= \sum_{k=0}^{M/2}\left(h[M/2-k]e^{jk\omega} - h[M/2-k]e^{-jk\omega}\right)\cdot e^{j\frac{M}{2}\omega} \\
&= \sum_{k=0}^{M/2}\left(2h[M/2-k]\cdot j\sin k\omega\right)\cdot e^{j\frac{M}{2}\omega} \\
&= \left(\sum_{k=1}^{M/2} 2h[M/2-k]\sin k\omega\right)\cdot je^{j\frac{M}{2}\omega} \\
&= \left(\sum_{k=1}^{M/2} c[k]\sin k\omega\right)\cdot e^{j(\frac{\pi}{2}-j\frac{M}{2}\omega)}
\end{aligned}$$

(b) tba

23. (a) Solution:
The impulse response is:

$$\begin{aligned} h_{\mathrm{lp}}[n] &= \frac{1}{2\pi}\int_{-\pi}^{\pi} \mathrm{e}^{-\mathrm{j}n_d\omega}\cdot \mathrm{e}^{\mathrm{j}\omega n}\mathrm{d}\omega = \frac{1}{2\pi}\int_{-\pi}^{\pi} \mathrm{e}^{-\mathrm{j}\omega(n-n_d)}\mathrm{d}\omega \\ &= \frac{1}{2\pi}\left(\frac{1}{-\mathrm{j}(n-n_d)}\right)\mathrm{e}^{-\mathrm{j}\omega(n-n_d)}\Big|_{-\pi}^{\pi} = \frac{\sin\pi(n-n_d)}{\pi(n-n_d)} \\ &= \mathrm{sinc}(n-n_d) \end{aligned}$$

(b) Proof:

$$x[n] \xrightarrow{\text{DTFT}} X(\mathrm{e}^{\mathrm{j}\omega})$$
$$Y(\mathrm{e}^{\mathrm{j}\omega}) = X(\mathrm{e}^{\mathrm{j}\omega})\cdot H_{\mathrm{lp}}(\mathrm{e}^{\mathrm{j}\omega}) = X(\mathrm{e}^{\mathrm{j}\omega})\cdot \mathrm{e}^{-\mathrm{j}n_d\omega}$$

Applying time-shifting property, we have

$$y[n] = x[n-n_d]$$

24. tba

25. (a) Solution:

$$\begin{aligned} w[n] &= \left[\frac{1}{2} - \frac{1}{2}\times\frac{1}{2}\left(\mathrm{e}^{\mathrm{j}\frac{2\pi n}{M}} - \mathrm{e}^{-\mathrm{j}\frac{2\pi n}{M}}\right)\right] w_R[n] \\ &= \frac{1}{2}w_R[n] - \frac{1}{4}w_R[n]\cdot \mathrm{e}^{\mathrm{j}\frac{2\pi n}{M}} + \frac{1}{4}w_R[n]\cdot \mathrm{e}^{-\mathrm{j}\frac{2\pi n}{M}} \end{aligned}$$

Hence, we have

$$W(\mathrm{e}^{\mathrm{j}\omega}) = \frac{1}{2}W_R(\mathrm{e}^{\mathrm{j}\omega}) - \frac{1}{4}W_R(\mathrm{e}^{\mathrm{j}(\omega-\frac{2\pi}{M})}) + \frac{1}{4}W_R(\mathrm{e}^{\mathrm{j}(\omega+\frac{2\pi}{M})})$$

(b) Comments:
The second and third terms widen the mainlobe of Hann window and the sidelobes are lowed by the scaling factor.

26. (a) See plot below.

    (b) See plot below.

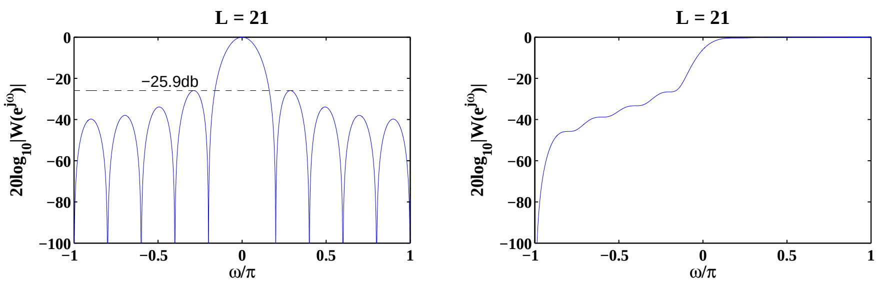


FIGURE 10.30: Log-magnitude response in dB and accumulated amplitude response in dB when window length is $L = 21$.

    (c) See plot below.

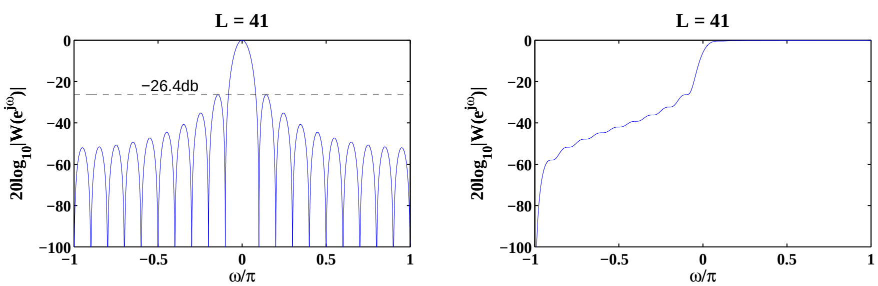


FIGURE 10.31: Log-magnitude response in dB and accumulated amplitude response in dB when window length is $L = 41$.

MATLAB script:

```
% P1026: Stude fixed window magnitude response
%        its peak of first side-lobe and transition bandwidth
%        Bartlett Window
close all; clc
% L = 21; % Part a
L = 41; % Part b
hw = bartlett(L)';
Nw = 10000;
w = linspace(-1,1,Nw)*pi;
H = freqz(hw,1,w);
```

```
Hmag = abs(H);
Hmagdb = 20*log10(Hmag/max(Hmag));
[Ha w2 P2 L2] = amplresp(hw,w);
Hac = abs(cumsum(Ha));
Hacdb = 20*log10(Hac/max(Hac));

%% Find Peak Values:
[peakH peakHind] = findpeak(Hmagdb);
[valleyH valleyHind] = findvalley(Hmagdb);
[tempL indL] = find(w(valleyHind)<=-1e-3);
[tempR indR] = find(w(valleyHind)>=1e-3);
bandwid = w(valleyHind(indR(1))) - w(valleyHind(indL(end)));
[peakHac peakHacind] = findpeak(Hacdb);
Lshind = w(peakHind) < -1e-3;
sidlobeH = max(peakH(Lshind));

bandwid/pi*L

%% Plot:
hfa = figconfg('P1026a','small');
plot(w/pi,Hmagdb);hold on
plot(w/pi,sidlobeH*ones(1,Nw),'--k')
text(w(Nw/5)/pi,sidlobeH,[num2str(sidlobeH,3),'db'],...
    'fontsize',LFS-2,'verticalalignment','bottom')
ylim([-100 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('20log_{10}|W(e^{j\omega})|','fontsize',LFS)
title(['L = ',num2str(L)],'fontsize',TFS)

hfb = figconfg('P1026b','small');
plot(w/pi,Hacdb); hold on
ylim([-100 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('20log_{10}|W(e^{j\omega})|','fontsize',LFS)
title(['L = ',num2str(L)],'fontsize',TFS)
```

27. (a) See plot below.

    (b) See plot below.

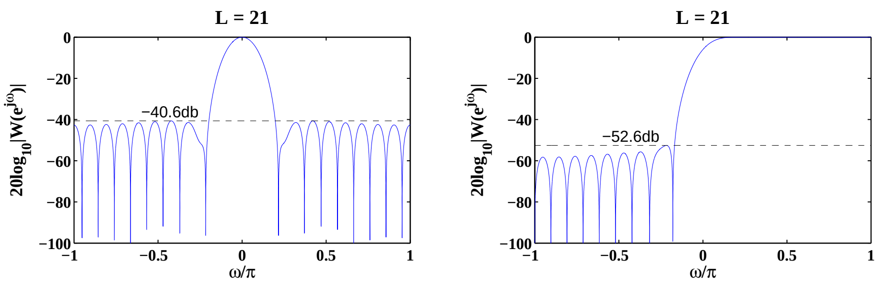


FIGURE 10.32: Log-magnitude response in dB and accumulated amplitude response in dB when window length is $L = 21$.

    (c) See plot below.

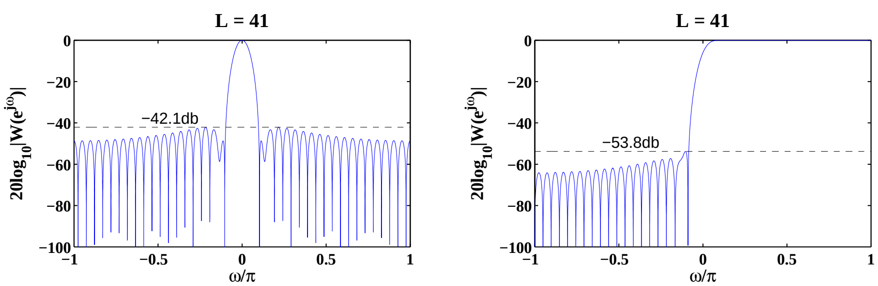


FIGURE 10.33: Log-magnitude response in dB and accumulated amplitude response in dB when window length is $L = 41$.

MATLAB script:

```
% P1027: Stude fixed window magnitude response
%        its peak of first side-lobe and transition bandwidth
%        Hamming Window
close all; clc
% L = 21; % Part a
L = 41; % Part b
hw = hamming(L)';
% Nw = 1000;
Nw = 10000;
w = linspace(-1,1,Nw)*pi;
```

```
H = freqz(hw,1,w);
Hmag = abs(H);
Hmagdb = 20*log10(Hmag/max(Hmag));
[Ha w2 P2 L2] = amplresp(hw,w);
Hac = abs(cumsum(Ha));
Hacdb = 20*log10(Hac/max(Hac));

%% Find Peak Values:
[peakH peakHind] = findpeak(Hmagdb);
[peakHac peakHacind] = findpeak(Hacdb);
Lshind = w(peakHind) < -1e-3;
sidlobeH = max(peakH(Lshind));
Lshind = w(peakHacind) < 0;
[sidlobeHac slind] = max(peakHac(Lshind));
bandwid = w(peakHacind(slind+1)) - w(peakHacind(slind));
bandwid/pi*L

%% Plot:
hfa = figconfg('P1027a','small');
plot(w/pi,Hmagdb);hold on
plot(w/pi,sidlobeH*ones(1,Nw),'--k')
text(w(Nw/5)/pi,sidlobeH,[num2str(sidlobeH,3),'db'],...
    'fontsize',LFS-2,'verticalalignment','bottom')
ylim([-100 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('20log_{10}|W(e^{j\omega})|','fontsize',LFS)
title(['L = ',num2str(L)],'fontsize',TFS)

hfb = figconfg('P1027b','small');
plot(w/pi,Hacdb); hold on
plot(w/pi,sidlobeHac*ones(1,Nw),'--k')
text(w(Nw/5)/pi,sidlobeHac,[num2str(sidlobeHac,3),'db'],...
    'fontsize',LFS-2,'verticalalignment','bottom')
ylim([-100 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('20log_{10}|W(e^{j\omega})|','fontsize',LFS)
title(['L = ',num2str(L)],'fontsize',TFS)
```

28. (a) See plot below.

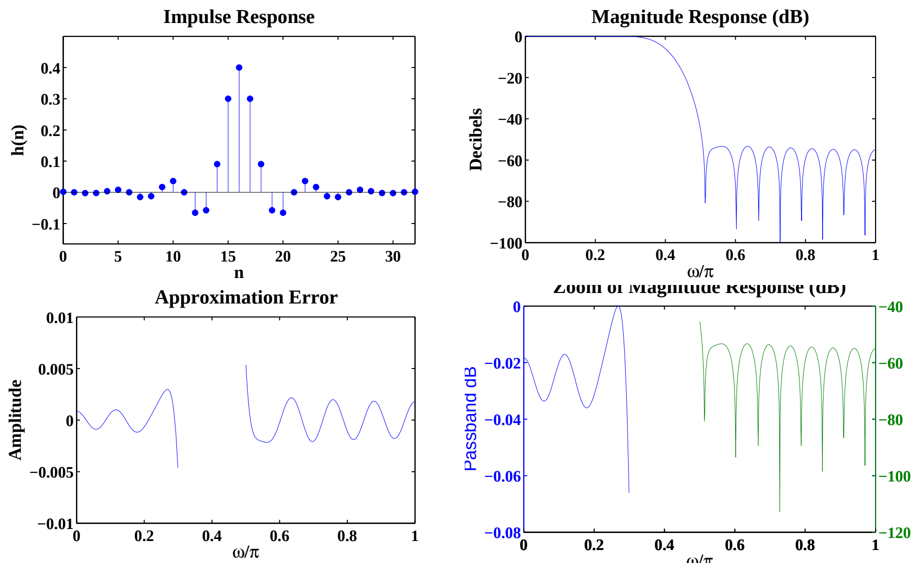


FIGURE 10.34: Plots of impulse response, magnitude response, approximation error and zoom magnitude plot using fixed window design technique.

(b) See plot below.

MATLAB script:

```
% P1028: Design lowpass filter using appropriate window
close all; clc
ws = 0.5*pi; wp = 0.3*pi;
As = 50; Ap = 0.5;
[deltap, deltas] = spec_convert(Ap,As,'rel','abs');
delta = min([deltap,deltas]);
A = -20*log10(delta);

%% Part (a)
wc = (ws+wp)/2;
dw = ws - wp;
L = 6.6*pi/dw;
M = L-1;
if mod(M,2) == 1
    M = M+1;
end
```

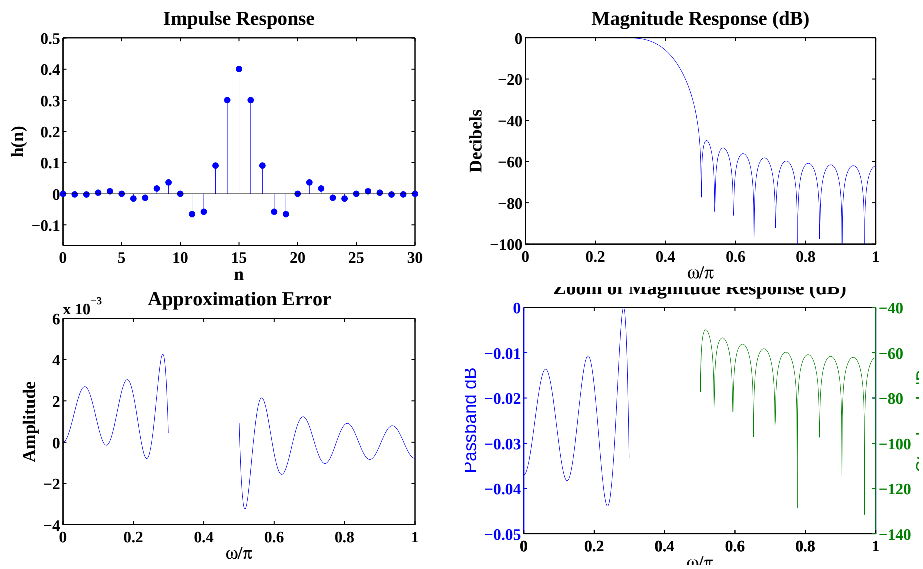


FIGURE 10.35: Plots of impulse response, magnitude response, approximation error and zoom magnitude plot using Kaiser window design technique.

```
hd = ideallp(wc,M);
h = hd.*hamming(M+1);

%% Part (b)
% [M,wn,beta,ftype] = kaiserord([0.3 0.5],[1 0],[deltas,deltap]);
% h = fir1(M,wn,ftype,kaiser(M+1,beta));

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
[Ha w2 P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
magz1 = nan(1,length(w));
magz2 = nan(1,length(w));
ind = w <= wp;
aperr(ind) = Ha(ind) - 1;
magz1(ind) = Hdb(ind);
ind = w >= ws;
aperr(ind) = Ha(ind);
```

```
magz2(ind) = Hdb(ind);
%% Plot:
hfa = figconfg('P1028a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1028b','small');
plot(w/pi,Hdb);
ylim([-100 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1028c','small');
plot(w/pi,aperr);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Approximation Error','fontsize',TFS)

hfd = figconfg('P1028d','small');
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
xlabel('\omega/\pi','fontsize',LFS)
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(1),'Ylabel'),'string','Passband dB','fontsize',LFS)
set(get(AX(2),'Ylabel'),'string','Stopband dB','fontsize',LFS)
```

29. (a) See plot below.
    (b) See plot below.

    MATLAB script:

```
% P1029: Design bandstop filter using hann window
close all; clc
wp1 = 0.2*pi; ws1 = 0.3*pi; ws2 = 0.5*pi; wp2 = 0.65*pi;
deltas = 0.01; deltap = 0.056;
delta = min([deltap,deltas]);
```

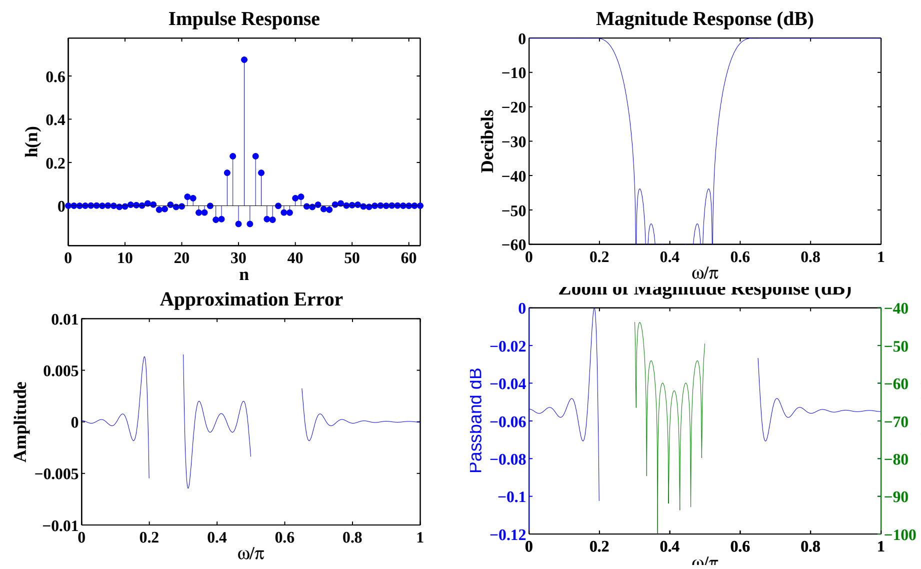


FIGURE 10.36: Plots of impulse response, magnitude response, approximation error and zoom magnitude plot using Hann window design technique.

```
A = -20*log10(delta);

%% Part (a)
wc1 = (ws1+wp1)/2; wc2 = (ws2+wp2)/2;
dw = min([ws1-wp1,wp2-ws2]);
L = 6.2*pi/dw;
M = L-1;
if mod(M,2) == 1
    M = M+1;
end
h = ideallp(wc1,M) + ideallp(pi,M) - ideallp(wc2,M);
h = h.*hann(M+1);

%% Part (b)
h = fir1(M,[wc1 wc2]/pi,'stop',hann(M+1));

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
```

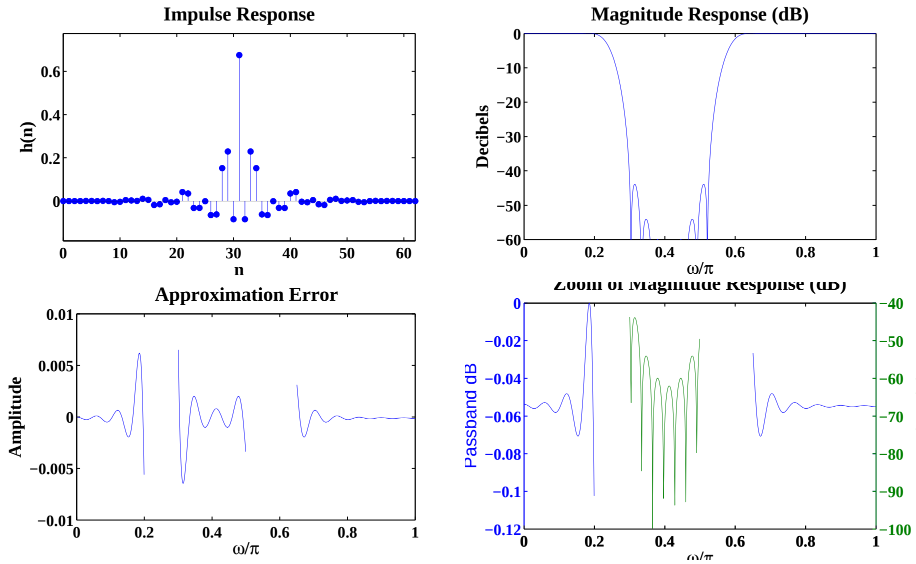


FIGURE 10.37: Plots of impulse response, magnitude response, approximation error and zoom magnitude plot using `fir1` function.

```
[Ha w2 P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
magz1 = nan(1,length(w));
magz2 = nan(1,length(w));
ind = w <= wp1;
aperr(ind) = Ha(ind) - 1;
magz1(ind) = Hdb(ind);
ind = (w >= ws1 & w <= ws2);
aperr(ind) = Ha(ind);
magz2(ind) = Hdb(ind);
ind = w >= wp2;
aperr(ind) = Ha(ind) - 1;
magz1(ind) = Hdb(ind);
%% Plot:
hfa = figconfg('P1029a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
```

```
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1029b','small');
plot(w/pi,Hdb);
ylim([-60 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1029c','small');
plot(w/pi,aperr);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Approximation Error','fontsize',TFS)

hfd = figconfg('P1029d','small');
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
xlabel('\omega/\pi','fontsize',LFS)
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(1),'Ylabel'),'string','Passband dB','fontsize',LFS)
set(get(AX(2),'Ylabel'),'string','Stopband dB','fontsize',LFS)
```

30. (a) See plot below.
    (b) See plot below.
    (c) See plot below.

    MATLAB script:

```
% P1030: Design bandpass filter using window
close all; clc
ws1 = 0.2*pi; wp1 = 0.3*pi; wp2 = 0.5*pi; ws2 = 0.65*pi;
As1 = 45; Ap = 0.75; As2 = 50;
As = max([As1,As2]);
[deltap, deltas] = spec_convert(Ap,As,'rel','abs');
delta = min([deltap,deltas]);
A = -20*log10(delta);

%% Part (a)
wc1 = (ws1+wp1)/2; wc2 = (ws2+wp2)/2;
dw = min([wp1-ws1,ws2-wp2]);
```

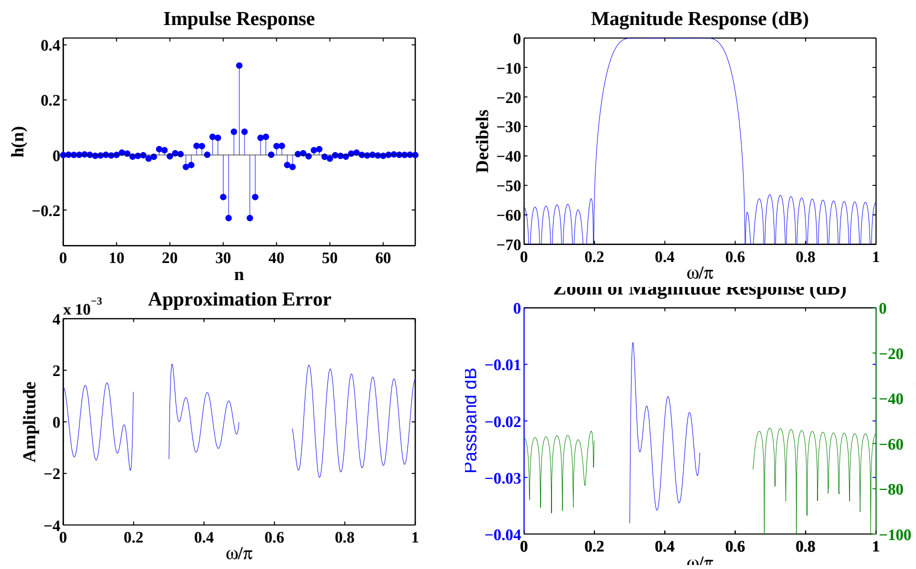


FIGURE 10.38: Plots of impulse response, magnitude response, approximation error and zoom magnitude plot using fixed window design technique.

```
L = 6.6*pi/dw;
M = L-1;
if mod(M,2) == 1
    M = M+1;
end
h = ideallp(wc2,M) - ideallp(wc1,M);
h = h.*hamming(M+1);

%% Part (b)
% [M,wn,beta,ftype] = ...
%   kaiserord([ws1 wp1 wp2 ws2]/pi,[0 1 0],[deltas,deltap, deltas]);
% h = fir1(M,wn,ftype,kaiser(M+1,beta));

%% Part (c)
% h = fir1(M,[wc1 wc2]/pi,'DC-0',hamming(M+1));

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
```

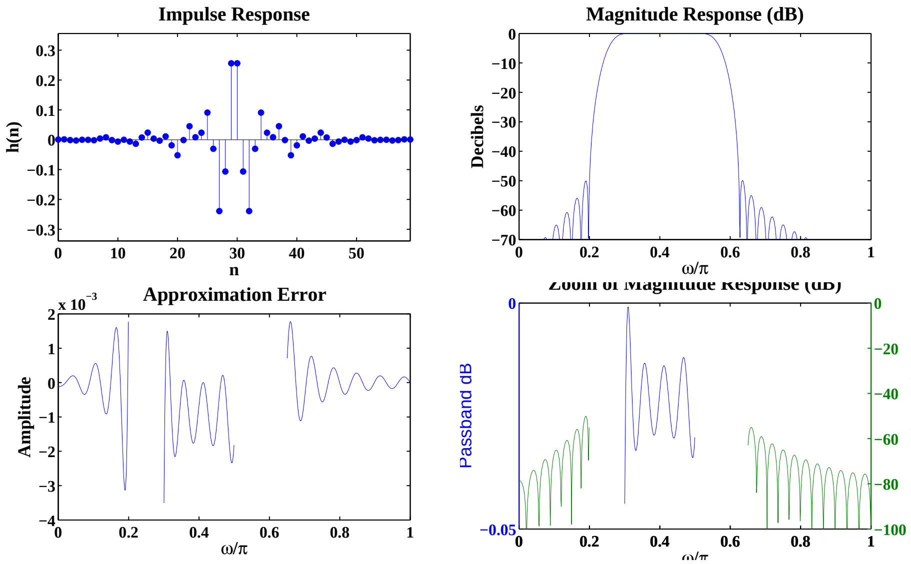


FIGURE 10.39: Plots of impulse response, magnitude response, approximation error and zoom magnitude plot using Kaiser window design technique.

```
[Ha w2 P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
magz1 = nan(1,length(w));
magz2 = nan(1,length(w));
ind = w <= ws1;
aperr(ind) = Ha(ind);
magz2(ind) = Hdb(ind);
ind = (w >= wp1 & w <= wp2);
aperr(ind) = Ha(ind) - 1;
magz1(ind) = Hdb(ind);
ind = w >= ws2;
aperr(ind) = Ha(ind);
magz2(ind) = Hdb(ind);
%% Plot:
hfa = figconfg('P1030a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
```

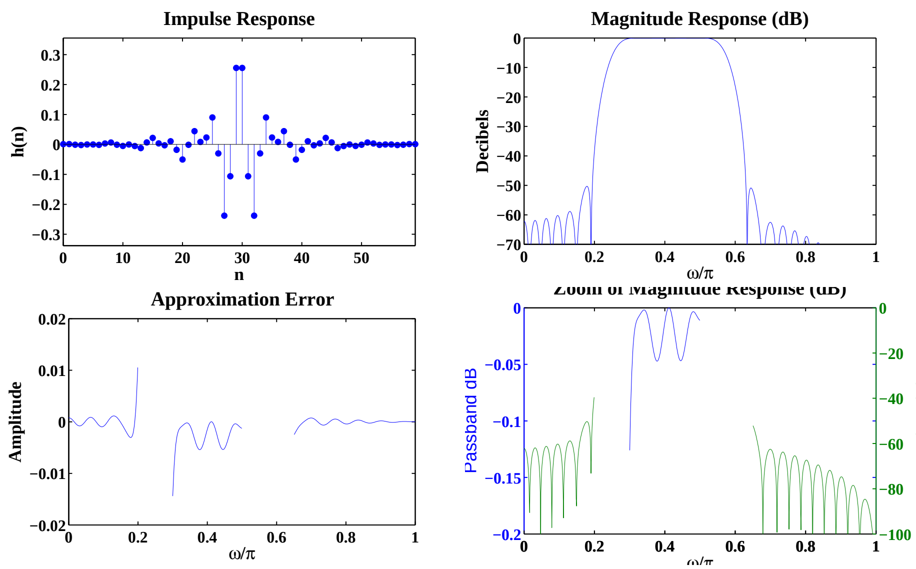


FIGURE 10.40: Plots of impulse response, magnitude response, approximation error and zoom magnitude plot using `fir1` function.

```
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1030b','small');
plot(w/pi,Hdb);
ylim([-70 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1030c','small');
plot(w/pi,aperr);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Approximation Error','fontsize',TFS)

hfd = figconfg('P1030d','small');
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
xlabel('\omega/\pi','fontsize',LFS)
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(1),'Ylabel'),'string','Passband dB','fontsize',LFS)
```

```
set(get(AX(2),'Ylabel'),'string','Stopband dB','fontsize',LFS)
set(AX(2),'Ylim',[-100 0],'YTick',-100:20:0)
```

31.

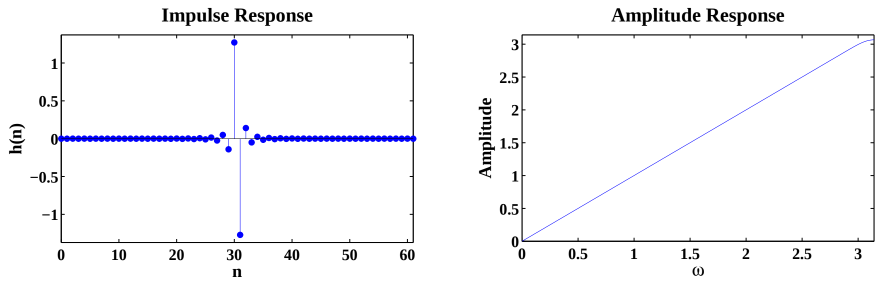


FIGURE 10.41: Plots of impulse response and amplitude response of designed type-IV differentiator using the Blackman window.

MATLAB script:

```
% P1031: Design a type-IV differentiator of order 61
%        using blackman window
close all; clc
M = 61; L = M + 1; n = 0:M;
alpha = M/2; na = (n-alpha);
hd = cos(pi*na)./na - sin(pi*na)./(pi*na.^2);
h = hd.*blackman(L)';

w = linspace(0,1,1000)*pi;
[Ha w2 P2 L2] = amplresp(h(:)',w);

%% Plot:
hfa = figconfg('P1031a','small');
stem(n,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1031b','small');
plot(w,Ha); xlim([0 pi]);ylim([0 pi])
```

```
xlabel('\omega','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Amplitude Response','fontsize',TFS)
```

32. (a) See plot below.

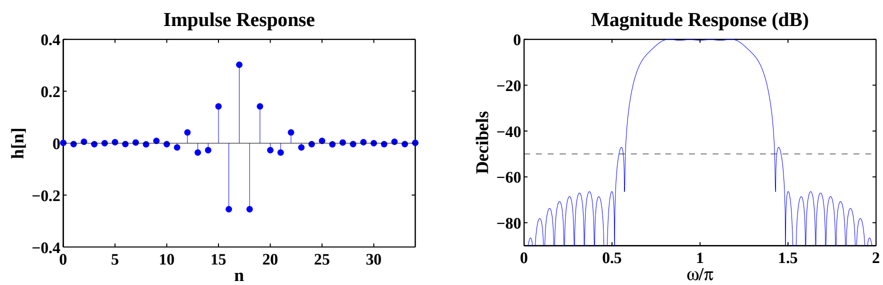


FIGURE 10.42: Plots of impulse response and log-magnitude response of designed highpass filter using linear transition.

(b) See plot below.

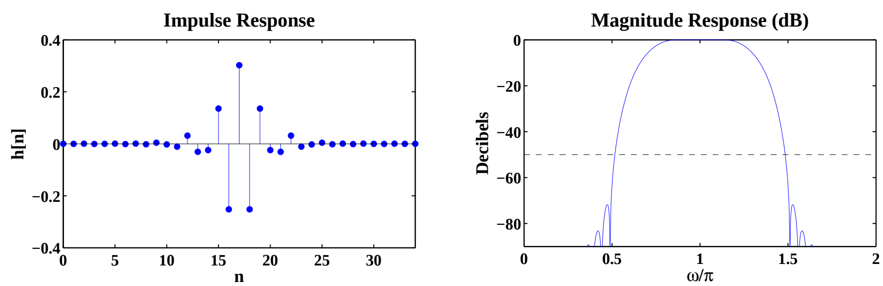


FIGURE 10.43: Plots of impulse response and log-magnitude response of designed highpass filter using the `fir2` function and the Hamming window.

MATLAB script:

```
% P1032: Design a highpass filter using frequency sampling approach
close all; clc
M = 34;
L = M + 1;
ws = 0.6*pi; wp = 0.8*pi;
As = 50; Ap = 1;
Dw = 2*pi/L;
```

```
om = (0:L-1)*Dw;
alpha = M/2; Q = floor(alpha);
psid = -alpha*Dw*[0:Q,-(L-(Q+1:M))];

%% Part a
k1 = floor(ws/Dw);
k2 = ceil(wp/Dw);
ind = (om>ws & om<wp);
A = (om(ind)-ws)/(wp-ws);
Ad = [zeros(1,k1+1),A,ones(1,L-2*k2+1),fliplr(A),zeros(1,k1)];
Hd = Ad.*exp(j*psid);
hd = real(ifft(Hd));
h = hd.*rectwin(L)';

%% Part b
ind = om < pi;
h = fir2(M,[om(ind) pi]/pi,[Ad(ind) 1]);

%% Plot
w = linspace(0,2,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag/max(Hmag));

hfa = figconfg('P1032a','small');
plot(w/pi,Hdb);hold on
plot(w/pi,-As*ones(1,length(w)),'--','color','k')
ylim([-As-40 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfb = figconfg('P1032a','small');
stem(0:M,h,'filled')
xlim([0 M])
xlabel('n','fontsize',LFS)
ylabel('h[n]','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfc = figconfg('P1032c','small');
```

```
plot(w/pi,Hmag);hold on
plot(om/pi,Ad,'.','color','r')
ylim([0 max(Hmag)+0.1])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Magnitude','fontsize',LFS)
title('Magnitude Response','fontsize',TFS)
```

33. (a) See plot below.

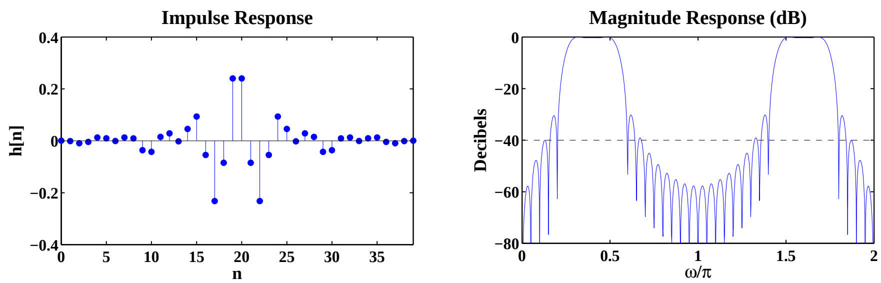


FIGURE 10.44: Plots of impulse response and log-magnitude response of designed bandpass filter using a raised-cosine transition.

(b) See plot below.

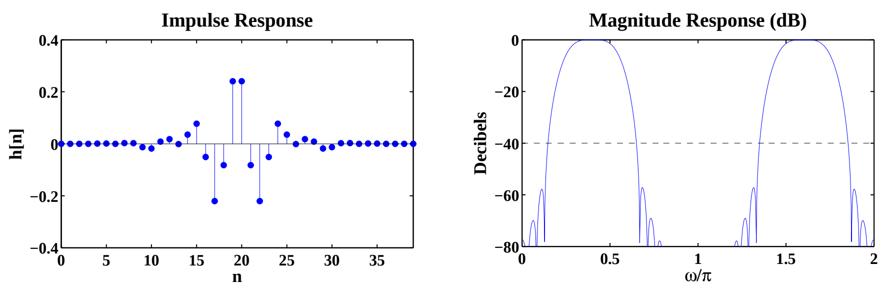


FIGURE 10.45: Plots of impulse response and log-magnitude response of designed bandpass filter using the `fir2` function and the Hann window.

MATLAB script:

```
% P1033: Design a bandpass filter using frequency sampling approach
close all; clc
L = 40;
M = L - 1;
```

```
ws1 = 0.2*pi; wp1 = 0.3*pi; wp2 = 0.5*pi; ws2 = 0.65*pi;
As1 = 40; Ap = 0.2; As2 = 40;
Dw = 2*pi/L;
om = (0:L-1)*Dw;
alpha = M/2; Q = floor(alpha);
psid = -alpha*Dw*[0:Q,-(L-(Q+1:M))];

%% Part a
k1 = floor(ws1/Dw);
k2 = ceil(wp1/Dw);
k3 = floor(wp2/Dw);
k4 = ceil((ws2-0.05*pi)/Dw);
ind = (om>ws1 & om<wp1);
A = 0.5 - 0.5*cos(pi*(om(ind)-ws1)/(wp1-ws1));
Ad = [zeros(1,k1+1),A,ones(1,k3-k2+1),fliplr(A),zeros(1,L-k4*2+1),...
    A,ones(1,k3-k2+1),fliplr(A),zeros(1,k1)];
Hd = Ad.*exp(j*psid);
hd = real(ifft(Hd));
h = hd.*rectwin(L)';

%% Part b
ind = om < pi;
% h = fir2(M,[om(ind) pi]/pi,[Ad(ind) 0],hann(L));

%% Plot
w = linspace(0,2,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag/max(Hmag));

hfa = figconfg('P1033a','small');
plot(w/pi,Hdb);hold on
plot(w/pi,-As1*ones(1,length(w)),'--','color','k')
ylim([-As1-40 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfb = figconfg('P1033a','small');
stem(0:M,h,'filled')
```

```
xlim([0 M])
xlabel('n','fontsize',LFS)
ylabel('h[n]','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfc = figconfg('P1033c','small');
plot(w/pi,Hmag);hold on
plot(om/pi,Ad,'.','color','r')
ylim([0 max(Hmag)+0.1])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Magnitude','fontsize',LFS)
title('Magnitude Response','fontsize',TFS)
```

34. (a) See plot below.

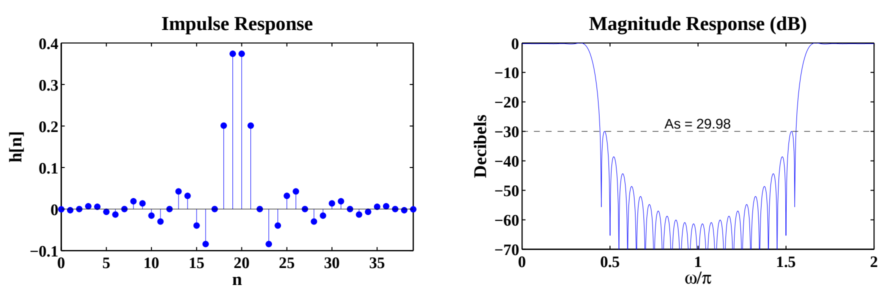


FIGURE 10.46: Plots of impulse response and log-magnitude response of designed lowpass filter when the sample at ω_c be equal to 0.5.

(b) See plot below.

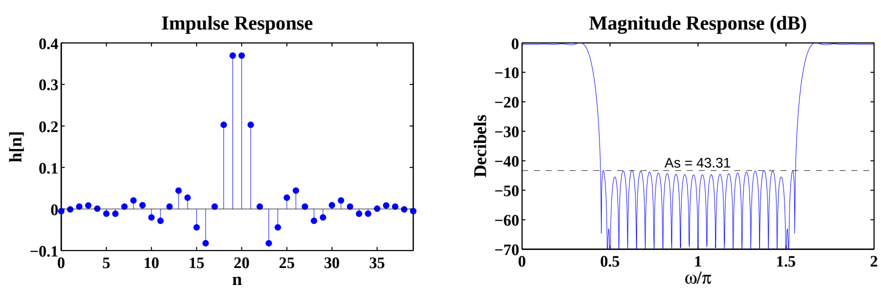


FIGURE 10.47: Plots of impulse response and log-magnitude response of designed lowpass filter when the sample at ω_c be chosen as optimal one.

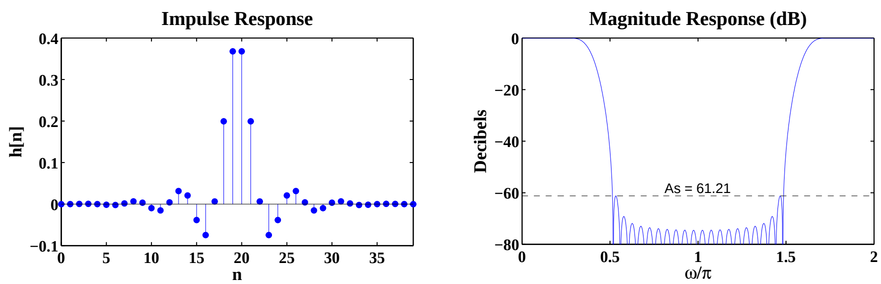


FIGURE 10.48: Plots of impulse response and log-magnitude response of designed lowpass filter using the `fir2` function.

(c) See plot above.

MATLAB script:

```
% P1034: Design a lowpass filter using frequency sampling approach
close all; clc
L = 40;
M = L - 1;
wc = 0.4*pi;
Dw = 2*pi/L;
om = (0:L-1)*Dw;
alpha = M/2; Q = floor(alpha);
psid = -alpha*Dw*[0:Q,-(L-(Q+1:M))];

%% Part a
k = wc/Dw;
% T = 0.5; % Part a
T = 0.3871; % Part b best one
Ad = [ones(1,k),T,zeros(1,L-k*2-1),T,ones(1,k-1)];
Hd = Ad.*exp(j*psid);
hd = real(ifft(Hd));
h = hd.*rectwin(L)';

%% Part c
ind = om < pi;
h = fir2(M,[om(ind) pi]/pi,[Ad(ind) 0]); % reference hamming

%% Plot
w = linspace(0,2,1000)*pi;
```

```
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag/max(Hmag));

% Find minimum stopband attenuation:
[Hdbpeak Hdbpeakind] = findpeak(Hdb);
ind = (w(Hdbpeakind) > wc & w(Hdbpeakind) < 2*pi-wc);
[As Asind] = max(Hdbpeak(ind));
Asloc = w(Asind);

hfa = figconfg('P1034a','small');
plot(w/pi,Hdb);hold on
plot(w/pi,As*ones(1,length(w)),'--','color','k')
text(w(500)/pi,As,['As = ',num2str(abs(As),'%.2f')],...
    'horizontalalignment','center','verticalalignment','bottom',...
    'fontsize',LFS-4)
ylim([-80 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfb = figconfg('P1034a','small');
stem(0:M,h,'filled')
xlim([0 M])
xlabel('n','fontsize',LFS)
ylabel('h[n]','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfc = figconfg('P1034c','small');
plot(w/pi,Hmag);hold on
plot(om/pi,Ad,'.','color','r')
ylim([0 max(Hmag)+0.1])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Magnitude','fontsize',LFS)
title('Magnitude Response','fontsize',TFS)
```

35. (a) See plot below.

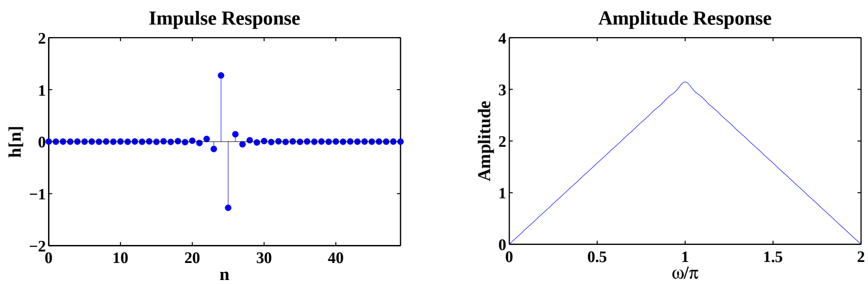


FIGURE 10.49: Plots of impulse response and amplitude response of designed differentiator.

(b) See plot below.

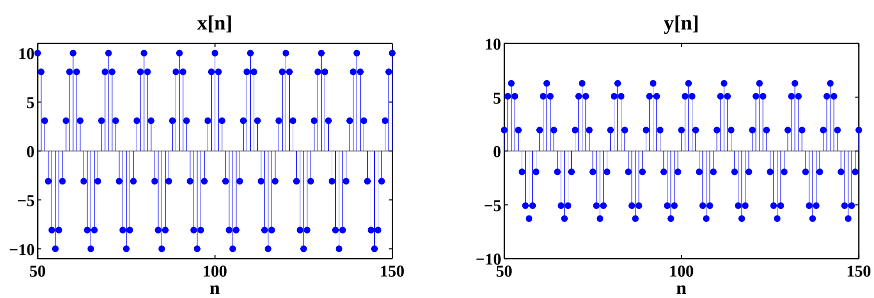


FIGURE 10.50: Subplots of $x[n]$ and $y[n]$ for $50 \leq n \leq 100$.

(c) tba

MATLAB script:

```
% P1035: Design a FIR differentiator using frequency sampling approach
close all; clc
%% Part a: filter design
L = 50; M = L - 1;
Dw = 2*pi/L;
om = (0:L-1)*Dw;
ind = om >= pi;
om(ind) = om(ind) - 2*pi;
alpha = M/2;
H = j*om.*exp(-j*om*alpha);
hd = real(ifft(H));
```

```
h = hd;

w = linspace(0,2,1000)*pi;
[Ha wt P2 L2] = amplresp(h(:)',w);

%% Part b: test
n = 0:150;
xn = 10*cos(0.2*pi*n);
yn = filter(h,1,xn);

%% Plot:
hfa = figconfg('P1035a','small');
stem(0:M,h,'filled')
xlim([0 M])
xlabel('n','fontsize',LFS)
ylabel('h[n]','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1035b','small');
plot(w/pi,Ha);hold on
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Amplitude Response','fontsize',TFS)

hfc = figconfg('P1035c','long');
subplot(121)
stem(n(51:end),xn(51:end),'filled')
ylim([-11 11])
xlabel('n','fontsize',LFS)
title('x[n]','fontsize',TFS)
subplot(122)
stem(n(51:end),yn(51:end),'filled'); hold on
ynref = diff(xn);
xlabel('n','fontsize',LFS)
title('y[n]','fontsize',TFS)
```

36.

MATLAB script:

```
% P1036: Design bandpass FIR filter using Parks-McClellan
```

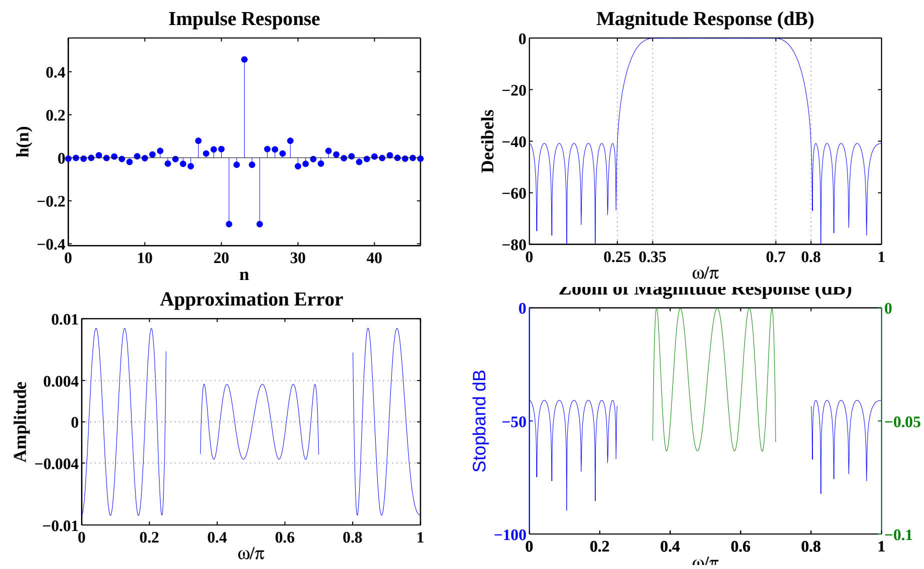


FIGURE 10.51: Plots of impulse response, magnitude response, approximation error and zoom magnitude response of the designed bandpass digital filter.

```
close all; clc
%% Specification:
ws1 = 0.25*pi; wp1 = 0.35*pi; wp2 = 0.7*pi; ws2 = 0.8*pi;
deltas1 = 0.01; deltap = 0.004; deltas2 = 0.01;
%% Estimated Filter order using FIRPMORD function:
[M,fo,ao,W] = ...
firpmord([ws1,wp1,wp2,ws2]/pi,[0,1,0],[deltas1,deltap,deltas2]);
M = M + 2
%% Filter Design using FIRPM function:
[h,delta] = firpm(M,fo,ao,W);
delta,
deltas1,

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
[Ha w2 P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
magz1 = nan(1,length(w));
```

```
magz2 = nan(1,length(w));
ind = w <= ws1;
aperr(ind) = Ha(ind);
magz1(ind) = Hdb(ind);
ind = w >= wp1 & w <= wp2;
aperr(ind) = Ha(ind)-1;
magz2(ind) = Hdb(ind);
ind = w >= ws2;
aperr(ind) = Ha(ind);
magz1(ind) = Hdb(ind);
%% Plot:
hfa = figconfg('P1036a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1036b','small');
plot(w/pi,Hdb);hold on
ylim([-80 0])
set(gca,'XTick',[0 ws1 wp1 wp2 ws2 pi]/pi,'Xgrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1036c','small');
plot(w/pi,aperr);
set(gca,'Ytick',[-deltas1 -deltap 0 deltap deltas1],'Ygrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Approximation Error','fontsize',TFS)

hfd = figconfg('P1036d','small');
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
xlabel('\omega/\pi','fontsize',LFS)
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(2),'Ylabel'),'string','Passband dB','fontsize',LFS)
set(get(AX(1),'Ylabel'),'string','Stopband dB','fontsize',LFS)
```

```
set(AX(1),'Ytick',[-100 -50 0],'ylim',[-100 0])
```

37.

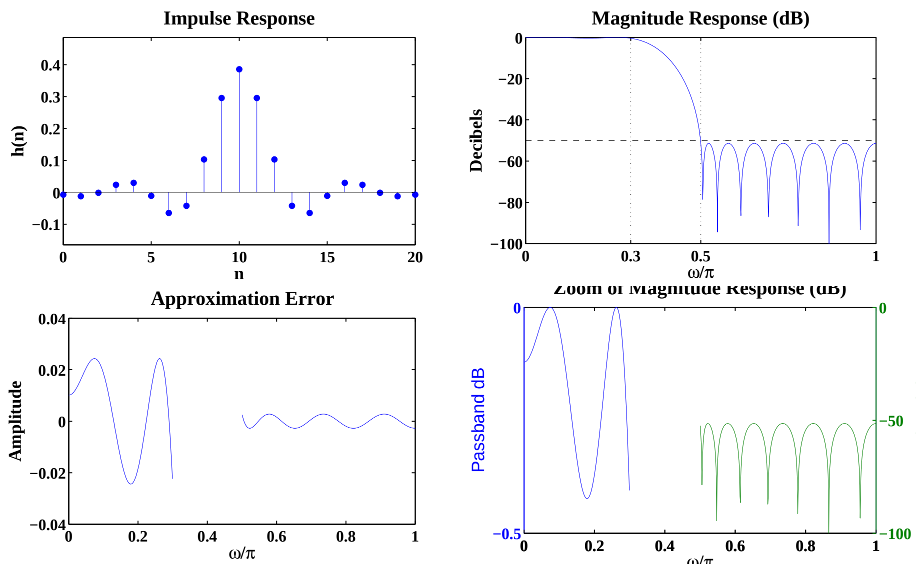


FIGURE 10.52: Plots of impulse response, magnitude response, approximation error and zoom magnitude response of the designed lowpass FIR filter.

MATLAB script:

```
% P1037: Design lowpass FIR filter using Parks-McClellan
close all; clc
%% Specification:
wp = 0.3*pi; ws = 0.5*pi; As = 50; Ap = 0.5;
%% Passband and Stopband Ripple Calculation:
[deltap, deltas] = spec_convert(Ap,As,'rel','abs');
%% Estimated Filter order using FIRPMORD function:
[M,fo,ao,W] = firpmord([wp,ws]/pi,[1,0],[deltap,deltas]);
M = M + 2
%% Filter Design using FIRPM function:
[h,delta] = firpm(M,fo,ao,W);
delta,
deltap,

w = linspace(0,1,1000)*pi;
```

```
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
[Ha w2 P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
magz1 = nan(1,length(w));
magz2 = nan(1,length(w));
ind = w <= wp;
aperr(ind) = Ha(ind)-1;
magz1(ind) = Hdb(ind);
ind = w >= ws;
aperr(ind) = Ha(ind);
magz2(ind) = Hdb(ind);
%% Plot:
hfa = figconfg('P1037a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1037b','small');
plot(w/pi,Hdb);hold on
plot(w/pi,-As*ones(1,length(w)),'--','color','k')
ylim([-100 0])
set(gca,'XTick',[0 wp ws pi]/pi,'Xgrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1037c','small');
plot(w/pi,aperr);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Approximation Error','fontsize',TFS)

hfd = figconfg('P1037d','small');
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
xlabel('\omega/\pi','fontsize',LFS)
```

```
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(1),'Ylabel'),'string','Passband dB','fontsize',LFS)
set(get(AX(2),'Ylabel'),'string','Stopband dB','fontsize',LFS)
set(AX(2),'Ytick',[-100 -50 0],'ylim',[-100 0])
```

38.

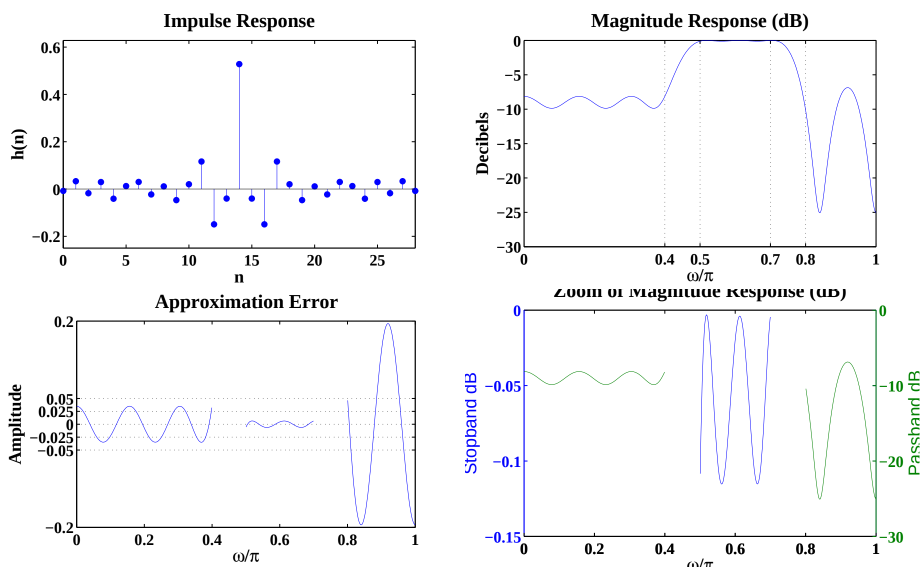


FIGURE 10.53: Plots of impulse response, magnitude response, approximation error and zoom magnitude response of the designed multiband filter.

MATLAB script:

```
% P1038: Design multiband FIR filter using Parks-McClellan
close all; clc
%% Specification:
w1 = 0.4*pi; w2 = 0.5*pi; w3 = 0.7*pi; w4 = 0.8*pi;
A1 = 0.35; A2 = 0.975; A3 = 0.25;
delta1 = 0.05; delta2 = 0.025; delta3 = 0.2;
%% Estimated Filter order using FIRPMORD function:
[M,fo,ao,W] = ...
firpmord([w1,w2,w3,w4]/pi,[A1,A2,A3],[delta1,delta2,delta3]);
M = M + 8
%% Filter Design using FIRPM function:
[h,delta] = firpm(M,fo,ao,W);
```

```
delta,
delta1,

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
[Ha ww P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
magz1 = nan(1,length(w));
magz2 = nan(1,length(w));
ind = w <= w1;
aperr(ind) = Ha(ind)-A1;
magz2(ind) = Hdb(ind);
ind = w >= w2 & w <= w3;
aperr(ind) = Ha(ind)-A2;
magz1(ind) = Hdb(ind);
ind = w >= w4;
aperr(ind) = Ha(ind)-A3;
magz2(ind) = Hdb(ind);
%% Plot:
hfa = figconfg('P1038a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1038b','small');
plot(w/pi,Hdb);hold on
set(gca,'XTick',[0 w1 w2 w3 w4 pi]/pi,'Xgrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1038c','small');
plot(w/pi,aperr);
delYtick = sort([delta1 delta2 delta3]);
set(gca,'Ytick',[-delYtick(end:-1:1) 0 delYtick],'Ygrid','on')
```

```
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Approximation Error','fontsize',TFS)

hfd = figconfg('P1038d','small');
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
xlabel('\omega/\pi','fontsize',LFS)
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(2),'Ylabel'),'string','Passband dB','fontsize',LFS)
set(get(AX(1),'Ylabel'),'string','Stopband dB','fontsize',LFS)
```

39. (a) See plot below.

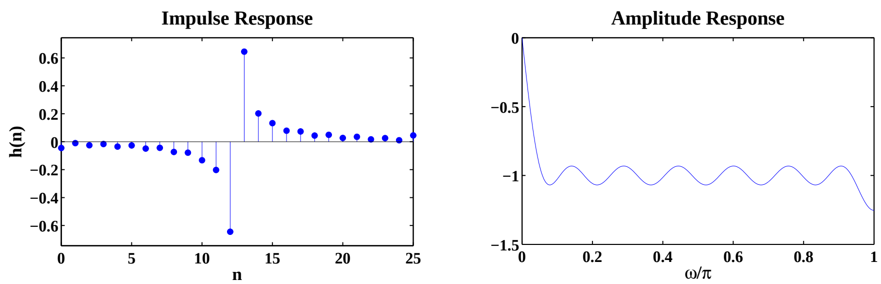


FIGURE 10.54: Plots of impulse response and magnitude response of the designed FIR Hilbert transformer.

(b) See plot below.

(c) tba.

MATLAB script:

```
% P1039: Design Hilbert transformer using Parks-McClellan
close all; clc
M = 25;
w1 = 0.05*pi; w2 = 0.95*pi;
[h,delta] = firpm(M,[w1 w2]/pi,[1 1],'hilbert');

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
[Ha wa P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
ind = (w >= w1 & w <= w2);
```

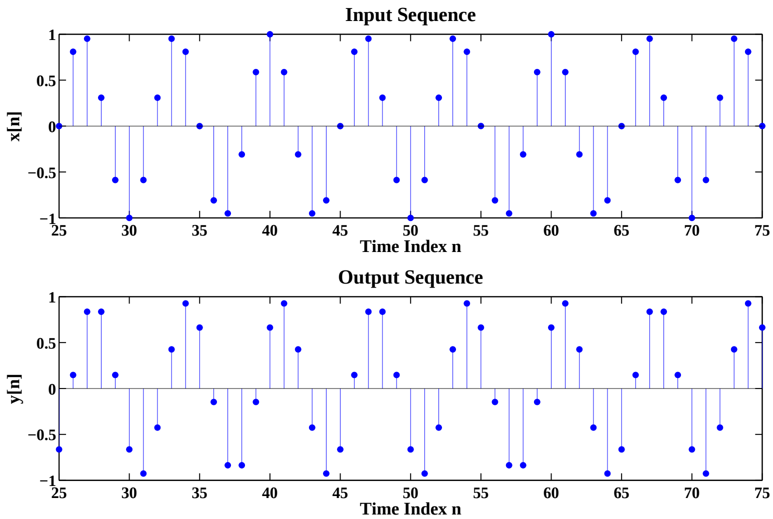


FIGURE 10.55: Stem subplots of both $x[n]$ and $y[n]$ for $25 \leq n \leq 75$.

```
aperr(ind) = Ha(ind)+1;

n = 0:100;
xn = cos(0.3*pi*n);
yn = filter(h,1,xn);
indn = n >= 25 & n <= 75;

%% Plot:
hfa = figconfg('P1039a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1039b','small');
plot(w/pi,Ha);hold on
xlabel('\omega/\pi','fontsize',LFS)
title('Amplitude Response','fontsize',TFS)
```

```
hfc = figconfg('P1039c');
subplot(211)
stem(n(indn),xn(indn),'filled')
xlabel('Time Index n','fontsize',LFS)
ylabel('x[n]','fontsize',LFS)
title('Input Sequence','fontsize',TFS)
subplot(212)
stem(n(indn),yn(indn),'filled')
xlabel('Time Index n','fontsize',LFS)
ylabel('y[n]','fontsize',LFS)
title('Output Sequence','fontsize',TFS)
```

40. MATLAB script:

```
% P1040: Investigate function 'Izero' and 'kaiser0'
close all; clc
K = 49;
x = rand*60+20;
y = Izero(x,K);
yref = Izero(x,50);
y1 = y*1e8;
y1 = y1 - mod(y1,1);
y1 = y1/1e8;
y2 = yref*1e8;
y2 = y2 - mod(y2,1);
y2 = y2/1e8;

isequal(y1,y2)
```

41.

MATLAB script:

```
% P1041: Comparison between Kaiser window and fixed windows
%        in terms of As and transition bandwidth
close all; clc
wc = pi/2; M = 32; L = M + 1; % lowpass filter
hd = ideallp(wc,M);
%% Part a
% h = h.*rectwin(M+1); delw = 1.8;
% h = h.*bartlett(M+1); delw = 6.1;
```

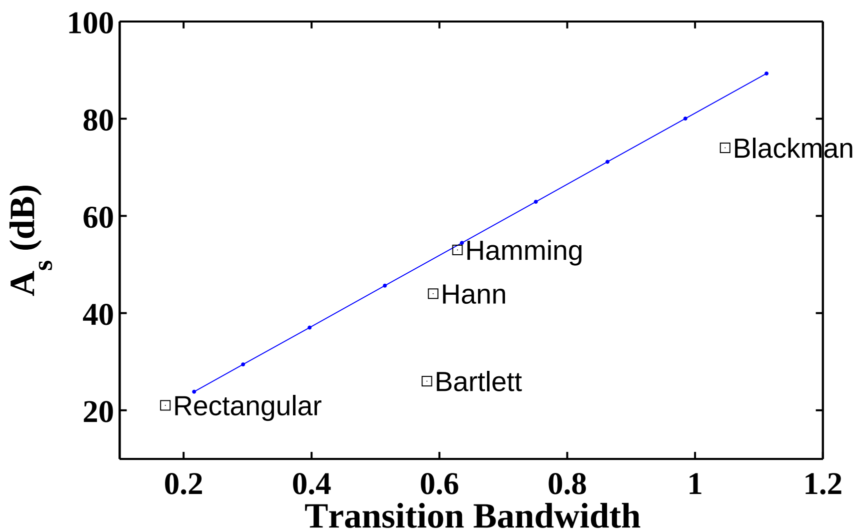


FIGURE 10.56: Plot of A_s versus transition-widths obtained in part (b) and the corresponding pairs for the fixed windows obtained in part (a).

```
% h = h.*hann(M+1); delw = 6.2;
% h = h.*hamming(M+1); delw = 6.6;
h = hd.*blackman(M+1); delw = 11;

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
[peakH peakHind] = findpeak(Hdb);
Lshind = w(peakHind) > wc;
As = max(peakH(Lshind))
bandwid = delw*pi/L

%% Part (b)
beta = 1:9; Nbeta = length(beta);
As_kaiser = zeros(1,Nbeta);
bandwid_kaiser = zeros(1,Nbeta);
for ii = 1:Nbeta
    hk = hd.*kaiser(L,beta(ii));
    Hk = freqz(hk,1,w);
```

```
    Hkmag = abs(Hk);
    Hkdb = 20*log10(Hkmag./max(Hkmag));
    [peakHk peakHkind] = findpeak(Hkdb);
    Lshind = w(peakHkind) > wc;
    As_kaiser(ii) = abs(max(peakHk(Lshind)));
    bandwid_kaiser(ii) = (As_kaiser(ii)-8)/M/2.285;

end
% Plot:
hfc = figconfg('P1041c','small');
plot(bandwid_kaiser,As_kaiser,'.-b'); hold on
xlabel('Transition Bandwidth','fontsize',LFS)
ylabel('A_s (dB)','fontsize',LFS)
% title('Magnitude Response (dB)','fontsize',TFS);
fw.name = {'Rectangular','Bartlett','Hann','Hamming','Blackman'};
fw.As = [21 26 44 53 74];
fw.bw = [1.8 6.1 6.2 6.6 11]*pi/L;
for jj = 1:5
plot(fw.bw(jj),fw.As(jj),'s-k')
text(fw.bw(jj),fw.As(jj),[' ',fw.name{jj}],'fontsize',LFS-4)
end
ylim([10 100]); xlim([0.1 1.2])
```

Assessment Problems

42. (a) Proof:

$$H\big(\mathrm{e}^{\mathrm{j}\omega}\big) = \left(\sum_{k=1}^{(M+1)/2} d[k]\sin[\omega(k-\frac{1}{2})]\right)\cdot \mathrm{j}\mathrm{e}^{-\mathrm{j}\omega M/2} \triangleq \mathrm{j}A\big(\mathrm{e}^{\mathrm{j}\omega}\big)\,\mathrm{e}^{-\mathrm{j}\omega M/2} \tag{10.38}$$

$$d[k] = 2h[(M+1)/2-k], \quad k = 1,2,\ldots,(M+1)/2 \tag{10.39}$$

$$\begin{aligned}
H\big(\mathrm{e}^{\mathrm{j}\omega}\big) &= \sum_{k=0}^{M} h[k]\cdot \mathrm{e}^{-\mathrm{j}k\omega} = \sum_{k=0}^{\frac{M-1}{2}} h[k]\mathrm{e}^{-\mathrm{j}k\omega} + \sum_{k=\frac{M+1}{2}}^{M} h[k]\mathrm{e}^{-\mathrm{j}k\omega} \\
&= \sum_{k=0}^{\frac{M-1}{2}} h[k]\mathrm{e}^{-\mathrm{j}k\omega} + \sum_{k=0}^{\frac{M-1}{2}} h[k+\frac{M+1}{2}]\mathrm{e}^{-\mathrm{j}(k+\frac{M+1}{2})\omega} \\
&= \left(\sum_{k=0}^{\frac{M-1}{2}} h[k]\mathrm{e}^{-\mathrm{j}(k-M/2)\omega} + \sum_{k=0}^{\frac{M-1}{2}} h[k+\frac{M+1}{2}]\mathrm{e}^{-\mathrm{j}(k+\frac{1}{2})\omega}\right)\cdot \mathrm{e}^{-\mathrm{j}\omega M/2} \\
&= \left(\sum_{k=0}^{\frac{M-1}{2}} h[\frac{M-1}{2}-k]\mathrm{e}^{-\mathrm{j}(\frac{M-1}{2}-k-M/2)\omega} - \sum_{k=0}^{\frac{M-1}{2}} h[M-k-\frac{M+1}{2}]\mathrm{e}^{-\mathrm{j}(k+\frac{1}{2})\omega}\right)\cdot \mathrm{e}^{-\mathrm{j}\omega M/2} \\
&= \sum_{k=0}^{\frac{M-1}{2}} \left(h[\frac{M-1}{2}-k]\mathrm{e}^{\mathrm{j}(k+1/2)\omega} - h[\frac{M-1}{2}-k]\mathrm{e}^{-\mathrm{j}(k+1/2)\omega}\right)\cdot \mathrm{e}^{-\mathrm{j}\omega M/2} \\
&= \left(\sum_{k=0}^{\frac{M-1}{2}} 2h[\frac{M-1}{2}-k]\,\mathrm{j}\sin(k+\frac{1}{2})\omega\right)\cdot \mathrm{e}^{-\mathrm{j}\omega M/2} \\
&= \left(\sum_{k=1}^{\frac{M+1}{2}} d[k]\sin(k-\frac{1}{2})\omega\right)\cdot \mathrm{e}^{\mathrm{j}(\pi/2-\omega M/2)}
\end{aligned}$$

(b) Proof:

$$A\big(\mathrm{e}^{\mathrm{j}\omega}\big) = \sin(\frac{\omega}{2})\sum_{k=0}^{(M-1)/2} \tilde{d}[k]\cos k\omega \tag{10.40}$$

$$d[k] = \begin{cases} \frac{1}{2}(2\tilde{d}[0]-\tilde{d}[1]), & k=1 \\ \frac{1}{2}(\tilde{d}[k-1]-\tilde{d}[k]), & 2\le k\le (M-1)/2 \\ \frac{1}{2}\tilde{d}[(M-1)/2], & k=(M+1)/2 \end{cases} \tag{10.41}$$

$$
\begin{aligned}
A(e^{j\omega}) &= \sin(\frac{\omega}{2}) \sum_{k=0}^{(M-1)/2} \tilde{d}[k] \cos k\omega \\
&= \frac{1}{2} \sum_{k=0}^{(M-1)/2} \tilde{d}[k][\sin(k+1/2)\omega - \sin(k-1/2)\omega] \\
&= (\tilde{d}[0] - \frac{1}{2}\tilde{d}[1]) \sin\frac{\omega}{2} + \sum_{k=2}^{(M-1)/2} (\tilde{d}[k-1] - \tilde{d}[k]) \sin(k-\frac{1}{2})\omega \\
&\quad + \frac{1}{2}\tilde{d}[(M-1)/2] \sin(\frac{M}{2}\omega)
\end{aligned}
$$

43. (a) Solution:

$$
\begin{aligned}
w[n] &= \left[0.42 - 0.5 \times 0.5(e^{j\frac{2\pi n}{M}} - e^{-j\frac{2\pi n}{M}}) + 0.08 \times 0.5(e^{j\frac{4\pi n}{M}} - e^{-j\frac{4\pi n}{M}})\right] w_R[n] \\
&= 0.42 w_R[n] - 0.25 w_R[n] e^{j\frac{2\pi n}{M}} + 0.25 w_R[n] e^{-j\frac{2\pi n}{M}} + 0.04 w_R[n] e^{j\frac{4\pi n}{M}} \\
&\quad - 0.04 w_R[n] e^{-j\frac{4\pi n}{M}}
\end{aligned}
$$

Hence, the DTFT of $w[n]$ is:

$$
\begin{aligned}
W(e^{j\omega}) &= 0.42 W_R(e^{j\omega}) - 0.25 W_R(e^{j(\omega - \frac{2\pi}{M})}) + 0.25 W_R(e^{j(\omega + \frac{2\pi}{M})}) \\
&\quad + 0.04 W_R(e^{j(\omega - \frac{4\pi}{M})}) - 0.04 W_R(e^{j(\omega - \frac{4\pi}{M})})
\end{aligned}
$$

(b) tba.

44. tba

45. (a) See plot below.
(b) See plot below.
(c) See plot below.
MATLAB script:

```
% P1045: Stude fixed window magnitude response
%        its peak of first side-lobe and transition bandwidth
%        Hann Window
close all; clc
% L = 21; % Part a
L = 41; % Part b
hw = hann(L)';
Nw = 10000;
```

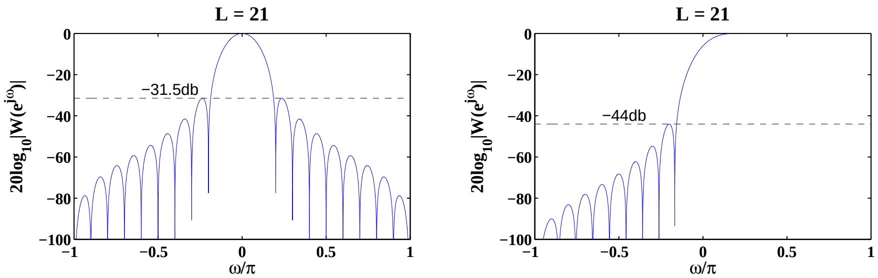


FIGURE 10.57: Log-magnitude response in dB and accumulated amplitude response in dB when window length is $L = 21$.

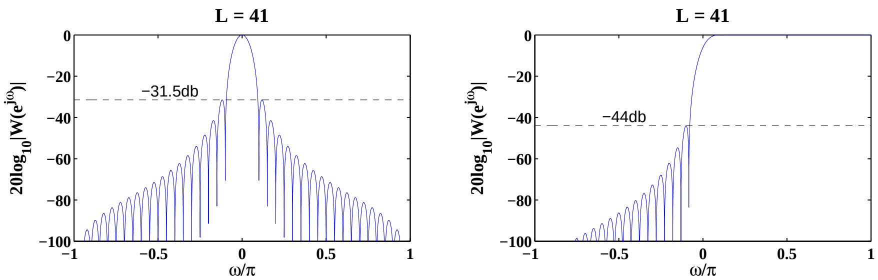


FIGURE 10.58: Log-magnitude response in dB and accumulated amplitude response in dB when window length is $L = 41$.

```
w = linspace(-1,1,Nw)*pi;
H = freqz(hw,1,w);
Hmag = abs(H);
Hmagdb = 20*log10(Hmag/max(Hmag));
[Ha w2 P2 L2] = amplresp(hw,w);
Hac = abs(cumsum(Ha));
Hacdb = 20*log10(Hac/max(Hac));

%% Find Peak Values:
[peakH peakHind] = findpeak(Hmagdb);
[peakHac peakHacind] = findpeak(Hacdb);
Lshind = w(peakHind) < -1e-3;
sidlobeH = max(peakH(Lshind));
Lshind = w(peakHacind) < 0;
[sidlobeHac slind] = max(peakHac(Lshind));
bandwid = w(peakHacind(slind+1)) - w(peakHacind(slind));
```

```
bandwid/pi*L

%% Plot:
hfa = figconfg('P1045a','small');
plot(w/pi,Hmagdb);hold on
plot(w/pi,sidlobeH*ones(1,Nw),'--k')
text(w(Nw/5)/pi,sidlobeH,[num2str(sidlobeH,3),'db'],...
    'fontsize',LFS-2,'verticalalignment','bottom')
ylim([-100 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('20log_{10}|W(e^{j\omega})|','fontsize',LFS)
title(['L = ',num2str(L)],'fontsize',TFS)

hfb = figconfg('P1045b','small');
plot(w/pi,Hacdb); hold on
plot(w/pi,sidlobeHac*ones(1,Nw),'--k')
text(w(Nw/5)/pi,sidlobeHac,[num2str(sidlobeHac,3),'db'],...
    'fontsize',LFS-2,'verticalalignment','bottom')
ylim([-100 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('20log_{10}|W(e^{j\omega})|','fontsize',LFS)
title(['L = ',num2str(L)],'fontsize',TFS)
```

46. (a) See plot below.

    (b) See plot below.

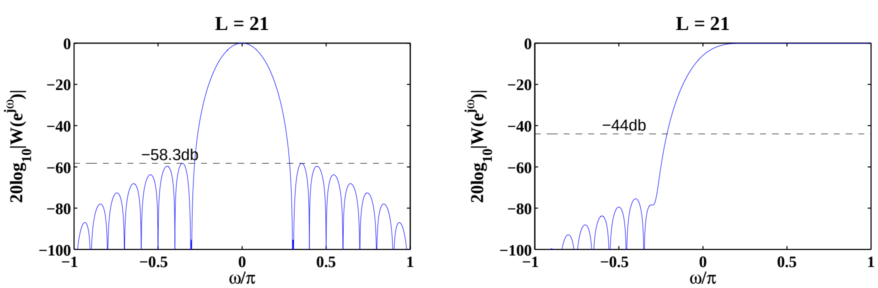


FIGURE 10.59: Log-magnitude response in dB and accumulated amplitude response in dB when window length is $L = 21$.

    (c) See plot below.

MATLAB script:

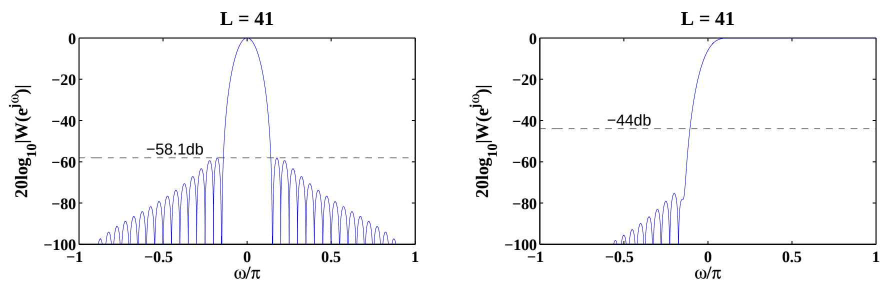


FIGURE 10.60: Log-magnitude response in dB and accumulated amplitude response in dB when window length is $L = 41$.

```
% P1046: Stude fixed window magnitude response
%        its peak of first side-lobe and transition bandwidth
%        Blackman Window
close all; clc
L = 21; % Part a
% L = 41; % Part b
hw = blackman(L)';
Nw = 10000;
w = linspace(-1,1,Nw)*pi;
H = freqz(hw,1,w);
Hmag = abs(H);
Hmagdb = 20*log10(Hmag/max(Hmag));
[Ha w2 P2 L2] = amplresp(hw,w);
Hac = abs(cumsum(Ha));
Hacdb = 20*log10(Hac/max(Hac));

%% Find Peak Values:
[peakH peakHind] = findpeak(Hmagdb);
[peakHac peakHacind] = findpeak(Hacdb);
Lshind = w(peakHind) < -1e-8;
sidlobeH = max(peakH(Lshind));
[temp Lshind] = find(w(peakHacind) < 0);
bandwid = w(peakHacind(Lshind(end)+1)) - w(peakHacind(Lshind(end)));
bandwid/pi*L

%% Plot:
hfa = figconfg('P1046a','small');
plot(w/pi,Hmagdb);hold on
```

```
plot(w/pi,sidlobeH*ones(1,Nw),'--k')
text(w(Nw/5)/pi,sidlobeH,[num2str(sidlobeH,3),'db'],...
    'fontsize',LFS-2,'verticalalignment','bottom')
ylim([-100 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('20log_{10}|W(e^{j\omega})|','fontsize',LFS)
title(['L = ',num2str(L)],'fontsize',TFS)

hfb = figconfg('P1046b','small');
plot(w/pi,Hacdb); hold on
plot(w/pi,sidlobeHac*ones(1,Nw),'--k')
text(w(Nw/5)/pi,sidlobeHac,[num2str(sidlobeHac,3),'db'],...
    'fontsize',LFS-2,'verticalalignment','bottom')
ylim([-100 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('20log_{10}|W(e^{j\omega})|','fontsize',LFS)
title(['L = ',num2str(L)],'fontsize',TFS)
```

47. (a) See plot below.

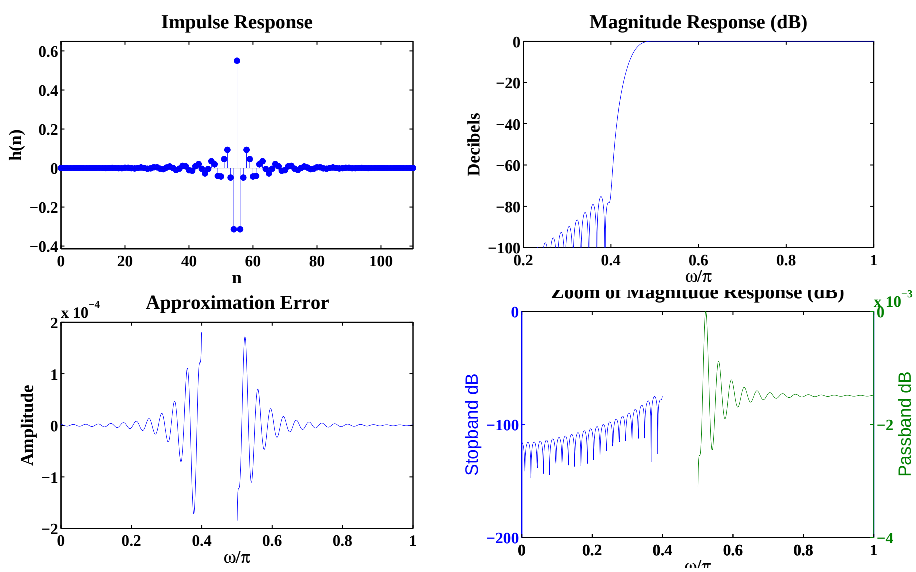


FIGURE 10.61: Plots of impulse response, magnitude response, approximation error and zoom magnitude response of the designed highpass FIR filter using fixed window technique.

(b) See plot below.

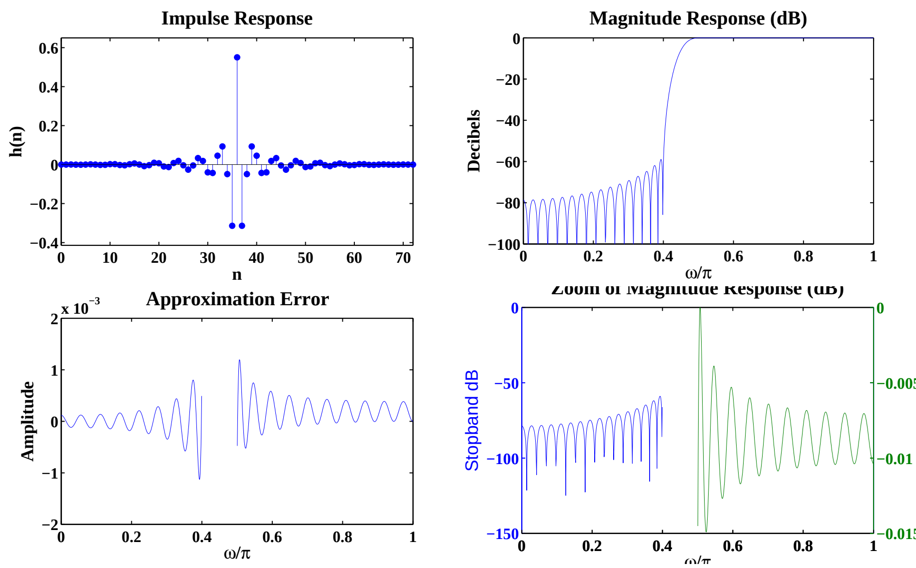


FIGURE 10.62: Plots of impulse response, magnitude response, approximation error and zoom magnitude response of the designed highpass FIR filter using Kaiser window technique.

MATLAB script:

```
% P1047: Design highpass filter using appropriate window
close all; clc
ws = 0.4*pi; wp = 0.5*pi;
As = 60; Ap = 1;
[deltap, deltas] = spec_convert(Ap,As,'rel','abs');
delta = min([deltap,deltas]);
A = -20*log10(delta);

%% Part (a)
wc = (ws+wp)/2;
delw = wp-ws;
L = ceil(11*pi/delw); M = L - 1;
if mod(M,2) == 1
    M = M + 1;
end
hd = ideallp(pi,M) - ideallp(wc,M);
```

```
h = hd.*blackman(M+1);

%% Part (b)
[M,wn,beta,ftype] = kaiserord([0.4 0.5],[0 1],[deltas,deltap]);
h = fir1(M,wn,ftype,kaiser(M+1,beta));

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
[Ha w2 P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
magz1 = nan(1,length(w));
magz2 = nan(1,length(w));
ind = w <= ws;
aperr(ind) = Ha(ind);
magz1(ind) = Hdb(ind);
ind = w >= wp;
aperr(ind) = Ha(ind) - 1;
magz2(ind) = Hdb(ind);
%% Plot:
hfa = figconfg('P1047a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1047b','small');
plot(w/pi,Hdb);
ylim([-100 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1047c','small');
plot(w/pi,aperr);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
```

```
title('Approximation Error','fontsize',TFS)

hfd = figconfg('P1047d','small');
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
xlabel('\omega/\pi','fontsize',LFS)
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(1),'Ylabel'),'string','Stopband dB','fontsize',LFS)
set(get(AX(2),'Ylabel'),'string','Passband dB','fontsize',LFS)
```

48. (a) See plot below.

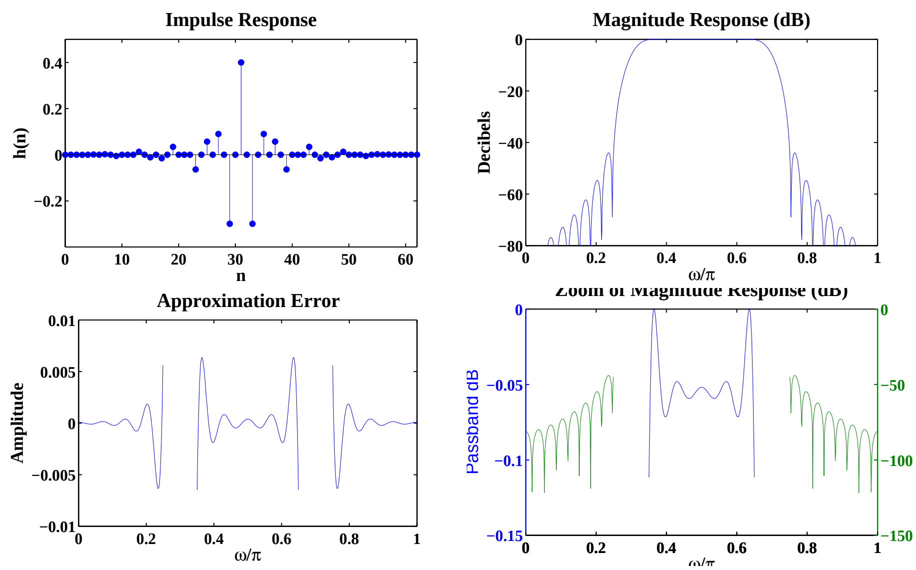


FIGURE 10.63: Plots of impulse response, magnitude response, approximation error and zoom magnitude response of the designed bandpass filter using fixed window technique.

(b) See plot below.

(c) See plot below.

MATLAB script:

```
% P1048: Design bandpass filter using window
close all; clc
ws1 = 0.25*pi; wp1 = 0.35*pi; wp2 = 0.65*pi; ws2 = 0.75*pi;
deltas = 0.05; deltap = 0.01;
```

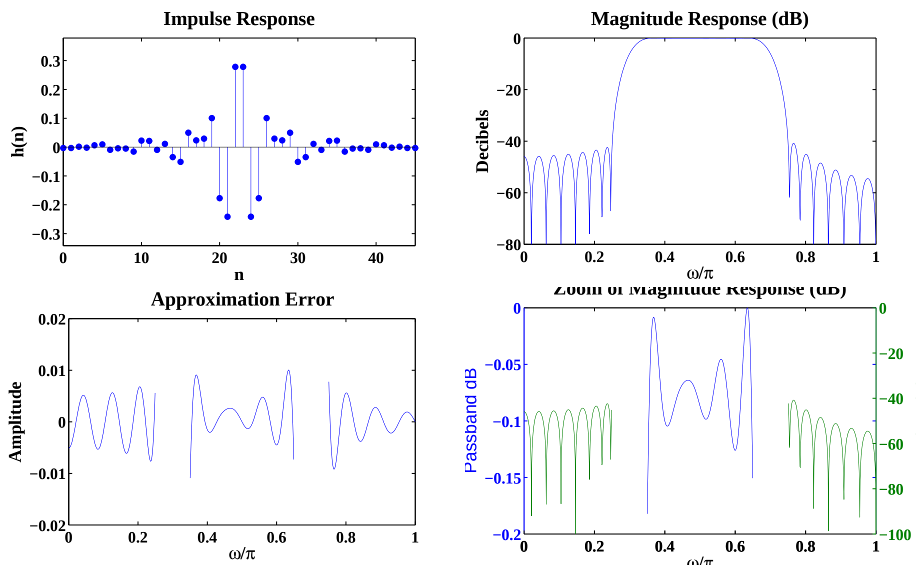


FIGURE 10.64: Plots of impulse response, magnitude response, approximation error and zoom magnitude response of the designed bandpass filter using Kaiser window technique.

```
delta = min([deltap,deltas]);
A = -20*log10(delta);

%% Part (a)
wc1 = (ws1+wp1)/2; wc2 = (ws2+wp2)/2;
dw = min([wp1-ws1,ws2-wp2]);
L = 6.2*pi/dw;
M = L-1;
if mod(M,2) == 1
    M = M+1;
end
hd = ideallp(wc2,M) - ideallp(wc1,M);
h = hd.*hann(M+1);

%% Part (b)
% [M,wn,beta,ftype] = ...
%   kaiserord([ws1 wp1 wp2 ws2]/pi,[0 1 0],[deltas,deltap, deltas]);
% h = fir1(M,wn,ftype,kaiser(M+1,beta));
```

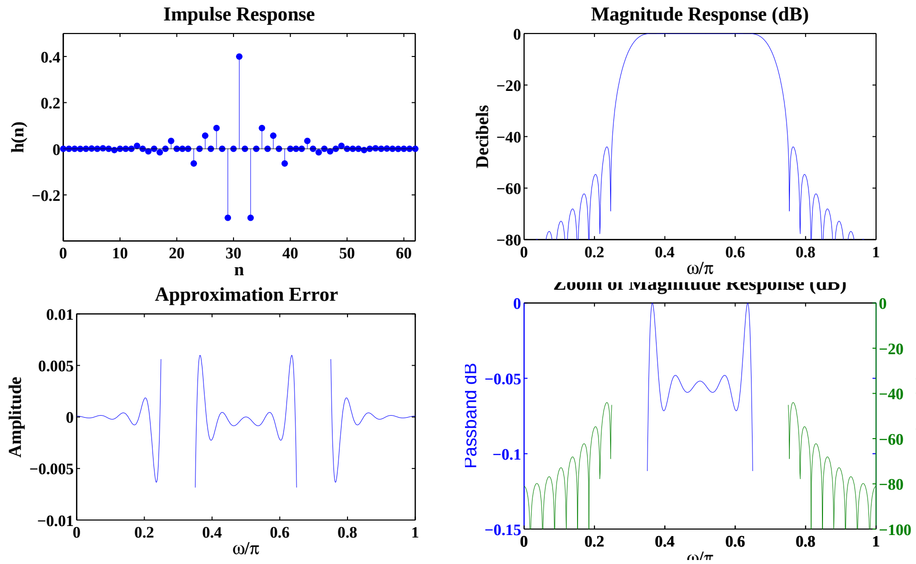


FIGURE 10.65: Plots of impulse response, magnitude response, approximation error and zoom magnitude response of the designed bandpass filter using the `fir1` function.

```
%% Part (c)
% h = fir1(M,[wc1 wc2]/pi,'DC-0',hann(M+1));

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
[Ha w2 P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
magz1 = nan(1,length(w));
magz2 = nan(1,length(w));
ind = w <= ws1;
aperr(ind) = Ha(ind);
magz2(ind) = Hdb(ind);
ind = (w >= wp1 & w <= wp2);
aperr(ind) = Ha(ind) - 1;
magz1(ind) = Hdb(ind);
ind = w >= ws2;
aperr(ind) = Ha(ind);
```

```
magz2(ind) = Hdb(ind);
%% Plot:
hfa = figconfg('P1048a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1048b','small');
plot(w/pi,Hdb);
ylim([-80 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1048c','small');
plot(w/pi,aperr);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Approximation Error','fontsize',TFS)

hfd = figconfg('P1048d','small');
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
xlabel('\omega/\pi','fontsize',LFS)
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(1),'Ylabel'),'string','Passband dB','fontsize',LFS)
set(get(AX(2),'Ylabel'),'string','Stopband dB','fontsize',LFS)
set(AX(2),'Ylim',[-100 0],'YTick',-100:20:0)
```

49. (a) See plot below.
    (b) See plot below.

MATLAB script:

```
% P1049: Design bandstop filter using hann window
close all; clc
wp1 = 0.4*pi; ws1 = 0.55*pi; ws2 = 0.65*pi; wp2 = 0.75*pi;
Ap1 = 0.5; As = 55; Ap2 = 1;
```

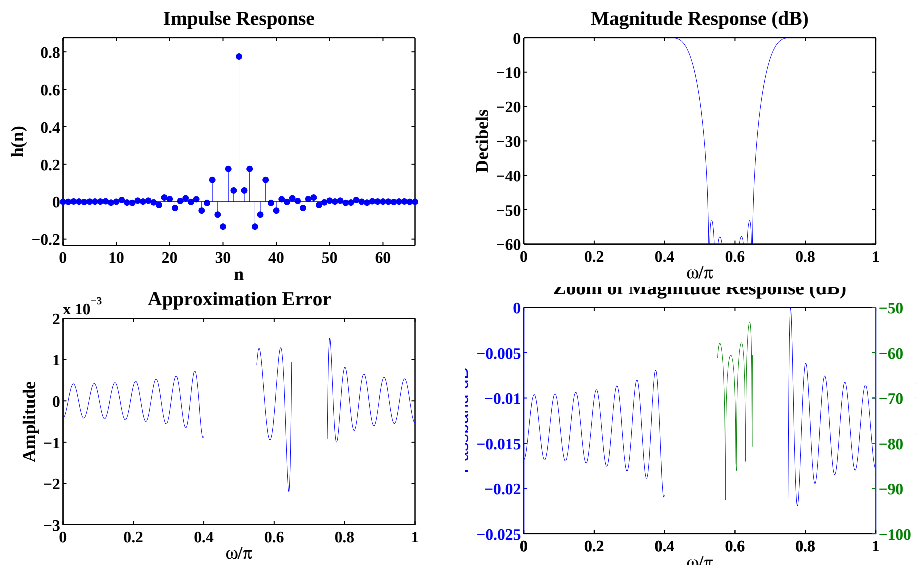


FIGURE 10.66: Plots of impulse response, magnitude response, approximation error and zoom magnitude response of the designed bandpass filter using Kaiser technique.

```
[deltap, deltas] = spec_convert(min([Ap1 Ap2]),As,'rel','abs');
delta = min([deltap,deltas]);
A = -20*log10(delta);

%% Part (a)
wc1 = (ws1+wp1)/2; wc2 = (ws2+wp2)/2;
[M,wn,beta,ftype] = ...
  kaiserord([wp1 ws1 ws2 wp2]/pi,[1 0 1],[deltap,deltas, deltap]);
hd = ideallp(wc1,M) + ideallp(pi,M) - ideallp(wc2,M);
h = hd.*kaiser(M+1,beta);

%% Part (b)
h = fir1(M,[wc1 wc2]/pi,'stop',kaiser(M+1,beta));

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
[Ha w2 P2 L2] = amplresp(h(:)',w);
```

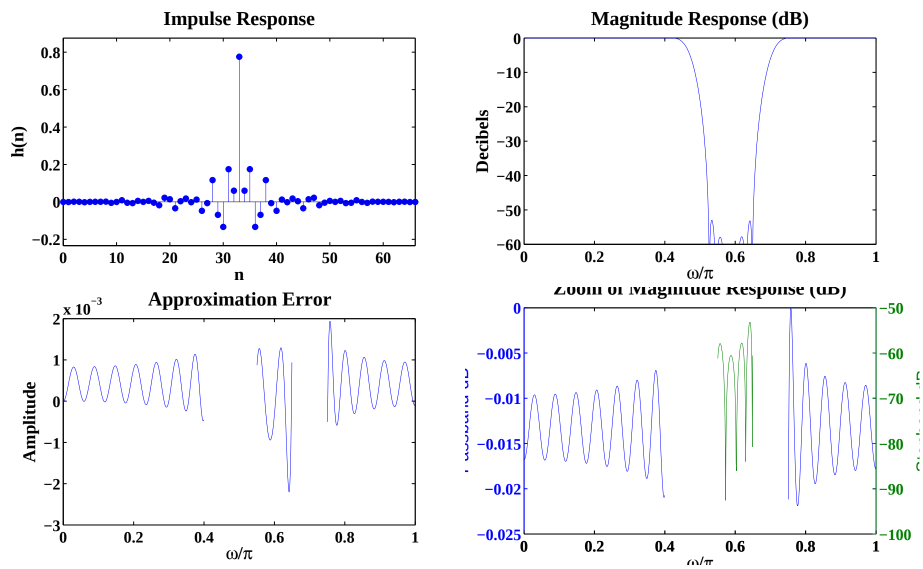


FIGURE 10.67: Plots of impulse response, magnitude response, approximation error and zoom magnitude response of the designed bandpass filter using the `fir1` function.

```
aperr = nan(1,length(w));
magz1 = nan(1,length(w));
magz2 = nan(1,length(w));
ind = w <= wp1;
aperr(ind) = Ha(ind) - 1;
magz1(ind) = Hdb(ind);
ind = (w >= ws1 & w <= ws2);
aperr(ind) = Ha(ind);
magz2(ind) = Hdb(ind);
ind = w >= wp2;
aperr(ind) = Ha(ind) - 1;
magz1(ind) = Hdb(ind);
%% Plot:
hfa = figconfg('P1049a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
```

```
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1049b','small');
plot(w/pi,Hdb);
ylim([-60 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1049c','small');
plot(w/pi,aperr);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Approximation Error','fontsize',TFS)

hfd = figconfg('P1049d','small');
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
xlabel('\omega/\pi','fontsize',LFS)
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(1),'Ylabel'),'string','Passband dB','fontsize',LFS)
set(get(AX(2),'Ylabel'),'string','Stopband dB','fontsize',LFS)
```

50.

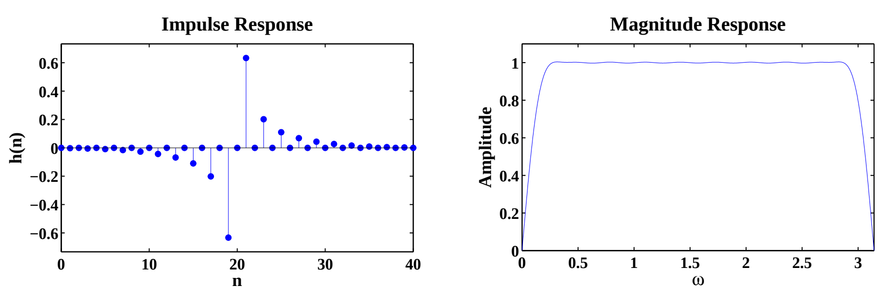


FIGURE 10.68: Plots of impulse response and magnitude response of the designed type-III Hilbert transformer.

MATLAB script:

```
% P1050: Design a type-III Hilbert Transformer of order 40
%        using hamming window
close all; clc
```

```
M = 40; L = M + 1; n = 0:M;
alpha = M/2; na = (n-alpha);
Dw = 2*pi/L;
w1 = 0*Dw; w2 = L/2*Dw;
hd = (cos(w1*na)-cos(w2*na))./(pi*na); hd(alpha+1) = 0;
h = hd.*hamming(L)';

%% Part b:
% dd = 1e-6;
% h = fir1(M,[dd 1-dd],'DC-0',hamming(M+1));

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
Ha = abs(H);

%% Plot:
hfa = figconfg('P1050a','small');
stem(n,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1050b','small');
plot(w,Ha);
xlim([0 pi]);ylim([0 1.1])
xlabel('\omega','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Magnitude Response','fontsize',TFS)
```

51.

MATLAB script:

```
% P1051: Design a lowpass filter using frequency sampling approach
close all; clc
M = 35;
L = M + 1;
wp = 0.3*pi; ws = 0.5*pi;
Ap = 0.5; As = 50;
```

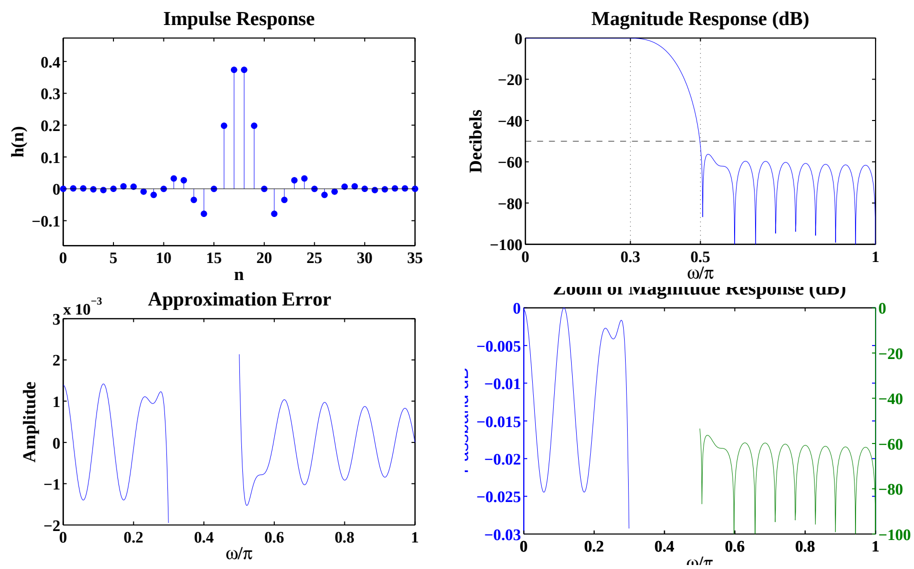


FIGURE 10.69: Plots of impulse response, magnitude response, approximation error and zoom magnitude response of the designed lowpass FIR filter.

```
Dw = 2*pi/L;
om = (0:L-1)*Dw;

wc = (wp+ws)/2;
k = floor(wc/Dw);
Ap = [ones(1,k+1),zeros(1,L-2*k-1),ones(1,k)];
h = fir2(M,[0 wc/pi wc/pi 1],[1 1 0 0]);

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
[Ha w2 P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
magz1 = nan(1,length(w));
magz2 = nan(1,length(w));
ind = w <= wp;
aperr(ind) = Ha(ind) - 1;
magz1(ind) = Hdb(ind);
ind = w >= ws;
```

```
aperr(ind) = Ha(ind);
magz2(ind) = Hdb(ind);
%% Plot:
hfa = figconfg('P1051a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1051b','small');
plot(w/pi,Hdb);hold on
plot(w/pi,-As*ones(1,length(w)),'--','color','k')
ylim([-100 0])
set(gca,'XTick',[0 wp ws pi]/pi,'Xgrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1051c','small');
plot(w/pi,aperr);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Approximation Error','fontsize',TFS)

hfd = figconfg('P1051d','small');
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
xlabel('\omega/\pi','fontsize',LFS)
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(1),'Ylabel'),'string','Passband dB','fontsize',LFS)
set(get(AX(2),'Ylabel'),'string','Stopband dB','fontsize',LFS)
set(AX(2),'Ylim',[-100 0],'YTick',-100:20:0)
```

52. (a) See plot below.

    (b) See plot below.

    MATLAB script:

```
% P1052: Design a highpass filter using frequency sampling approach
```

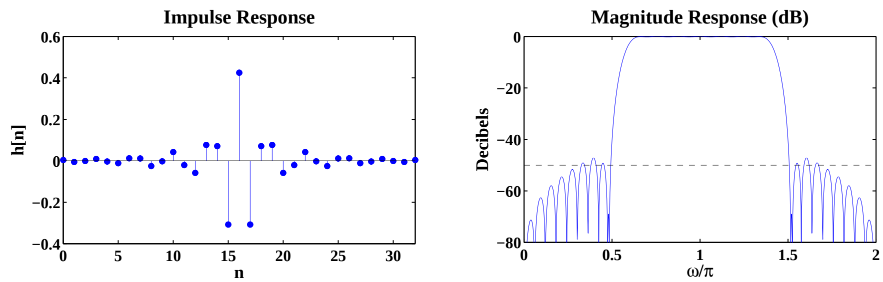


FIGURE 10.70: Plots of impulse response and magnitude response of the designed highpass filter using raised-cosine transition.

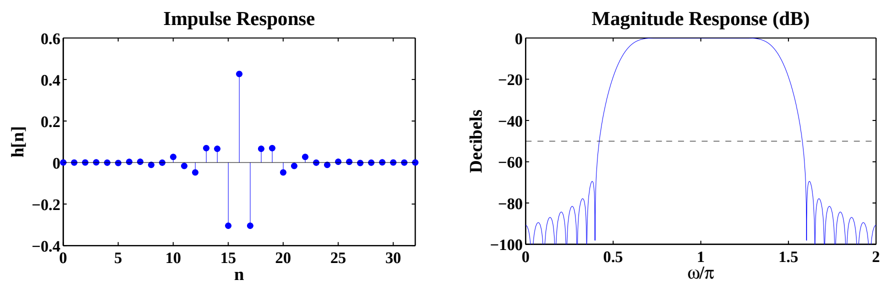


FIGURE 10.71: Plots of impulse response and magnitude response of the designed highpass filter using the `fir2` function and the Hamming window.

```
close all; clc
M = 32;
L = M + 1;
ws = 0.5*pi; wp = 0.65*pi;
As = 50; Ap = 1;
alpha = M/2; Q = floor(alpha);
psid = -alpha*Dw*[0:Q,-(L-(Q+1:M))];
Dw = 2*pi/L;
om = (0:M)*Dw;
k1 = floor(ws/Dw);
k2 = ceil(wp/Dw);
ind = (om>ws & om<wp);
A = 0.5 + 0.5*cos(pi*(om(ind)-wp)/(wp-ws));
Ad = [zeros(1,k1+1) A ones(1,L-2*k2+1) fliplr(A) zeros(1,k1)];

%% Part a
```

```
Hd = Ad.*exp(1j*psid);
hd = real(ifft(Hd));
h = hd.*rectwin(L)';

%% Part b
ind = om < pi;
h = fir2(M,[om(ind) pi]/pi,[Ad(ind) 1]);

%% Plot
w = linspace(0,2,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag/max(Hmag));

hfa = figconfg('P1052a','small');
plot(w/pi,Hdb);hold on
plot(w/pi,-As*ones(1,length(w)),'--','color','k')
% ylim([-As-30 0])
ylim([-100 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfb = figconfg('P1052a','small');
stem(0:M,h,'filled')
xlim([0 M])
xlabel('n','fontsize',LFS)
ylabel('h[n]','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfc = figconfg('P1052c','small');
plot(w/pi,Hmag);hold on
plot(om/pi,Ad,'.','color','r')
ylim([0 max(Hmag)+0.1])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Magnitude','fontsize',LFS)
title('Magnitude Response','fontsize',TFS)
```

53. (a) See plot below.
    (b) See plot below.

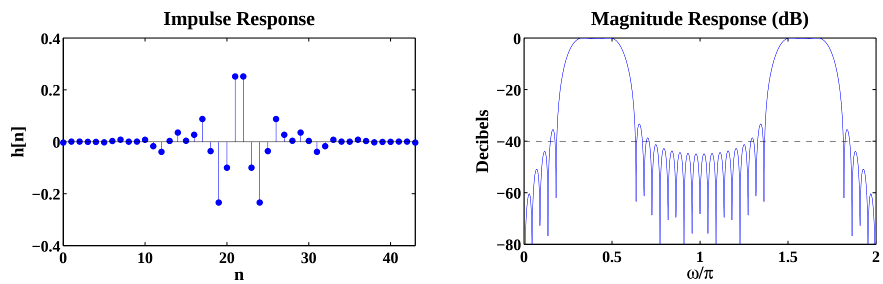


FIGURE 10.72: Plots of impulse response and magnitude response of the designed bandpass filter using linear transition.

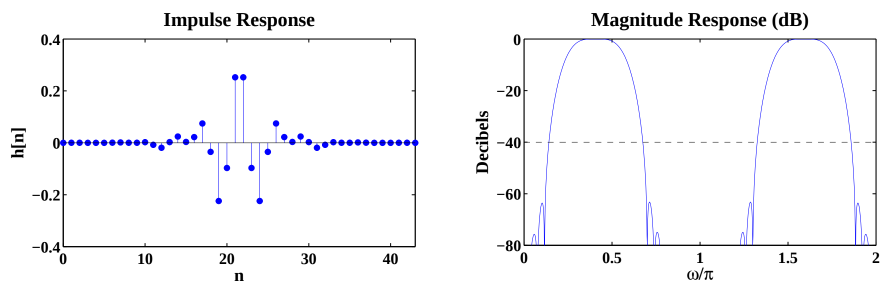


FIGURE 10.73: Plots of impulse response and magnitude response of the designed bandpass filter using the `fir2` function and the Hann window.

MATLAB script:

```
% P1053: Design a bandpass filter using frequency sampling approach
close all; clc
% L = 40;
L = 44;
M = L - 1;
ws1 = 0.2*pi; wp1 = 0.3*pi; wp2 = 0.5*pi; ws2 = 0.65*pi;
As1 = 40; Ap = 0.2; As2 = 40;
Dw = 2*pi/L;
om = (0:L-1)*Dw;
alpha = M/2; Q = floor(alpha);
psid = -alpha*Dw*[0:Q,-(L-(Q+1:M))];

%% Part a
k1 = floor(ws1/Dw);
k2 = ceil(wp1/Dw);
```

```
k3 = floor(wp2/Dw);
k4 = ceil((ws2-0.05*pi)/Dw);
ind = (om>ws1 & om<wp1);
A = (om(ind)-ws1)/(wp1-ws1);
Ad = [zeros(1,k1+1),A,ones(1,k3-k2+1),fliplr(A),zeros(1,L-k4*2+1),...
    A,ones(1,k3-k2+1),fliplr(A),zeros(1,k1)];
Hd = Ad.*exp(j*psid);
hd = real(ifft(Hd));
h = hd.*rectwin(L)';

%% Part b
% ind = om < pi;
% h = fir2(M,[om(ind) pi]/pi,[Ad(ind) 0],hann(L));

%% Plot
w = linspace(0,2,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag/max(Hmag));

hfa = figconfg('P1053a','small');
plot(w/pi,Hdb);hold on
plot(w/pi,-As1*ones(1,length(w)),'--','color','k')
ylim([-80 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfb = figconfg('P1053a','small');
stem(0:M,h,'filled')
xlim([0 M])
xlabel('n','fontsize',LFS)
ylabel('h[n]','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfc = figconfg('P1053c','small');
plot(w/pi,Hmag);hold on
plot(om/pi,Ad,'.','color','r')
ylim([0 max(Hmag)+0.1])
xlabel('\omega/\pi','fontsize',LFS)
```

```
ylabel('Magnitude','fontsize',LFS)
title('Magnitude Response','fontsize',TFS)
```

54.

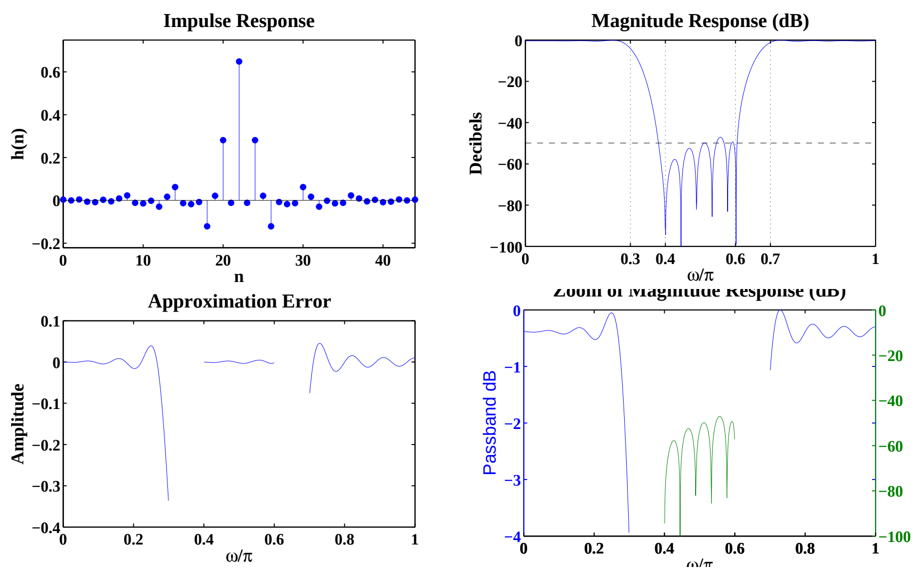


FIGURE 10.74: Plots of impulse response, magnitude response, approximation error and zoom magnitude response of the designed bandstop filter.

MATLAB script:

```
% P1054: Design a bandstop filter using frequency sampling approach
close all; clc
L = 45;
M = L - 1;
wp1 = 0.3*pi; ws1 = 0.4*pi; ws2 = 0.6*pi; wp2 = 0.7*pi;
deltap = 0.02; deltas = 0.0032;
delta = min([deltap deltas]);
As = -20*log10(delta);
Dw = 2*pi/L;
om = (0:L-1)*Dw;
alpha = M/2; Q = floor(alpha);
psid = -alpha*Dw*[0:Q,-(L-(Q+1:M))];

%% Part a
```

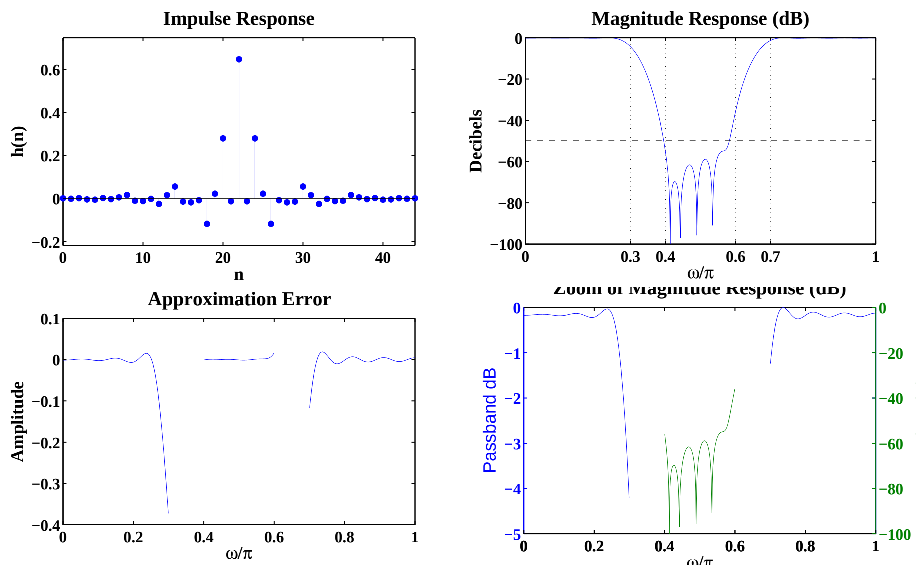


FIGURE 10.75: Plots of impulse response, magnitude response, approximation error and zoom magnitude response of the designed bandstop filter using the fir2 function.

```
ind = (om > wp1 & om < ws1);
sum(ind)
k1 = floor(wp1/Dw);
k2 = ceil(ws1/Dw);
k3 = floor(ws2/Dw);
k4 = ceil((wp2)/Dw);

T1 = 0.05029373; T2 = 0.49149549; % ref
A = [T2 T1];
Ad = [ones(1,k1+1),A,zeros(1,k3-k2+1),fliplr(A),ones(1,L-k4*2+1),...
    A,zeros(1,k3-k2+1),fliplr(A),ones(1,k1)];
Hd = Ad.*exp(j*psid);
hd = real(ifft(Hd));
h = hd.*rectwin(L)';

%% Part b
% ind = om < pi;
% h = fir2(M,[om(ind) pi]/pi,[Ad(ind) 1],rectwin(L));
```

```
w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
[Ha w2 P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
magz1 = nan(1,length(w));
magz2 = nan(1,length(w));
ind = w <= wp1;
aperr(ind) = Ha(ind) - 1;
magz1(ind) = Hdb(ind);
ind = (w >= ws1 & w <= ws2);
aperr(ind) = Ha(ind);
magz2(ind) = Hdb(ind);
ind = w >= wp2;
aperr(ind) = Ha(ind) - 1;
magz1(ind) = Hdb(ind);
%% Plot:
hfa = figconfg('P1054a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1054b','small');
plot(w/pi,Hdb);hold on
plot(w/pi,-As*ones(1,length(w)),'--','color','k')
ylim([-100 0])
set(gca,'XTick',[0 wp1 ws1 ws2 wp2 pi]/pi,'Xgrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1054c','small');
plot(w/pi,aperr);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
```

```
title('Approximation Error','fontsize',TFS)

hfd = figconfg('P1054d','small');
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
xlabel('\omega/\pi','fontsize',LFS)
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(1),'Ylabel'),'string','Passband dB','fontsize',LFS)
set(get(AX(2),'Ylabel'),'string','Stopband dB','fontsize',LFS)
set(AX(2),'Ylim',[-100 0],'YTick',-100:20:0)

hfe = figconfg('P1054e','small');
plot(w/pi,Hmag);hold on
ind = om < pi;
plot(om(ind)/pi,Ad(ind),'.','color','r')
ylim([0 max(Hmag)+0.1])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Magnitude','fontsize',LFS)
title('Magnitude Response','fontsize',TFS)
```

55. (a) See plot below.

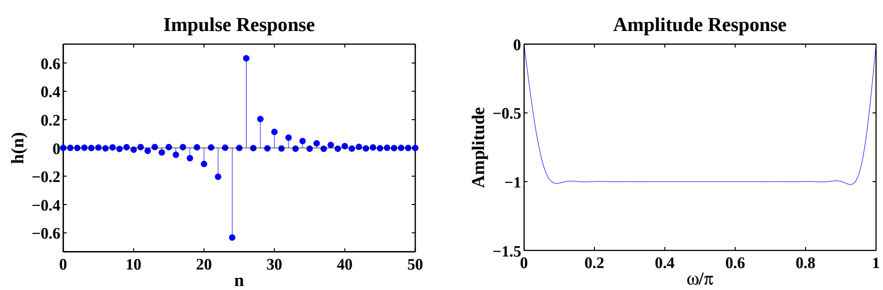


FIGURE 10.76: Plots of impulse response and amplitude response of the designed Hilbert transformer.

(b) See plot below.

(c) tba.

MATLAB script:

```
% P1055: Design Hilbert transformer using frequency sampling approach
close all; clc
%% Part a: filter design
```

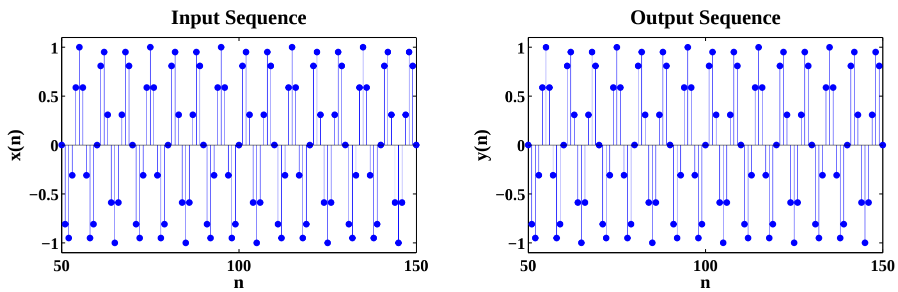


FIGURE 10.77: Stem plots of $x[n]$ and $y[n]$ for $50 \leq n \leq 100$.

```
M = 50;
n = 0:M; L = M+1; % Impulse response length
alpha = M/2; Q = floor(alpha); % phase delay parameters
k = 0:M; % Frequency sample index
Dw = 2*pi/L; % Width between frequency samples
% Transformer Design using Frequency Sampling (Smooth transition)
Ad = [0,sin(pi/4),ones(1,23),0.5,-0.5,-ones(1,23),-sin(pi/4)];
psid = -alpha*2*pi/L*[(0:Q),-(L-(Q+1:M))]; % Desired Phase
Hd = -1j*Ad.*exp(1j*psid); % Desired Freq Resp Samples
hd = real(ifft(Hd)); % Desired Impulse response
h = hd.*rectwin(L)'; % Actual Impulse response

w = linspace(0,1,1000)*pi;
[Ha wt P2 L2] = amplresp(h(:)',w);
%% Plot:
hfa = figconfg('P1055a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1055b','small');
plot(w/pi,Ha);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Amplitude Response','fontsize',TFS)
```

```
%% Part b: verification
nn = 0:150;
xn = sin(0.3*pi*nn);
yn = filter(h,1,xn);
ind = nn >= 50;
hfc = figconfg('P1055c','long');
subplot(121)
stem(nn(ind),xn(ind),'filled');
ylim([-1.1 1.1])
xlabel('n','fontsize',LFS)
ylabel('x(n)','fontsize',LFS)
title('Input Sequence','fontsize',TFS)
subplot(122)
stem(nn(ind),yn(ind),'filled');
ylim([-1.1 1.1])
xlabel('n','fontsize',LFS)
ylabel('y(n)','fontsize',LFS)
title('Output Sequence','fontsize',TFS)
```

56. tba

57.

MATLAB script:

```
% P1057: Design highpass FIR filter using Parks-McClellan
close all; clc
%% Specification:
ws = 0.7*pi; wp = 0.8*pi; As = 55; Ap = 1;
%% Passband and Stopband Ripple Calculation:
[deltap, deltas] = spec_convert(Ap,As,'rel','abs');
%% Estimated Filter order using FIRPMORD function:
[M,fo,ao,W] = firpmord([ws,wp]/pi,[0,1],[deltas,deltap]);
M = M + 2
%% Filter Design using FIRPM function:
[h,delta] = firpm(M,fo,ao,W);
delta,
deltap,

w = linspace(0,1,1000)*pi;
```

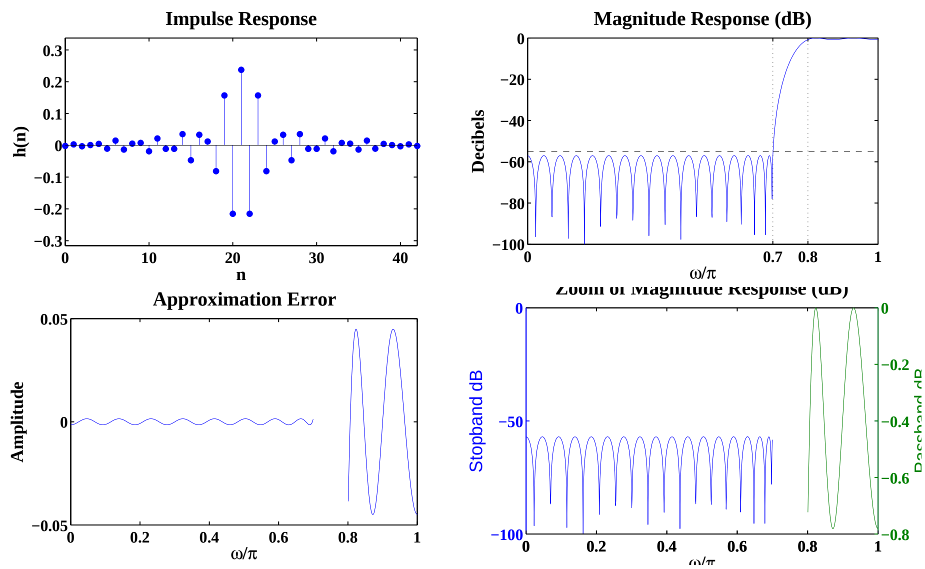


FIGURE 10.78: Plots of impulse response, magnitude response, approximation error and zoom magnitude response of the designed highpass filter.

```
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
[Ha w2 P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
magz1 = nan(1,length(w));
magz2 = nan(1,length(w));
ind = w <= ws;
aperr(ind) = Ha(ind);
magz1(ind) = Hdb(ind);
ind = w >= wp;
aperr(ind) = Ha(ind)-1;
magz2(ind) = Hdb(ind);
%% Plot:
hfa = figconfg('P1057a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
```

```
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1057b','small');
plot(w/pi,Hdb);hold on
plot(w/pi,-As*ones(1,length(w)),'--','color','k')
ylim([-100 0])
set(gca,'XTick',[0 ws wp pi]/pi,'Xgrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1057c','small');
plot(w/pi,aperr);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Approximation Error','fontsize',TFS)

hfd = figconfg('P1057d','small');
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
xlabel('\omega/\pi','fontsize',LFS)
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(2),'Ylabel'),'string','Passband dB','fontsize',LFS)
set(get(AX(1),'Ylabel'),'string','Stopband dB','fontsize',LFS)
set(AX(1),'Ytick',[-100 -50 0],'ylim',[-100 0])
```

58.

MATLAB script:

```
% P1058: Design bandstop FIR filter using Parks-McClellan
close all; clc
%% Specification:
wp1 = 0.35*pi; ws1 = 0.45*pi; ws2 = 0.55*pi; wp2 = 0.65*pi;
deltap1 = 0.01; deltas = 0.004; deltap2 = 0.01;
%% Estimated Filter order using FIRPMORD function:
[M,fo,ao,W] = ...
firpmord([wp1,ws1,ws2,wp2]/pi,[1,0,1],[deltap1,deltas,deltap2]);
M = M + 4
%% Filter Design using FIRPM function:
[h,delta] = firpm(M,fo,ao,W);
delta,
```

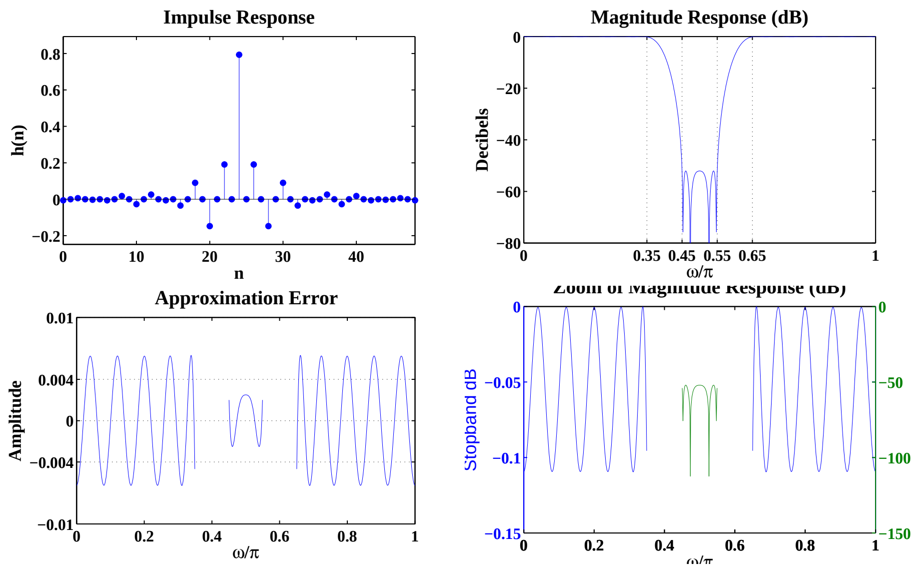


FIGURE 10.79: Plots of impulse response, magnitude response, approximation error and zoom magnitude response of the designed bandstop filter.

```
deltap1,

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
[Ha w2 P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
magz1 = nan(1,length(w));
magz2 = nan(1,length(w));
ind = w <= wp1;
aperr(ind) = Ha(ind)-1;
magz1(ind) = Hdb(ind);
ind = w >= ws1 & w <= ws2;
aperr(ind) = Ha(ind);
magz2(ind) = Hdb(ind);
ind = w >= wp2;
aperr(ind) = Ha(ind)-1;
magz1(ind) = Hdb(ind);
%% Plot:
```

```
hfa = figconfg('P1058a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1058b','small');
plot(w/pi,Hdb);hold on
% plot(w/pi,-As*ones(1,length(w)),'--','color','k')
ylim([-80 0])
set(gca,'XTick',[0 wp1 ws1 ws2 wp2 pi]/pi,'Xgrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1058c','small');
plot(w/pi,aperr);
delYtick = sort(unique([deltap1 deltap2 deltas]));
set(gca,'Ytick',[-delYtick(end:-1:1) 0 delYtick],'Ygrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Approximation Error','fontsize',TFS)

hfd = figconfg('P1058d','small');
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
xlabel('\omega/\pi','fontsize',LFS)
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(2),'Ylabel'),'string','Passband dB','fontsize',LFS)
set(get(AX(1),'Ylabel'),'string','Stopband dB','fontsize',LFS)
```

59.

MATLAB script:

```
% P1059: Design multiband FIR filter using Parks-McClellan
close all; clc
%% Specification:
w1 = 0.3*pi; w2 = 0.4*pi; w3 = 0.7*pi; w4 = 0.8*pi;
A1 = 0; A2 = 0.5; A3 = 1;
```

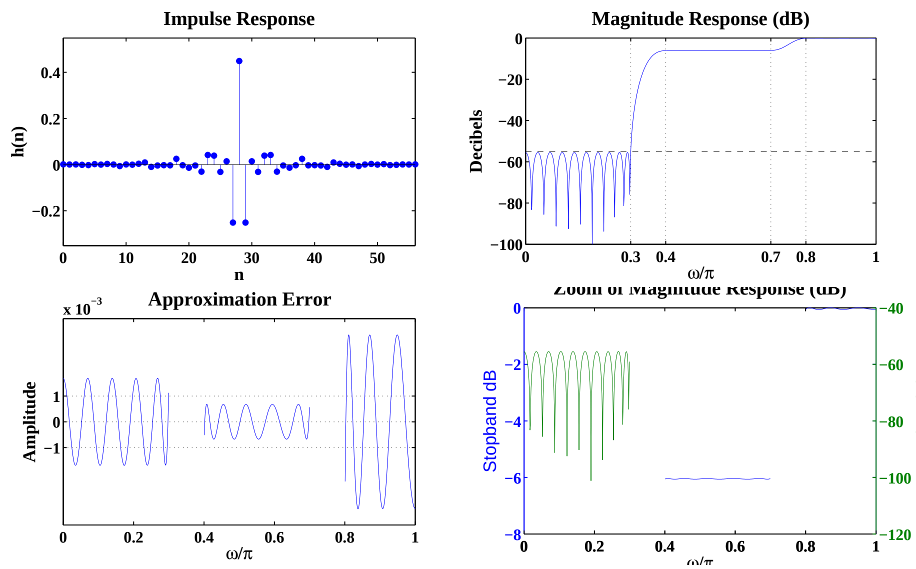


FIGURE 10.80: Plots of impulse response, magnitude response, approximation error and zoom magnitude response of the designed multiband filter.

```
delta1 = 0.005; delta2 = 0.001; delta3 = 0.01;
%% Estimated Filter order using FIRPMORD function:
[M,fo,ao,W] = ...
firpmord([w1,w2,w3,w4]/pi,[A1,A2,A3],[delta1,delta2,delta3]);
M = M + 4
%% Filter Design using FIRPM function:
[h,delta] = firpm(M,fo,ao,W);
delta,
delta1,

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
[Ha ww P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
magz1 = nan(1,length(w));
magz2 = nan(1,length(w));
ind = w <= w1;
aperr(ind) = Ha(ind)-A1;
```

```
magz2(ind) = Hdb(ind);
ind = w >= w2 & w <= w3;
aperr(ind) = Ha(ind)-A2;
magz1(ind) = Hdb(ind);
ind = w >= w4;
aperr(ind) = Ha(ind)-A3;
magz1(ind) = Hdb(ind);
%% Plot:
hfa = figconfg('P1059a','small');
stem(0:M,h,'filled');
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1059b','small');
plot(w/pi,Hdb);hold on
plot(w/pi,-As*ones(1,length(w)),'--','color','k')
ylim([-100 0])
set(gca,'XTick',[0 w1 w2 w3 w4 pi]/pi,'Xgrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1059c','small');
plot(w/pi,aperr);
delYtick = sort([delta1 delta2 delta3]);
set(gca,'Ytick',[-delYtick(end:-1:1) 0 delYtick],'Ygrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Approximation Error','fontsize',TFS)

hfd = figconfg('P1059d','small');
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
xlabel('\omega/\pi','fontsize',LFS)
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(2),'Ylabel'),'string','Passband dB','fontsize',LFS)
set(get(AX(1),'Ylabel'),'string','Stopband dB','fontsize',LFS)
```

60. (a) See plot below.

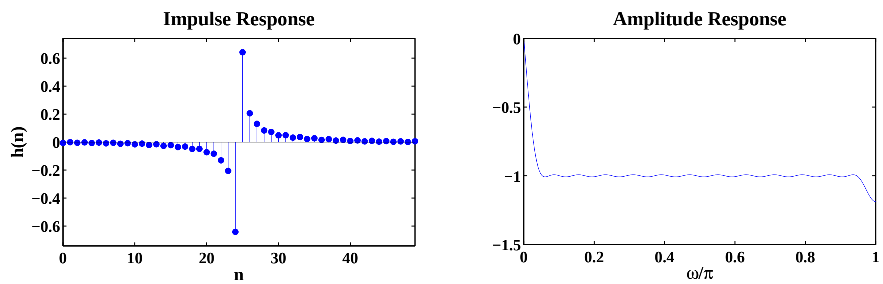


FIGURE 10.81: Plots of impulse response and amplitude response of the designed FIR differentiator.

(b) See plot below.

(c) tba.

MATLAB script:

```
% P1060: Design Hilbert transformer using Parks-McClellan
close all; clc
L = 50;
M = L - 1;
w1 = 0.05*pi; w2 = 0.95*pi;
[h,delta] = firpm(M,[w1 w2]/pi,[1 1],'hilbert');

w = linspace(0,1,1000)*pi;
H = freqz(h,1,w);
[Ha wa P2 L2] = amplresp(h(:)',w);
aperr = nan(1,length(w));
ind = (w >= w1 & w <= w2);
aperr(ind) = Ha(ind)+1;

n = 0:150;
xn = 10*cos(0.2*pi*n);
yn = filter(h,1,xn);
indn = n >= 50 & n <= 100;

%% Plot:
hfa = figconfg('P1039a','small');
stem(0:M,h,'filled');
```

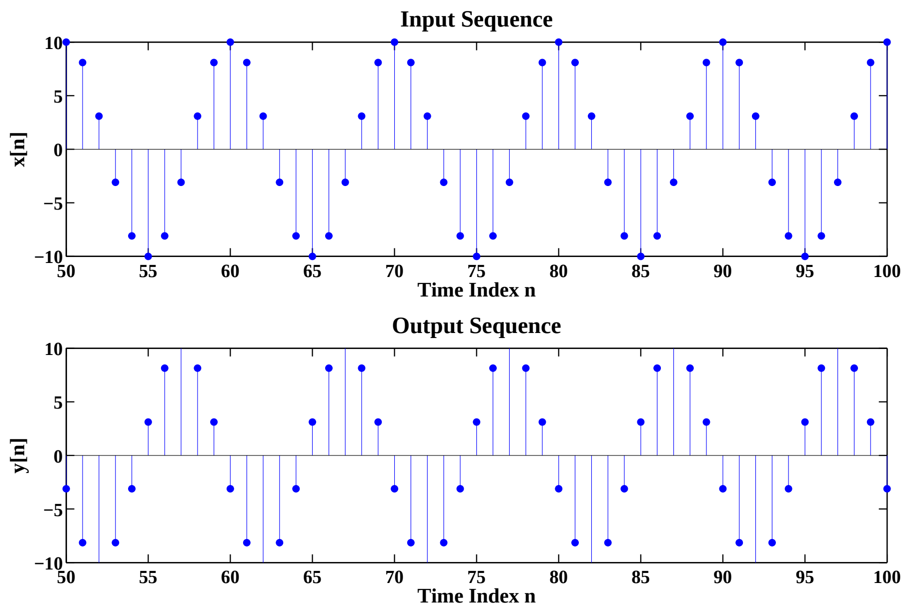


FIGURE 10.82: Stem plots of $x[n]$ and $y[n]$ for $50 \leq n \leq 100$.

```
xlim([0 M])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1039b','small');
plot(w/pi,Ha);hold on
xlabel('\omega/\pi','fontsize',LFS)
title('Amplitude Response','fontsize',TFS)

hfc = figconfg('P1039c');
subplot(211)
stem(n(indn),xn(indn),'filled')
ylim([-10 10])
xlabel('Time Index n','fontsize',LFS)
ylabel('x[n]','fontsize',LFS)
title('Input Sequence','fontsize',TFS)
```

```
subplot(212)
stem(n(indn),yn(indn),'filled')
ylim([-10 10])
xlabel('Time Index n','fontsize',LFS)
ylabel('y[n]','fontsize',LFS)
title('Output Sequence','fontsize',TFS)
```

Review Problems

61. (a) See plot below.

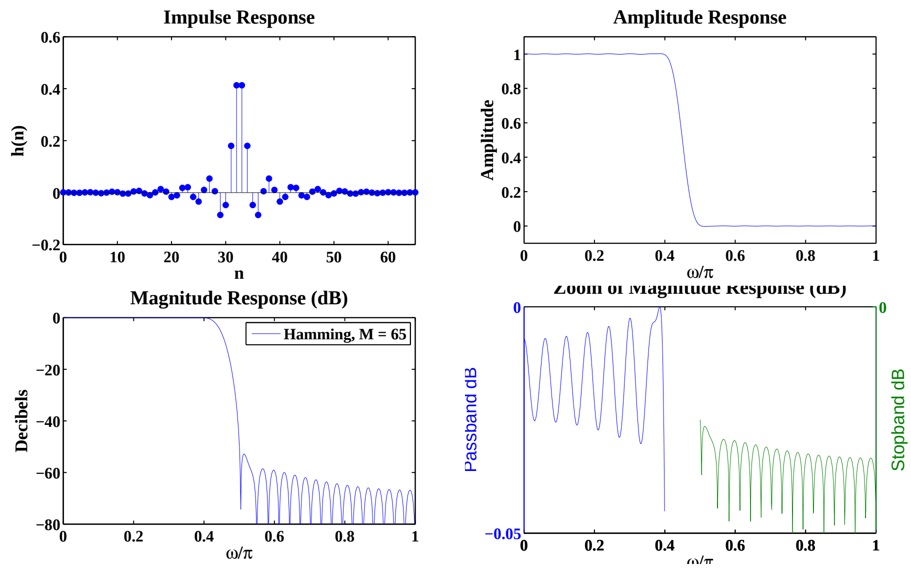


FIGURE 10.83: Impulse, amplitude, log-magnitude, and error response subplots of FIR filter designed by Hamming window in part (a).

(b) See plot below.

(c) See plot below

(d) Comments:
See plots for reference.

(e) See plot below.

MATLAB script:

```
% P1061: Lowpass filter design; All methods
close all; clc
%% Specification:
Fs = 1e3; T = 1/Fs;
n = 0:200; nT = n*T;
xn = 5*cos(400*pi*nT)+10*sin(500*pi*nT);
w1 = 400*pi/Fs; w2 = 500*pi/Fs;
Ap = 1; As = 50;
```

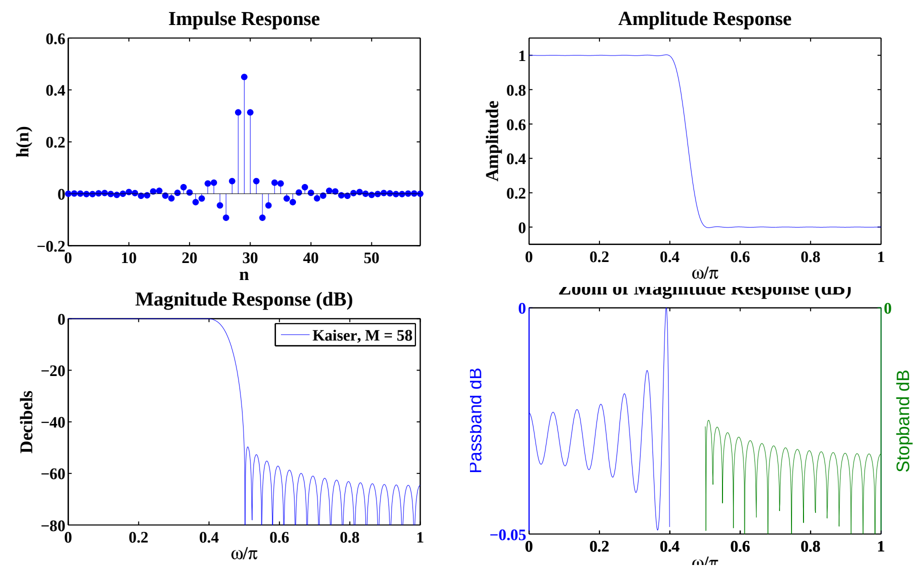


FIGURE 10.84: Impulse, amplitude, log-magnitude, and error response subplots of FIR filter designed by Kaiser window in part (b).

```
[deltap, deltas] = spec_convert(Ap,As,'rel','abs');
delta = min([deltap,deltas]);
A = -20*log10(delta);
wc = (w1+w2)/2;
delw = w2-w1;

%% Part a: Fixed window
L = 6.6*pi/delw; Mfw = L - 1;
hd = ideallp(wc,Mfw);
hfw = hd.*hamming(Mfw+1);

%% Part b: Kaiser window
[Mk,wn,beta,ftype] = ...
  kaiserord([w1 w2]/pi,[1 0],[deltap,deltas]);
hkai = fir1(Mk,wc/pi,kaiser(Mk+1,beta));

%% Part c: Parks-McClellan
[Mpm,fo,ao,W] = firpmord([w1,w2]/pi,[1,0],[deltap,deltas]);
Mpm = Mpm + 2
[hpm,delta] = firpm(Mpm,fo,ao,W);
```

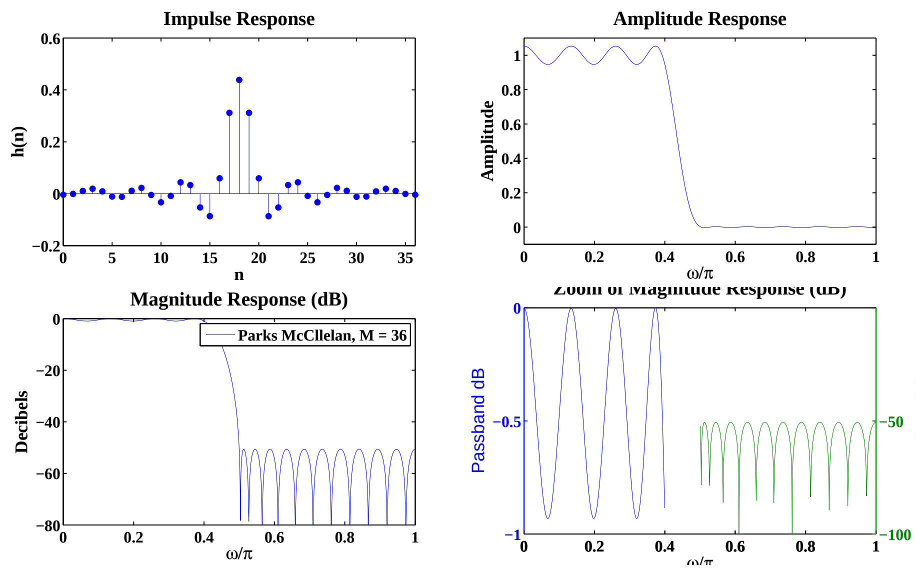
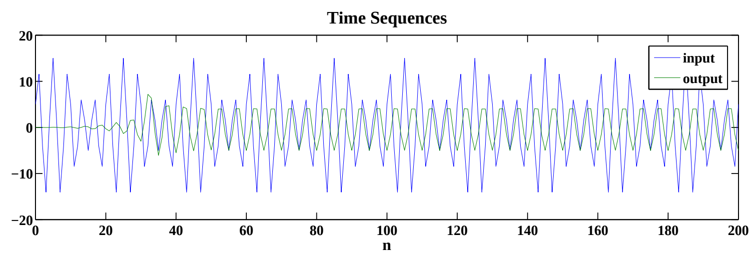


FIGURE 10.85: Impulse, amplitude, log-magnitude, and error response subplots of FIR filter designed by Parks-McClellan in part (c).

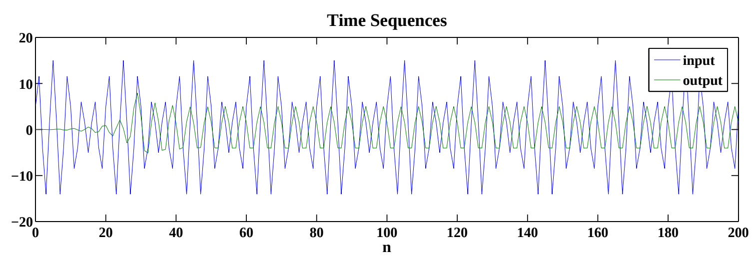
```
delta,
deltap,

%% Plot:
% hp = hfw; M = Mfw; Method = 'Hamming'; % Part a
% hp = hkai; M = Mk; Method = 'Kaiser'; % Part b
hp = hpm; M = Mpm; Method = 'Parks McCllelan';% Part c

w = linspace(0,1,1000)*pi;
H = freqz(hp,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag/max(Hmag));
[Ha wt P2 L2] = amplresp(hp(:)',w);
aperr = nan(1,length(w));
magz1 = nan(1,length(w));
magz2 = nan(1,length(w));
ind = w <= w1;
aperr(ind) = Ha(ind) - 1;
magz1(ind) = Hdb(ind);
ind = w >= w2;
```

```
aperr(ind) = Ha(ind);
magz2(ind) = Hdb(ind);

yn = filter(hp,1,xn);

hfa = figconfg('P1061a','small');
stem(0:M,hp,'filled');
xlim([0 M])
xlabel('n','fontsize',LFS)
ylabel('h(n)','fontsize',LFS)
title('Impulse Response','fontsize',TFS)

hfb = figconfg('P1061b','small');
plot(w/pi,Ha);
ylim([-0.1 1.1])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Amplitude Response','fontsize',TFS)

hfc = figconfg('P1061c','small');
plot(w/pi,Hdb);
ylim([-80 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)
legend([Method,', M = ',num2str(M)],'location','northeast')

hfd = figconfg('P1061d','small');
plot(w/pi,aperr);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Approximation Error','fontsize',TFS)

hfe = figconfg('P1061e','small');
[AX hf1 hf2] = plotyy(w/pi,magz1,w/pi,magz2);
set(AX(2),'ylim',[-100 0])
xlabel('\omega/\pi','fontsize',LFS)
title('Zoom of Magnitude Response (dB)','fontsize',TFS)
set(get(AX(1),'Ylabel'),'string','Passband dB','fontsize',LFS)
set(get(AX(2),'Ylabel'),'string','Stopband dB','fontsize',LFS)
```

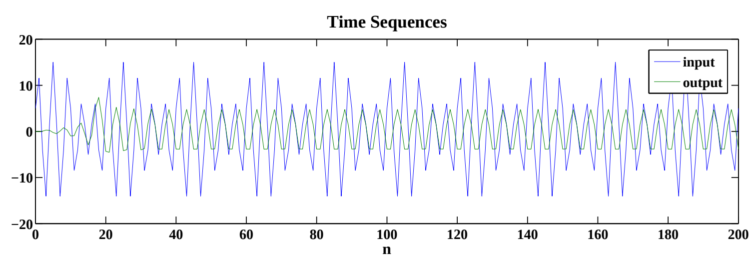
```
hff = figconfg('P1061f','long');
plot(n,xn,n,yn)
xlabel('n','fontsize',LFS)
title('Time Sequences','fontsize',TFS)
legend('input','output','location','best')
```



(a)



(b)



(c)

FIGURE 10.86: Plot of input and output sequences passing through filters designed by (a) Hamming window. (b) Kaiser window. (c) Parks-McClellan.

62. (a) See plot below.

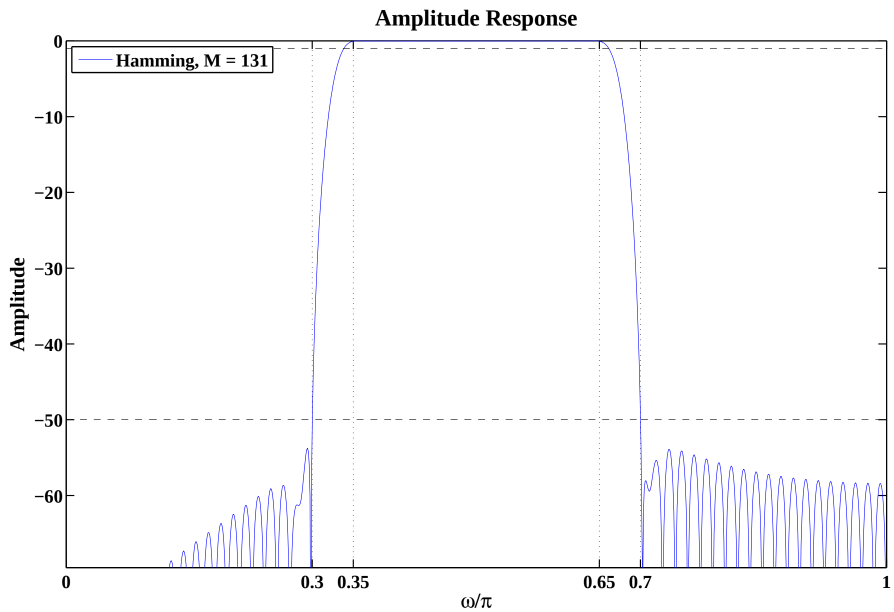


FIGURE 10.87: Amplitude response of FIR filter designed by Hamming window in part (a).

(b) See plot below.

(c) See plot below.

(d) See plot below.

(e) See plot below.

MATLAB script:

```
% P1062: Bandpass filter design; All methods
close all; clc
%% Specification:
ws1 = 0.3*pi; wp1 = 0.35*pi; wp2 = 0.65*pi; ws2 = 0.7*pi;
As = 50; Ap = 1;
[deltap, deltas] = spec_convert(Ap,As,'rel','abs');
delta = min([deltap,deltas]);
A = -20*log10(delta);
```

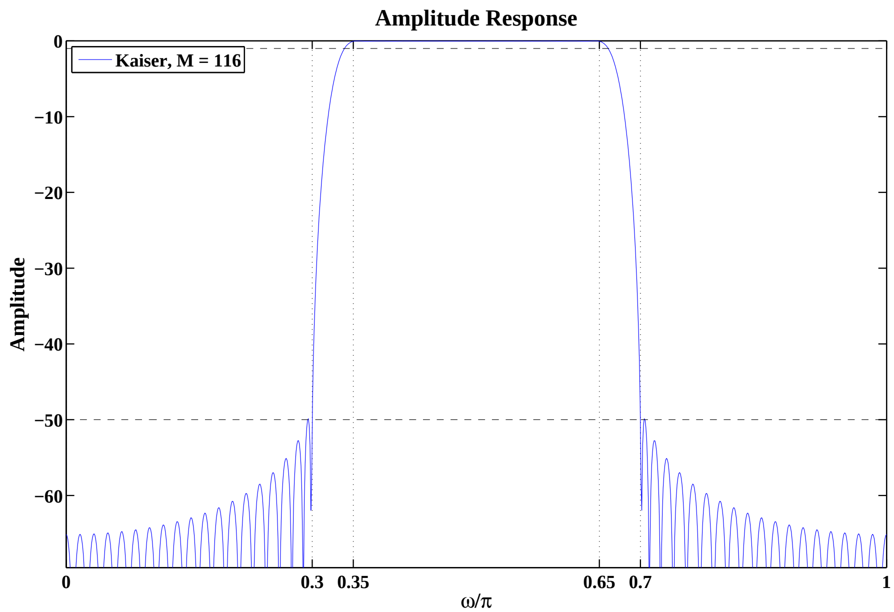


FIGURE 10.88: Amplitude response of FIR filter designed by Hamming window in part (b).

```
wc1 = (ws1+wp1)/2; wc2 = (wp2+ws2)/2;
delw = min([wp1-ws1,ws2-wp2]);

n = 0:200;
xn = 10*cos(0.2*pi*n)+sin(0.5*pi*n)+15*cos(0.9*pi*n+pi/3);
indn = n >= 100;

%% Part a: Fixed window
L = 6.6*pi/delw; Mfw = L-1;
hd = ideallp(wc2,Mfw) - ideallp(wc1,Mfw);
hfw = hd.*hamming(Mfw+1);

%% Part b: Kaiser window
[Mk,wn,beta,ftype] = ...
  kaiserord([ws1 wp1 wp2 ws2]/pi,[0 1 0],[deltas,deltap, deltas]);
hkai = fir1(Mk,[wc1 wc2]/pi,'DC-0',kaiser(Mk+1,beta));
```

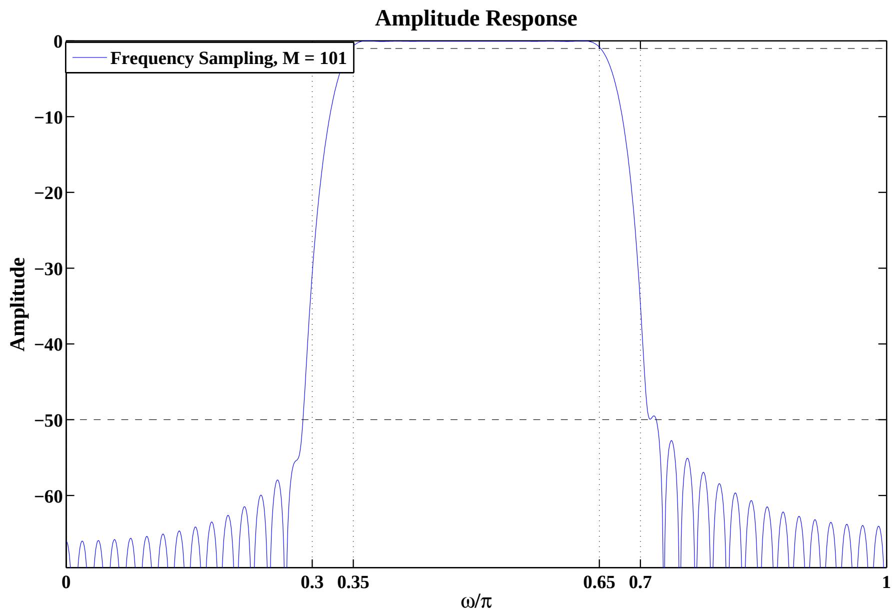


FIGURE 10.89: Amplitude response of FIR filter designed by Hamming window in part (c).

```
%% Part c: Frequency sampling
Mfs = 101;
L = Mfs + 1;
Dw = 2*pi/L;
om = (0:Mfs)*Dw;
ind = (om > ws1 & om < wp1);
sum(ind)
k1 = floor(ws1/Dw);
k2 = ceil(wp1/Dw);
k3 = ceil(wp2/Dw);
k4 = k3+2;
% T1 = 0.10288086; T2 = 0.58097354; % ref
T1 = 0.09288086; T2 = 0.61097354;
AT = [T1 T2];
Ad = [zeros(1,k1+1),AT,ones(1,k3-k2),fliplr(AT),zeros(1,L-2*k4+1),...
    AT,ones(1,k3-k2),fliplr(AT),zeros(1,k1)];
ind = om < pi;
```

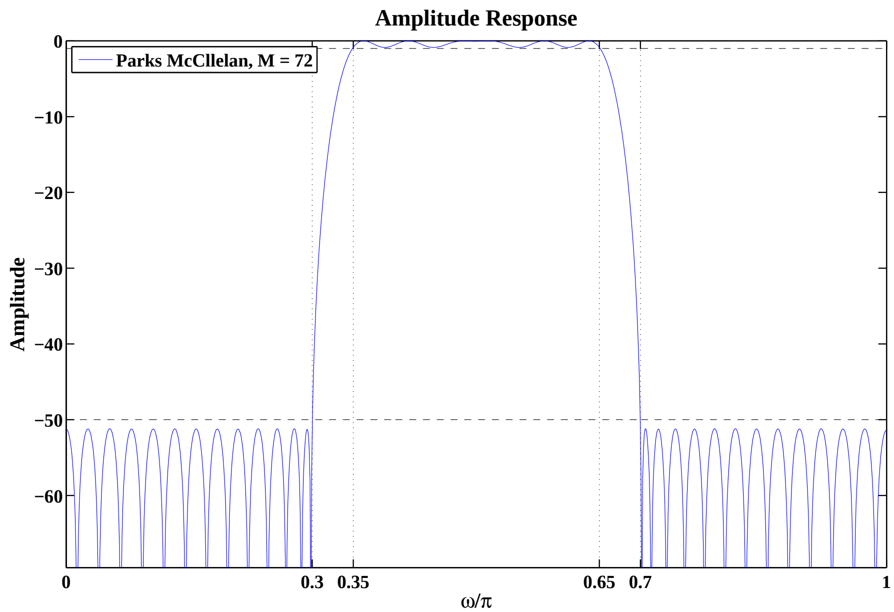
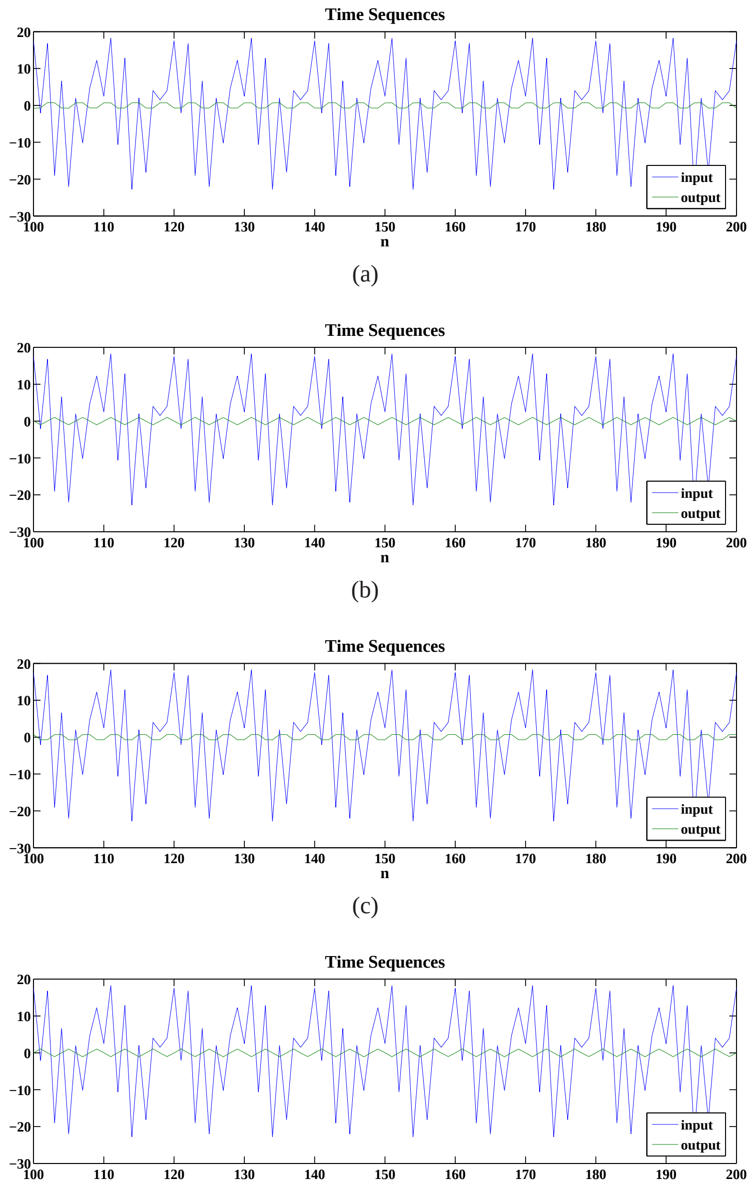


FIGURE 10.90: Amplitude response of FIR filter designed by Hamming window in part (d).

```
hfs = fir2(Mfs,[om(ind) pi]/pi,[Ad(ind) 0],kaiser(L,1.1));

%% Part d: Parks-McClellan
[Mpm,fo,ao,W] = ...
    firpmord([ws1,wp1,wp2,ws2]/pi,[0,1,0],[deltas,deltap, deltas]);
Mpm = Mpm + 5
[hpm,delta] = firpm(Mpm,fo,ao,W);
delta,
deltap

%% Plot:
% hp = hfw; M = Mfw; Method = 'Hamming'; % Part a
% hp = hkai; M = Mk; Method = 'Kaiser'; % Part b
% hp = hfs; M = Mfs; Method = 'Frequency Sampling'; % Part c
hp = hpm; M = Mpm; Method = 'Parks McCllelan';% Part d

w = linspace(0,1,1000)*pi;
```

```
[Ha wt P2 L2] = amplresp(hp(:)',w);
H = freqz(hp,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag/max(Hmag));
yn = filter(hp,1,xn);

hfb = figconfg('P1062b','long');
plot(n(indn),xn(indn),n(indn),yn(indn))
xlabel('n','fontsize',LFS)
title('Time Sequences','fontsize',TFS)
legend('input','output','location','best')

hfc = figconfg('P1062c');
plot(w/pi,Hdb); hold on
plot(w/pi,-Ap*ones(1,length(w)),'--','color','k')
plot(w/pi,-As*ones(1,length(w)),'--','color','k')
ylim([-A-20 0])
set(gca,'Xtick',[0 ws1 wp1 wp2 ws2 pi]/pi,'Xgrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Amplitude Response','fontsize',TFS)
legend([Method,', M = ',num2str(M)],'location','northwest')
```



(a) (b) (c) (d)

FIGURE 10.91: Plot of input and output sequences passing through filters designed by (a) Hamming window. (b) Kaiser window. (c) Frequency-sampling. (d) Parks-McClellan.

63. (a) See plot below.

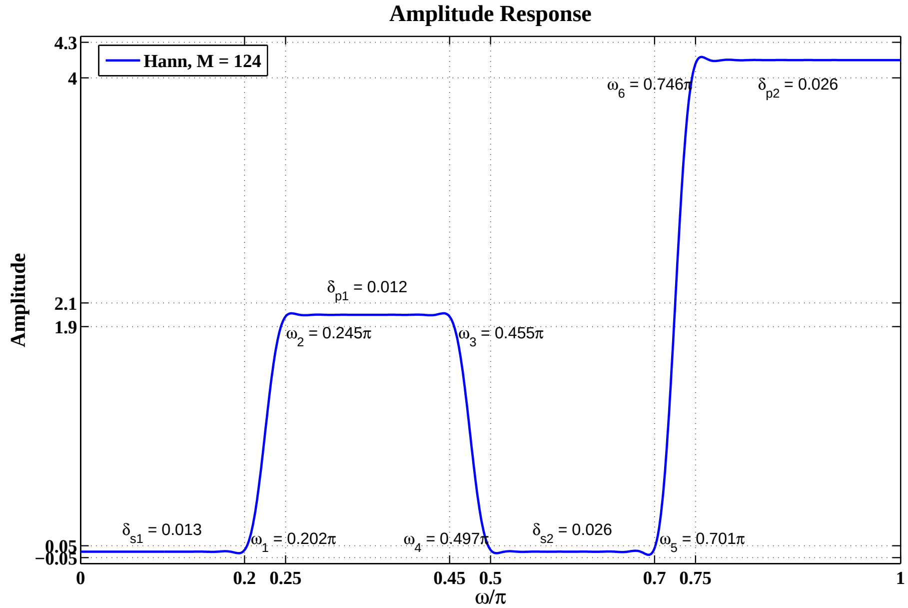


FIGURE 10.92: Amplitude response of FIR filter designed by Hann window in part (a).

(b) See plot below.

(c) See plot below.

(d) See plot below.

(e) Comment:
See each plot for reference.

MATLAB script:

```
% P1063: Multiband filter design; All methods
close all; clc
%% Specification:
ws1 = 0.2*pi; wp1 = 0.25*pi; wp2 = 0.45*pi;
ws2 = 0.5*pi; ws3 = 0.7*pi; wp3 = 0.75*pi;
G1 = 0; G2 = 2; G3 = 0; G4 = 4.15;
deltas1 = 0.05; deltap1 = 0.1; deltas2 = 0.05; deltap2 = 0.15;
delta = min([deltas1 deltap1 deltap2 deltas2]);
```

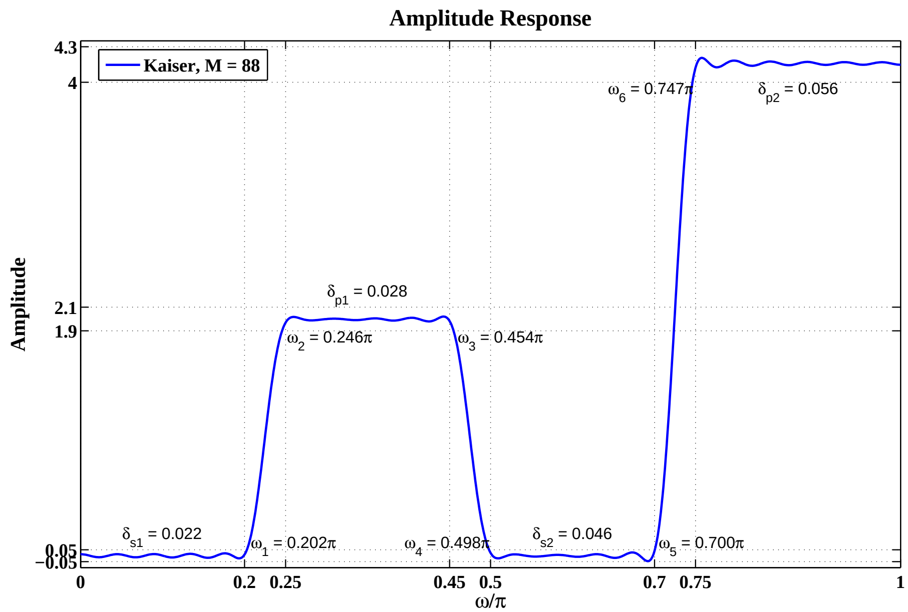


FIGURE 10.93: Amplitude response of FIR filter designed by Kaiser window in part (b).

```
A = -20*log10(delta);

wbp1 = (ws1+wp1)/2; wbp2 = (wp2+ws2)/2; whp = (ws3+wp3)/2;
delw = 0.05*pi;

%% Part a: Fixed window
L = ceil(6.2*pi/delw); Mfw = L - 1;
if mod(Mfw,2) == 1
    Mfw = Mfw + 1;
end
hfw1 = fir1(Mfw,[wbp1 wbp2]/pi,'DC-0',hann(Mfw+1));
hfw2 = fir1(Mfw,whp/pi,'high',hann(Mfw+1));
hfw = G2*hfw1 + G4*hfw2;

%% Part b: Kaiser window
[Mk,wn,beta,ftype] = ...
  kaiserord([ws1 wp1 wp2 ws2]/pi,[0 1 0],...
```

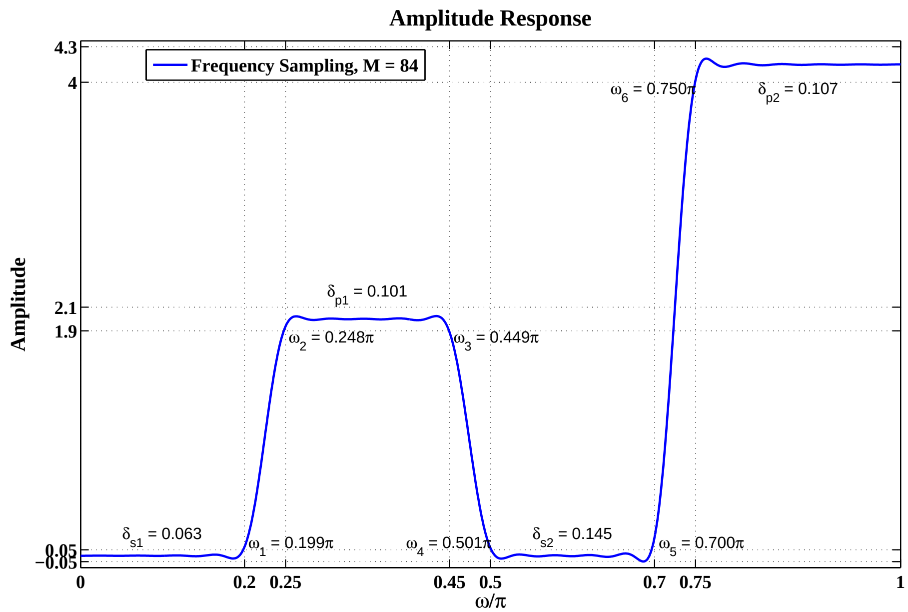


FIGURE 10.94: Amplitude response of FIR filter designed by frequency-sampling in part (c).

```
      [deltas1,deltap1,deltas2/4.5]);
  if mod(Mk,2)==1
      Mk = Mk + 1;
  end
  hkai1 = fir1(Mk,[wbp1 wbp2]/pi,'DC-0',kaiser(Mk+1,beta));
  hkai2 = fir1(Mk,whp/pi,'high',kaiser(Mk+1,beta));
  hkai = G2*hkai1 + G4*hkai2;

  %% Part c: Frequency sampling
  % Mfs = 90;
  Mfs = 84;
  L = Mfs + 1;
  hfs = fir2(Mfs,[0 ws1+0.002*pi wp1 wp2 ws2 ws3+0.001*pi wp3 pi]/pi,...
      [G1 G1 G2 G2 G3 G3 G4 G4],rectwin(L));

  %% Part d: Parks-McClellan
  [Mpm,fo,ao,W] = firpmord([ws1,wp1,wp2,ws2,ws3,wp3]/pi,[G1,G2,G3,G4],...
```

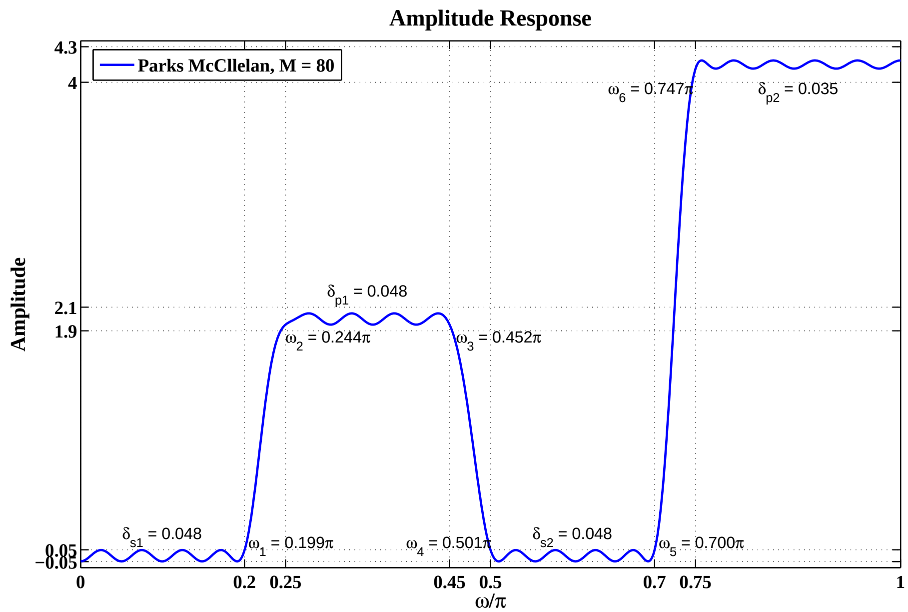


FIGURE 10.95: Amplitude response of FIR filter designed by Parks-McClellan in part (d).

```
    [deltas1,deltap1, deltas2,deltap2]);
Mpm = Mpm + 34
[hpm,delta] = firpm(Mpm,fo,ao,W);
delta,
% deltas,
deltas1

%% Plot:
hp = hfw; M = Mfw; Method = 'Hann'; % Part a
% hp = hkai; M = Mk; Method = 'Kaiser'; % Part b
% hp = hfs; M = Mfs; Method = 'Frequency Sampling'; % Part c
% hp = hpm; M = Mpm; Method = 'Parks McCllelan';% Part d

w = linspace(0,1,1000)*pi;
[Ha wt P2 L2] = amplresp(hp(:)',w);

% hfa = figconfg('P1063a','small');
```

```
hfa = figconfg('P1063a');
plot(w/pi,Ha,'linewidth',2);
ylim([-0.1 G4+0.2])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Amplitude Response','fontsize',TFS)
set(gca,'XTick',[0 ws1 wp1 wp2 ws2 ws3 wp3 pi]/pi)
set(gca,'YTick',[-deltas1 deltas1 G2-deltap1 G2+deltap1...
    G4-deltap2 G4+deltap2])
grid on

%% Part e:
legend([Method,', M = ',num2str(M)],'location','best')
ind = w <= ws1;
d1 = max(abs(Ha(ind)));
text(w(100)/pi,deltas1,['\delta_{s1} = ',num2str(d1,'%.3f')]...
    ,'HorizontalAlignment','center','verticalalignment',...
    'bottom','fontsize',LFS-4)
ind = (w>=wp1 & w <= wp2);
d2 = max(abs(Ha(ind)-G2));
text(w(350)/pi,G2+deltap1,['\delta_{p1} = ',num2str(d2,'%.3f')]...
    ,'HorizontalAlignment','center','verticalalignment',...
    'bottom','fontsize',LFS-4)
ind = (w>=ws2 & w <= ws3);
d3 = max(abs(Ha(ind)));
text(w(600)/pi,deltas1,['\delta_{s2} = ',num2str(d3,'%.3f')]...
    ,'HorizontalAlignment','center','verticalalignment',...
    'bottom','fontsize',LFS-4)
ind = w >= wp3;
d4 = max(abs(Ha(ind)-G4));
text(w(875)/pi,G4-deltap2,['\delta_{p2} = ',num2str(d4,'%.3f')]...
    ,'HorizontalAlignment','center','verticalalignment',...
    'top','fontsize',LFS-4)
ind1 = Ha>deltas1;
ind2 =  (w > ws1 & w < wp1);
ind = ind1(:) & ind2(:);
f1 = find(ind==1,1,'first')-1;
text(w(f1)/pi,deltas1,[' \omega_1 = ',...
    num2str(w(f1)/pi,'%.3f'),'\pi'],'fontsize',LFS-4,...
    'horizontal','left','verticalalignment','middle')
```

```
ind1 = Ha<G2-deltap1;
ind2 =  (w > ws1 & w < wp1);
ind = ind1(:) & ind2(:);
f2 = find(ind==1,1,'last')+1;
text(w(f2)/pi,G2-deltap1,[' \omega_2 = ',...
    num2str(w(f2)/pi,'%.3f'),'\pi'],'fontsize',LFS-4,...
    'horizontal','left','verticalalignment','top')
ind1 = Ha<G2-deltap1;
ind2 =  (w > wp2 & w < ws2);
ind = ind1(:) & ind2(:);
f3 = find(ind==1,1,'first')-1;
text(w(f3)/pi,G2-deltap1,[' \omega_3 = ',...
    num2str(w(f3)/pi,'%.3f'),'\pi'],'fontsize',LFS-4,...
    'horizontal','left','verticalalignment','top')
ind1 = Ha>deltas1;
ind2 =  (w > wp2 & w < ws2);
ind = ind1(:) & ind2(:);
f4 = find(ind==1,1,'last')+1;
text(w(f4)/pi,deltas1,[' \omega_4 = ',...
    num2str(w(f4)/pi,'%.3f'),'\pi'],'fontsize',LFS-4,...
    'horizontal','right','verticalalignment','middle')
ind1 = Ha>deltas1;
ind2 =  (w > ws3 & w < wp3);
ind = ind1(:) & ind2(:);
f5 = find(ind==1,1,'first')-1;
text(w(f5)/pi,deltas1,[' \omega_5 = ',...
    num2str(w(f5)/pi,'%.3f'),'\pi'],'fontsize',LFS-4,...
    'horizontal','left','verticalalignment','middle')
ind1 = Ha<G4-deltap2;
ind2 =  (w > ws3 & w < wp3);
ind = ind1(:) & ind2(:);
f6 = find(ind==1,1,'last')+1;
text(w(f6)/pi,G4-deltap2,[' \omega_6 = ',...
    num2str(w(f6)/pi,'%.3f'),'\pi'],'fontsize',LFS-4,...
    'horizontal','right','verticalalignment','top')
```

64. (a) See plot below.

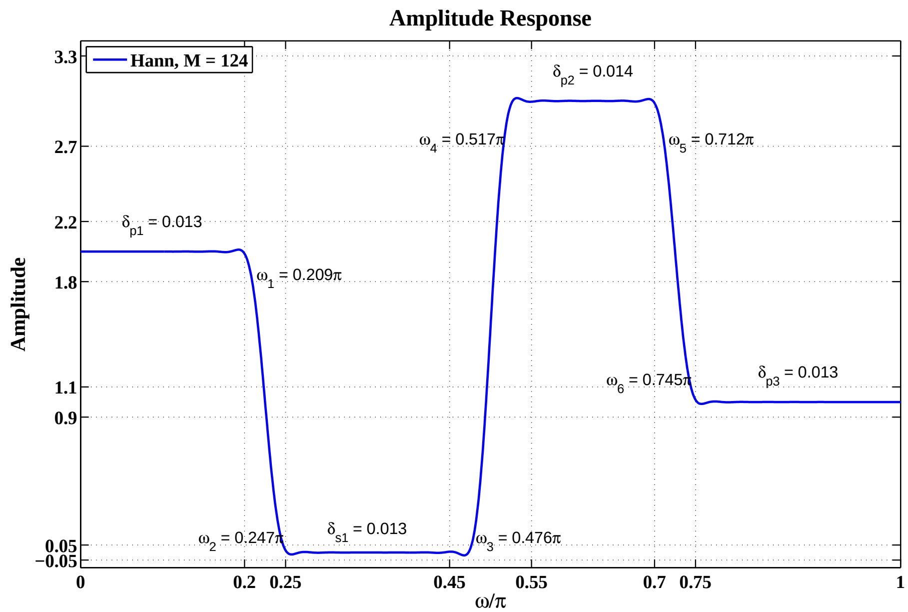


FIGURE 10.96: Amplitude response of FIR filter designed by Hann window in part (a).

(b) See plot below.

(c) See plot below.

(d) See plot below.

(e) Comment:
See each plot for reference.

MATLAB script:

```
% P1064: Multiband filter design; All methods
close all; clc
%% Specification:
wp1 = 0.2*pi; ws1 = 0.25*pi; ws2 = 0.45*pi;
wp2 = 0.55*pi; wp3 = 0.7*pi; wp4 = 0.75*pi;
G1 = 2; G2 = 0; G3 = 3; G4 = 1;
deltap1 = 0.2; deltas = 0.05; deltap2 = 0.3; deltap3 = 0.1;
delta = min([deltas deltap1 deltap2 deltap3]);
```

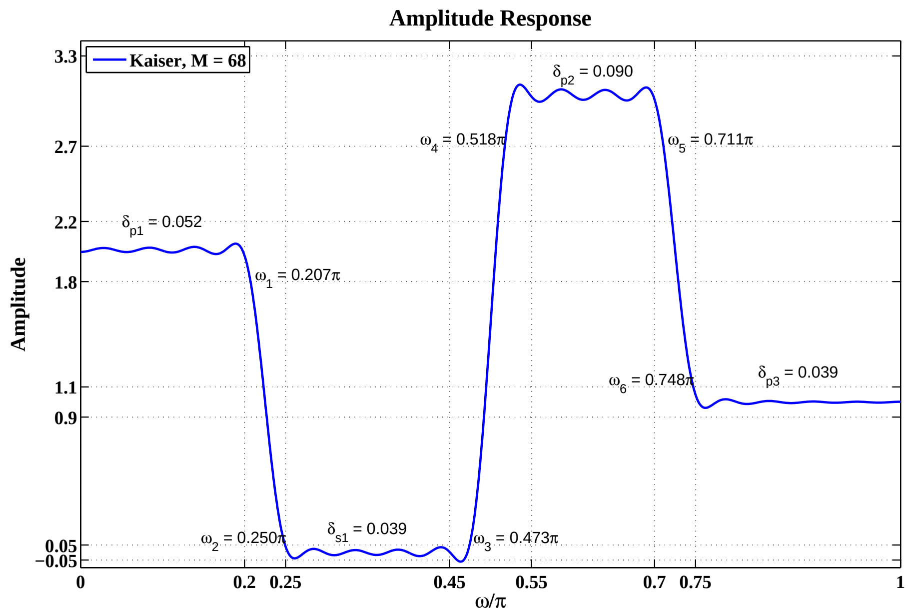


FIGURE 10.97: Amplitude response of FIR filter designed by Kaiser window in part (b).

```
A = -20*log10(delta);

wlp = (wp1+ws1)/2; wbp1 = (wp2+ws2)/2; wbp2 = (wp3+wp4)/2;
whp = wbp2;
delw = 0.05*pi;

%% Part a: Fixed window
L = ceil(6.2*pi/delw); Mfw = L - 1;
if mod(Mfw,2) == 1
    Mfw = Mfw + 1;
end
hfw1 = fir1(Mfw,wlp/pi,hann(Mfw+1));
hfw2 = fir1(Mfw,[wbp1 wbp2]/pi,'DC-0',hann(Mfw+1));
hfw3 = fir1(Mfw,whp/pi,'high',hann(Mfw+1));
hfw = G1*hfw1 + G3*hfw2 + G4*hfw3;

%% Part b: Kaiser window
```

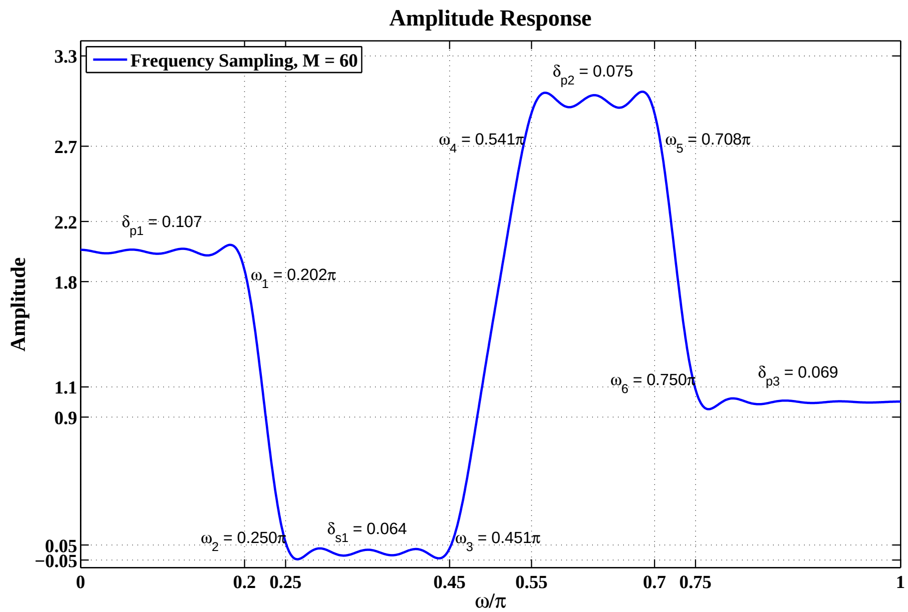


FIGURE 10.98: Amplitude response of FIR filter designed by frequency-sampling in part (c).

```
[Mk,wn,beta,ftype] = ...
  kaiserord([ws2 wp2 wp3 wp4]/pi,[0 1 0],...
  [deltas,deltap2,deltas/2]);
if mod(Mk,2)==1
    Mk = Mk + 1;
end
hkai1 = fir1(Mk,wlp/pi,kaiser(Mk+1,beta));
hkai2 = fir1(Mk,[wbp1 wbp2]/pi,'DC-0',kaiser(Mk+1,beta));
hkai3 = fir1(Mk,whp/pi,'high',kaiser(Mk+1,beta));
hkai = G1*hkai1 + G3*hkai2 + G4*hkai3;

%% Part c: Frequency sampling
% Mfs = 70;
Mfs = 60;
L = Mfs + 1;
hfs = fir2(Mfs,[0 wp1 ws1 ws2+0.005*pi wp2 wp3 wp4 pi]/pi,...
    [G1 G1 G2 G2 G3 G3 G4 G4],rectwin(L));
```

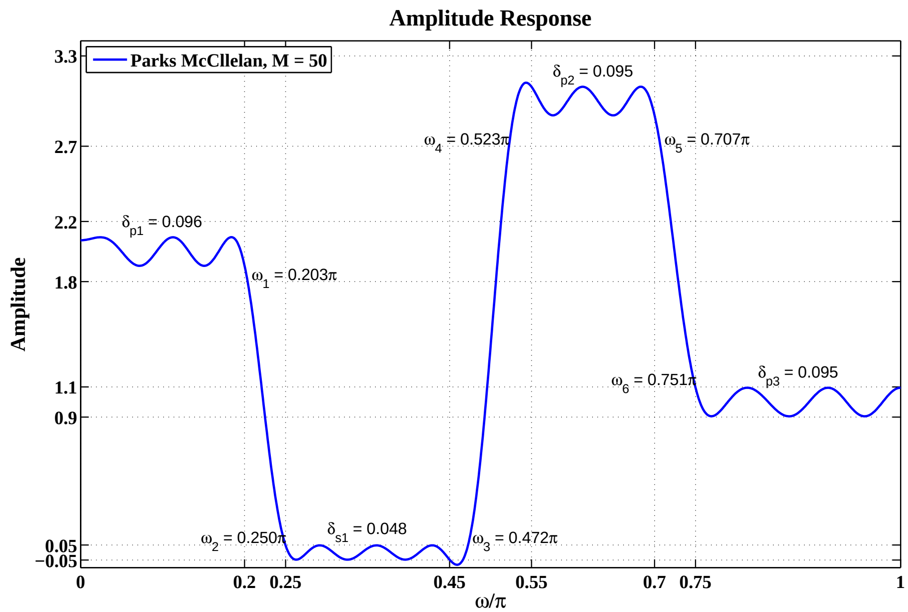


FIGURE 10.99: Amplitude response of FIR filter designed by Parks-McClellan in part (d).

```
%% Part d: Parks-McClellan
[Mpm,fo,ao,W] = firpmord([wp1,ws1,ws2,wp2,wp3,wp4]/pi,[G1,G2,G3,G4],...
    [deltap1,deltas, deltap2,deltap3]);
Mpm = Mpm + 14
[hpm,delta] = firpm(Mpm,fo,ao,W);
delta,
deltap1,

%% Plot:
hp = hfw; M = Mfw; Method = 'Hann'; % Part a
% hp = hkai; M = Mk; Method = 'Kaiser'; % Part b
% hp = hfs; M = Mfs; Method = 'Frequency Sampling'; % Part c
% hp = hpm; M = Mpm; Method = 'Parks McCllelan';% Part d

w = linspace(0,1,1000)*pi;
[Ha wt P2 L2] = amplresp(hp(:)',w);
```

```
hf = figconfg('P1064');
plot(w/pi,Ha,'linewidth',2);
ylim([-0.1 G3+0.4])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Amplitude','fontsize',LFS)
title('Amplitude Response','fontsize',TFS)
set(gca,'XTick',[0 wp1 ws1 ws2 wp2 wp3 wp4 pi]/pi)
set(gca,'YTick',[-deltas deltas G4-deltap3 G4+deltap3...
    G1-deltap1 G1+deltap1 G3-deltap2 G3+deltap2])
grid on

%% Part e:
legend([Method,', M = ',num2str(M)],'location','northwest')
ind = w <= wp1;
d1 = max(abs(Ha(ind)-G1));
text(w(100)/pi,G1+0.15,['\delta_{p1} = ',num2str(d1,'%.3f')]...
    ,'HorizontalAlignment','center','verticalalignment',...
    'middle','fontsize',LFS-4)
ind = (w>=ws1 & w <= ws2);
d2 = max(abs(Ha(ind)));
text(w(350)/pi,deltas,['\delta_{s1} = ',num2str(d2,'%.3f')]...
    ,'HorizontalAlignment','center','verticalalignment',...
    'bottom','fontsize',LFS-4)
ind = (w>=wp2 & w <= wp3);
d3 = max(abs(Ha(ind)-G3));
text(w(625)/pi,G3+0.15,['\delta_{p2} = ',num2str(d3,'%.3f')]...
    ,'HorizontalAlignment','center','verticalalignment',...
    'middle','fontsize',LFS-4)
ind = w >= wp4;
d4 = max(abs(Ha(ind)-G4));
text(w(875)/pi,G4+0.15,['\delta_{p3} = ',num2str(d4,'%.3f')]...
    ,'HorizontalAlignment','center','verticalalignment',...
    'middle','fontsize',LFS-4)

ind1 = Ha<G1-deltap1;
ind2 =  (w > wp1 & w < ws1);
ind = ind1(:) & ind2(:);
f1 = find(ind==1,1,'first')-1;
text(w(f1)/pi,G1-deltap1,[' \omega_1 = ',...
```

```
    num2str(w(f1)/pi,'%.3f'),'\pi'],'fontsize',LFS-4,...
    'horizontal','left','verticalalignment','middle')
ind1 = Ha>deltas;
ind2 =  (w > wp1 & w < ws1);
ind = ind1(:) & ind2(:);
f2 = find(ind==1,1,'last')+1;
text(w(f2)/pi,deltas,[' \omega_2 = ',...
    num2str(w(f2)/pi,'%.3f'),'\pi'],'fontsize',LFS-4,...
    'horizontal','right','verticalalignment','middle')
ind1 = Ha>deltas;
ind2 =  (w > ws2 & w < wp2);
ind = ind1(:) & ind2(:);
f3 = find(ind==1,1,'first')-1;
text(w(f3)/pi,deltas,[' \omega_3 = ',...
    num2str(w(f3)/pi,'%.3f'),'\pi'],'fontsize',LFS-4,...
    'horizontal','left','verticalalignment','middle')
ind1 = Ha<G3-deltap2;
ind2 =  (w > ws2 & w < wp2);
ind = ind1(:) & ind2(:);
f4 = find(ind==1,1,'last')+1;
text(w(f4)/pi,G3-deltap2,[' \omega_4 = ',...
    num2str(w(f4)/pi,'%.3f'),'\pi'],'fontsize',LFS-4,...
    'horizontal','right','verticalalignment','middle')
ind1 = Ha<G3-deltap2;
ind2 =  (w > wp3 & w < wp4);
ind = ind1(:) & ind2(:);
f5 = find(ind==1,1,'first')-1;
text(w(f5)/pi,G3-deltap2,[' \omega_5 = ',...
    num2str(w(f5)/pi,'%.3f'),'\pi'],'fontsize',LFS-4,...
    'horizontal','left','verticalalignment','middle')
ind1 = Ha>G4+deltap3;
ind2 =  (w > wp3 & w < wp4);
ind = ind1(:) & ind2(:);
f6 = find(ind==1,1,'last')+1;
text(w(f6)/pi,G4+deltap3,[' \omega_6 = ',...
    num2str(w(f6)/pi,'%.3f'),'\pi'],'fontsize',LFS-4,...
    'horizontal','right','verticalalignment','middle')
```