CHAPTER 12

Multirate Signal Processing

Tutorial Problems

1. (a) See script below.

   (b) See plot below.

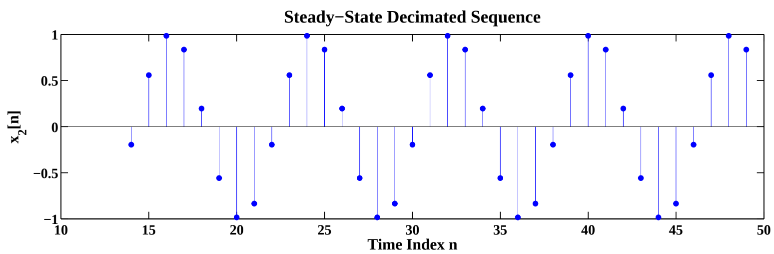

FIGURE 12.1: Steady-state values of $x_{\mathrm{D}}[n]$ computed by `src` function.

   (c) See plot below.

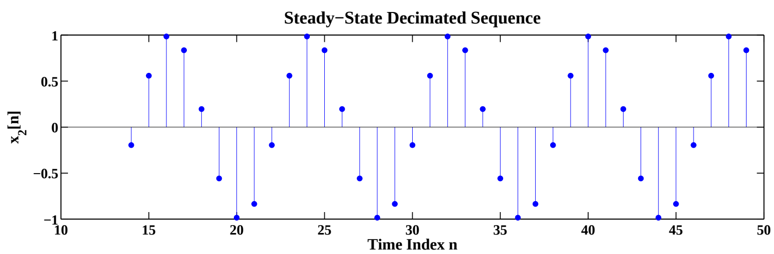

FIGURE 12.2: Steady-state values of $x_{\mathrm{D}}[n]$ computed by `firdec` function.

   (d) See plot below.

   (e) tba.

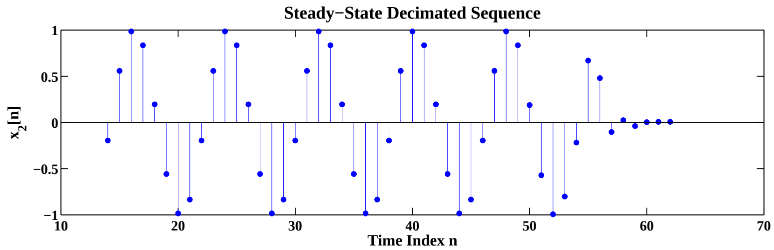

FIGURE 12.3: Steady-state values of $x_{\mathrm{D}}[n]$ computed by upfirdn function.

MATLAB script:

```
% P1201: Decimation functions comparison
close all; clc
N = 100;
n = 0:N-1;
om0 = 0.125*pi;
xn = sin(om0*n);
D = 2;
%% Part a: Lowpass filter
M = 25;
hn = firpm(M,[0 0.5 0.6 1],[1 1 0 0],[1 1]);
vn = filter(hn,1,xn);
%% Part b:
ynb = src(vn,D);
%% Part c:
ync = firdec(hn,xn,D);
%% Part d:
ynd = upfirdn(xn,hn,1,D);
%% Plot
yn = ynb; % part b
% yn = ync; % part c
% yn = ynd; % part d
hfa = figconfg('P1201a','long');
Lp = length(yn); Ls = 15;
stem(Ls-1:Lp-1,yn(Ls:end),'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel(['x_',num2str(D),'[n]'],'fontsize',LFS);
title('Steady-State Decimated Sequence','fontsize',TFS);
```

2. (a) Comments: tba.
   (b) Comments: tba.
3. (a) See script below.
   (b) See plot below.

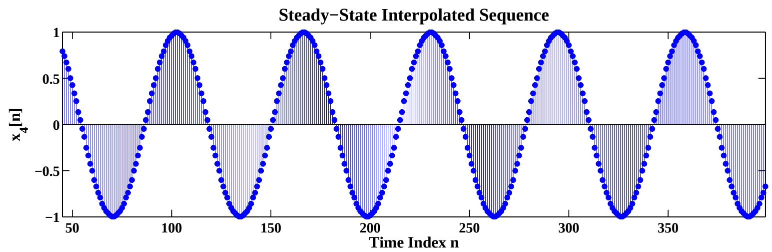

FIGURE 12.4: Steady-state values of $x_{\mathrm{I}}[n]$ computed by `sre` function.

   (c) See plot below.

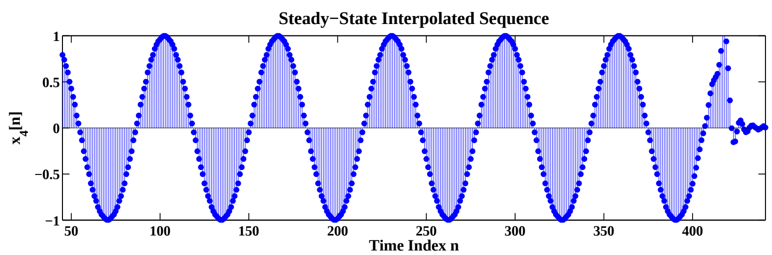

FIGURE 12.5: Steady-state values of $x_{\mathrm{I}}[n]$ computed by `upfirdn` function.

   (d) See plot below.

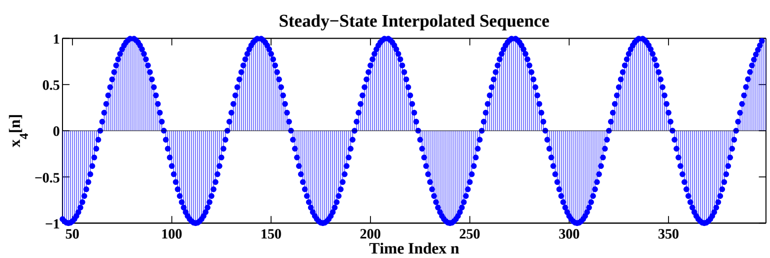

FIGURE 12.6: Steady-state values of $x_{\mathrm{I}}[n]$ computed by `interp` function.

   (e) tba.

MATLAB script:

```
% P1203: Interpolation functions comparison
close all; clc
N = 100;
n = 0:N-1;
om0 = 0.125*pi;
xn = sin(om0*n);
I = 4;
%% Part a: Lowpass filter
M = 45;
hn = firpm(M,[0 0.25 0.35 1],[1 1 0 0],[1 1]);
hn = hn*I;
w = linspace(0,1,501)*pi;
H = freqz(hn,1,w); Hmag = abs(H);
figure, plot(w/pi,Hmag)
vn = sre(xn,I);
%% Part b:
ynb = filter(hn,1,vn);
%% Part c:
ync = upfirdn(xn,hn,I,1);
%% Part d:
ynd = interp(xn,I);
%% Plot
% yn = ynb; % part b
% yn = ync; % part c
yn = ynd; % part d
hfa = figconfg('P1203a','long');
Lp = length(yn); Ls = length(hn);
stem(Ls-1:Lp-1,yn(Ls:end),'filled')
ylim([-1 1]); xlim([Ls-1 Lp-1])
xlabel('Time Index n','fontsize',LFS);
ylabel(['x_',num2str(I),'[n]'],'fontsize',LFS);
title('Steady-State Interpolated Sequence','fontsize',TFS);
```

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

   MATLAB script:

```
% P1204: Interpolation function "interp"
close all; clc
```

```
n = 0:50;
xn = cos(0.9*pi*n);
I = 2;
% I = 4;
% I = 8;
[yn b] = interp(xn,I);
%% Plot
hfa = figconfg('P1204a','long');
stem(n,xn,'filled')
ylim([-1 1]);
xlabel('Time Index n','fontsize',LFS);
ylabel('x[n]','fontsize',LFS);
title('Original Sequence','fontsize',TFS);

hfb = figconfg('P1204b','long');
stem(0:length(yn)-1,yn,'filled')
ylim([-1 1]); xlim([0 50*I])
xlabel('Time Index n','fontsize',LFS);
ylabel(['x_',num2str(I),'[n]'],'fontsize',LFS);
title('Interpolated Sequence','fontsize',TFS);

w = linspace(0,1,501)*pi;
H = freqz(b,1,w); Hmag = abs(H);
hfc = figconfg('P1204c','small');
plot(w/pi,Hmag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
```

5. (a) See plot below.
   (b) See plot below.
   (c) See plot below.
   (d) See plot below.
   (e) tba.

   MATLAB script:

```
% P1205: Interpolation; Frequency Investigation
close all; clc
L = 101; M = L - 1;
```

```
xn = fir2(M,[0,0.1,0.2,0.5,0.55,0.6,1],[2,2,1.5,1,0.5,0,0]);
w = linspace(0,1,501)*pi;
Hx = freqz(xn,1,w); Hxmag = abs(Hx);
I = 2;
% I = 3;
% I = 4;
yn = interp(xn,I);
Hy = freqz(yn,1,w); Hymag = abs(Hy);
%% Plot
hfa = figconfg('P1205a','small');
plot(w/pi,Hxmag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
hfb = figconfg('P1205b','small');
plot(w/pi,Hymag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
```

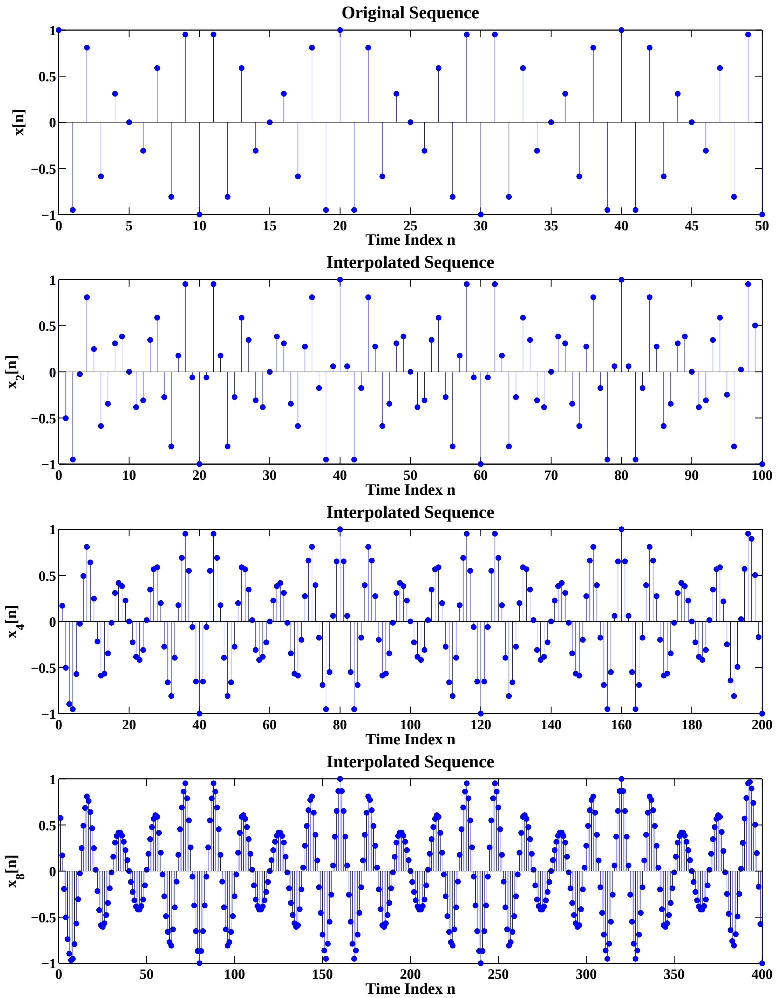

FIGURE 12.7: Original signal $x[n]$ and interpolated signal using $I = 2$, $I = 4$ and $I = 8$.

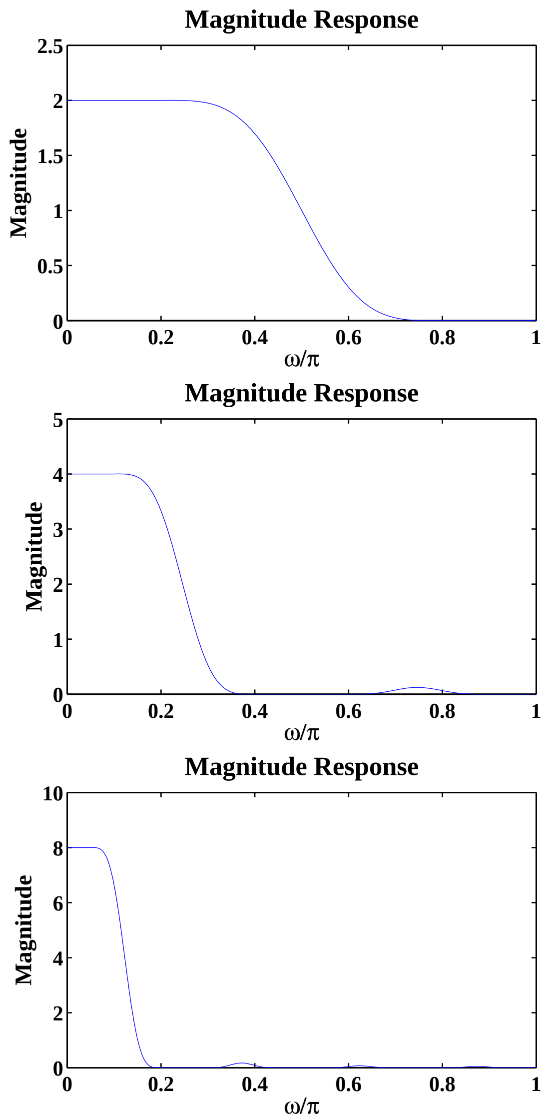

FIGURE 12.8: Magnitude response of the lowpass filter when $I = 2$, $I = 4$ and $I = 8$.

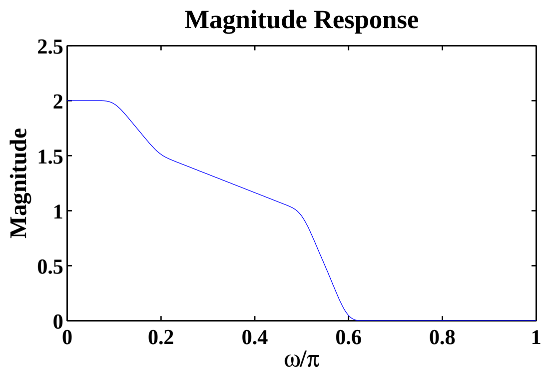

FIGURE 12.9: Magnitude spectra of $x[n]$.

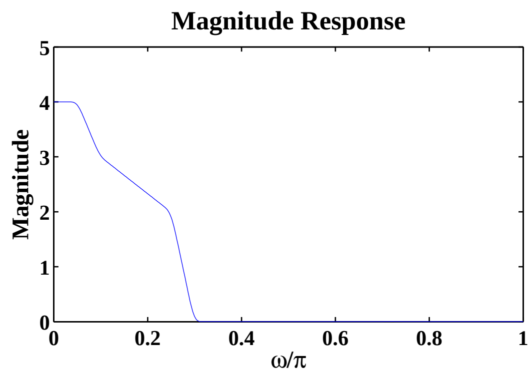

FIGURE 12.10: Magnitude spectra of the decimated signal by $I = 2$.

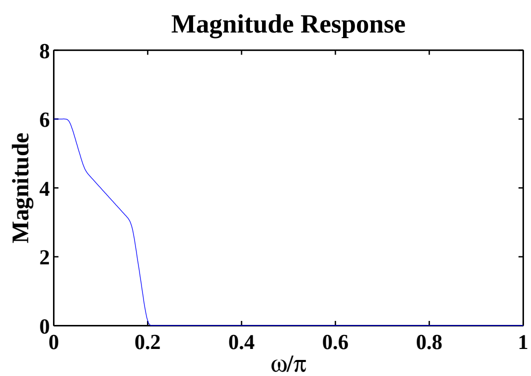

FIGURE 12.11: Magnitude spectra of the decimated signal by $I = 3$.

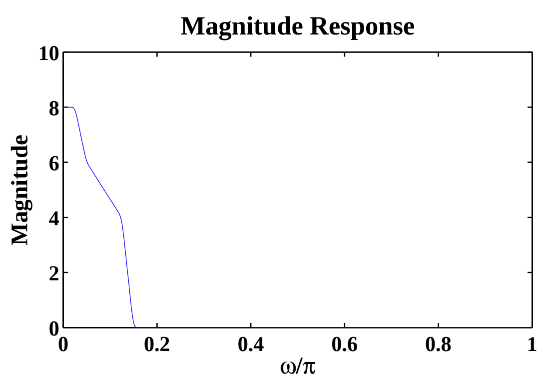

FIGURE 12.12: Magnitude spectra of the decimated signal by $I = 4$.

6. Solution:

We can express a similar convolution summation given in (12.44) as:

$$x_{\mathrm{I}}[n] = \sum_{k=-\infty}^{\infty} x_{\mathrm{u}}[k] g_{\mathrm{lin}}[n-k]$$

A brief verification is as follows:

$$\begin{aligned}
x_{\mathrm{I}}[(m-1)I+k] &= \sum_{p=-\infty}^{\infty} x_{\mathrm{u}}[pI] g_{\mathrm{lin}}[(m-1)I+k-pI] \\
&= x_{\mathrm{u}}[(m-1)I] g_{\mathrm{lin}}[k] + x_{\mathrm{u}}[mI] g_{\mathrm{lin}}[-I+k] \\
&= x_{\mathrm{u}}[(m-1)I]\left(1-\frac{|k|}{I}\right) + x_{\mathrm{u}}[mI]\left(1-\frac{|-I+k|}{I}\right) \\
&= x_{\mathrm{u}}[(m-1)I]\left(1-\frac{k}{I}\right) + x_{\mathrm{u}}[mI]\left(\frac{k}{I}\right) \quad k = 0, 1, \ldots, I-1
\end{aligned}$$

7. (a) See plot below.

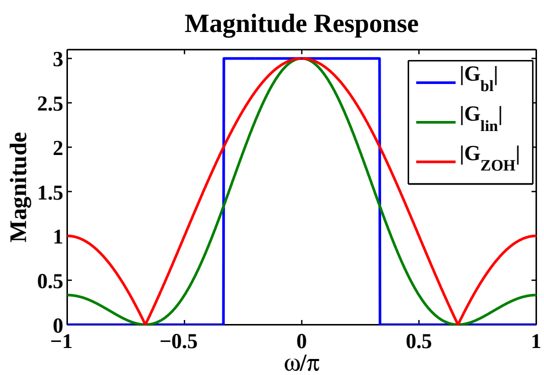

FIGURE 12.13: Magnitude responses of the ideal, ZOH, and FOH interpolators for $I = 3$.

(b) See plot below.

MATLAB script:

```
% P1207: Zero-order-hold (ZOH) Interpretor
close all; clc
w = linspace(-1,1,1001)*pi;
I = 3; % Part a
```

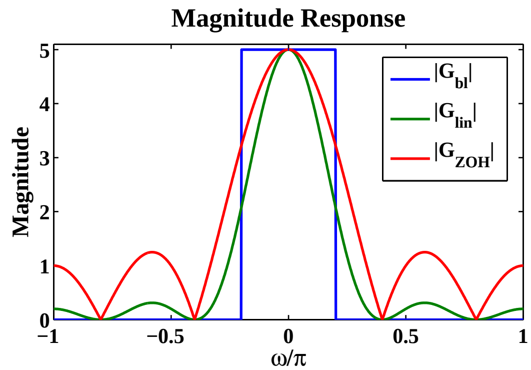

FIGURE 12.14: Magnitude responses of the ideal, ZOH, and FOH interpolators for $I = 5$.

```
% I = 5; % Part b
G_bl = zeros(size(w));
ind = (abs(w) <= pi/I);
G_bl(ind) = I; magG_bl = abs(G_bl);
G_lin = (sin(w*I/2)./sin(w/2)).^2/I;
magG_lin = abs(G_lin);
G_zoh = (1-exp(-1j*I*w))./(1-exp(-1j*w));
magG_zoh = abs(G_zoh);
%% Plot:
hfa = figconfg('P1207a','small');
plot(w/pi,[magG_bl;magG_lin;magG_zoh],'linewidth',2)
ylim([0 I+0.1])
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
legend('|G_{bl}|','|G_{lin}|','|G_{ZOH}|','location','best')
```

8. (a) See plot below.

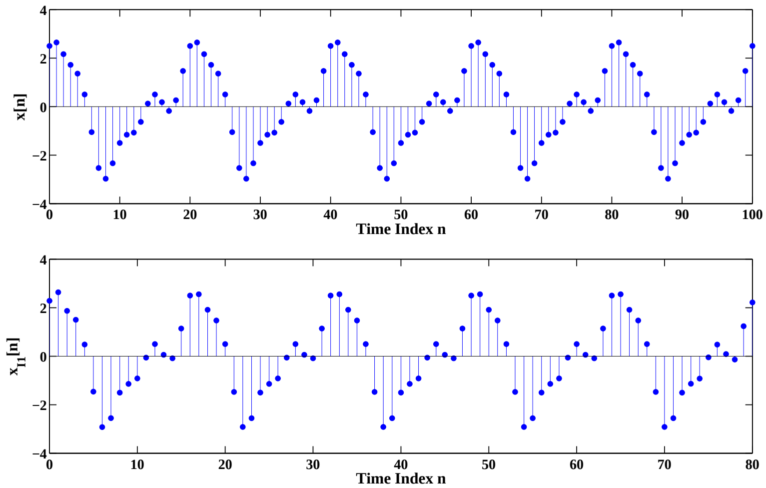

FIGURE 12.15: Stem plots of sequence $x[n]$ and resampled sequence $x_{I_1}[m]$.

(b) See plot below.

(c) See plot below.

(d) Comments:
Upsampled sequence $x_{I_2}[m]$ retains the "shape" of the original sequence $x[n]$.

MATLAB script:

```
% P1208: Illustrating function "resample"
close all; clc
n = 0:100;
xn = 2*cos(0.1*pi*n) + sin(0.2*pi*n) + 0.5*cos(0.4*pi*n);
xI1 = resample(xn,4,5); % Part a
xI2 = resample(xn,5,4); % Part b
xI3 = resample(xn,2,3); % Part c
%% Plot
hfa = figconfg('P1208a','long');
stem(n,xn,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel('x[n]','fontsize',LFS);

hfb = figconfg('P1208b','long');
```

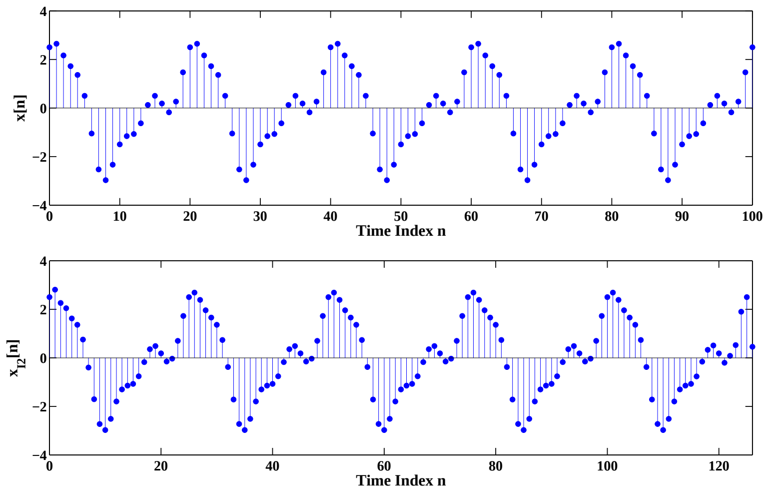

FIGURE 12.16: Stem plots of sequence $x[n]$ and resampled sequence $x_{\mathrm{I}_2}[m]$.

```
stem(0:length(xI1)-1,xI1,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel('x_{I1}[n]','fontsize',LFS);
xlim([0 length(xI1)-1])

hfc = figconfg('P1208c','long');
stem(0:length(xI2)-1,xI2,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel('x_{I2}[n]','fontsize',LFS);
xlim([0 length(xI2)-1])

hfd = figconfg('P1208d','long');
stem(0:length(xI3)-1,xI3,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel('x_{I3}[n]','fontsize',LFS);
xlim([0 length(xI3)-1])
```

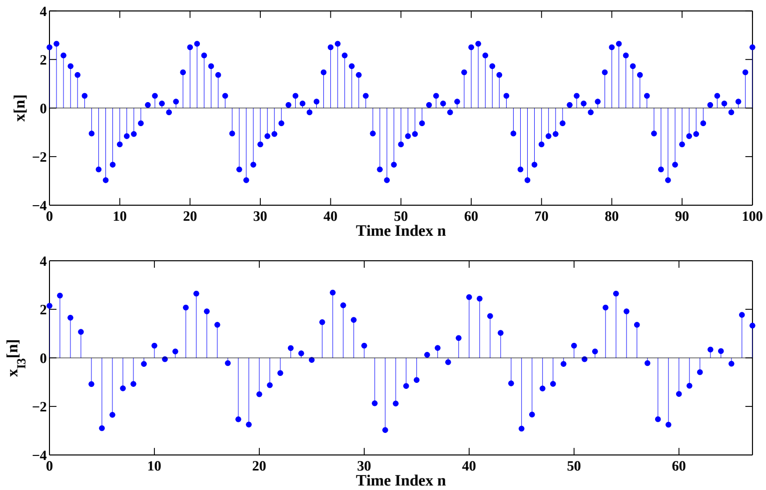

FIGURE 12.17: Stem plots of sequence $x[n]$ and resampled sequence $x_{\mathrm{I}_3}[m]$.

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

   MATLAB script:

```
% P1209: Decimation recovered by Interpolation
close all; clc
n = 0:80;
xn = cos(0.04*pi*n) + 3*sin(0.0072*pi*n);
% D = 3; I = 3;
% D = 5; I = 5;
D = 10; I = 10;
xd = downsample(xn,D);
xu = upsample(xd,I);
glin = 1:I-1; glin = [glin I fliplr(glin)]/I;
xi = filter(glin,1,xu);
%% Plot:
hfa = figconfg('P1209a','long');
stem(0:length(xn)-1,xn,'filled');
xlim([0 length(xn)-1])
xlabel('Time Index n','fontsize',LFS);
ylabel('x[n]','fontsize',LFS);
```

```
hfb = figconfg('P1209b','long');
stem(0:length(xd)-1,xd,'filled');
xlim([0 length(xd)-1])
xlabel('Time Index n','fontsize',LFS);
ylabel('x_d[n]','fontsize',LFS);

hfc = figconfg('P1209c','long');
stem(0:length(xu)-1,xu,'filled');
xlim([0 length(xu)-1])
xlabel('Time Index n','fontsize',LFS);
ylabel('x_u[n]','fontsize',LFS);

hfd = figconfg('P1209d','long');
stem(0:length(xi)-1,xi,'filled');
xlim([0 length(xi)-1])
xlabel('Time Index n','fontsize',LFS);
ylabel('x_i[n]','fontsize',LFS);
```

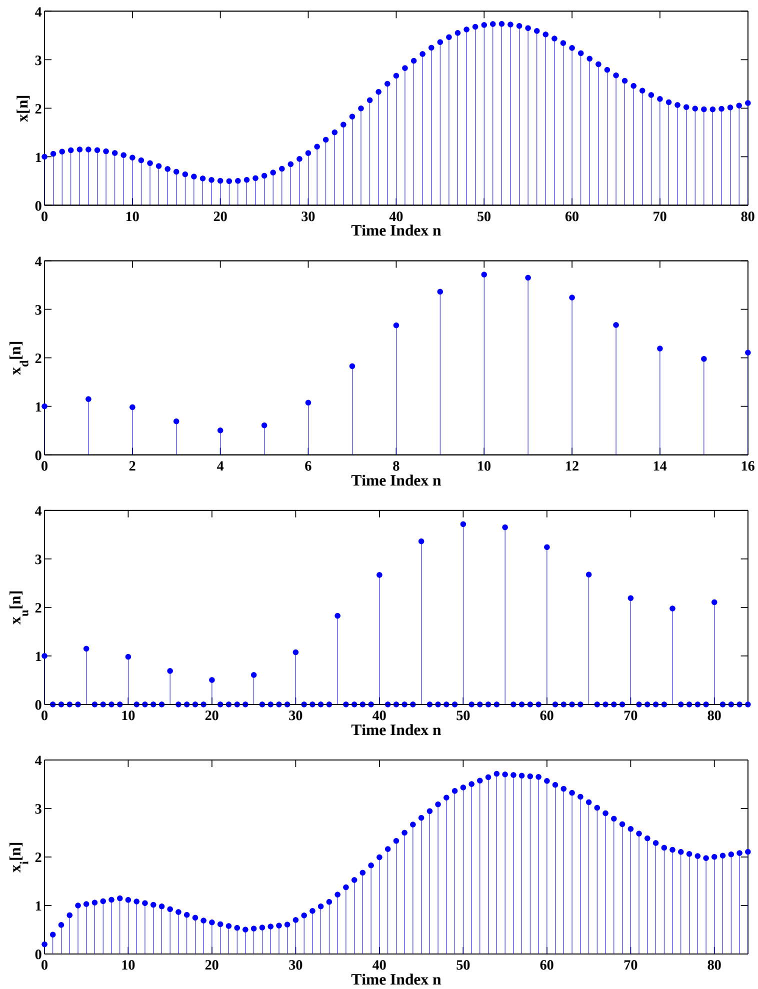

FIGURE 12.18: Stem plots of sequence $x[n]$, $x_d[n]$, $x_u[n]$ and $x_i[n]$ for $D = I = 5$.

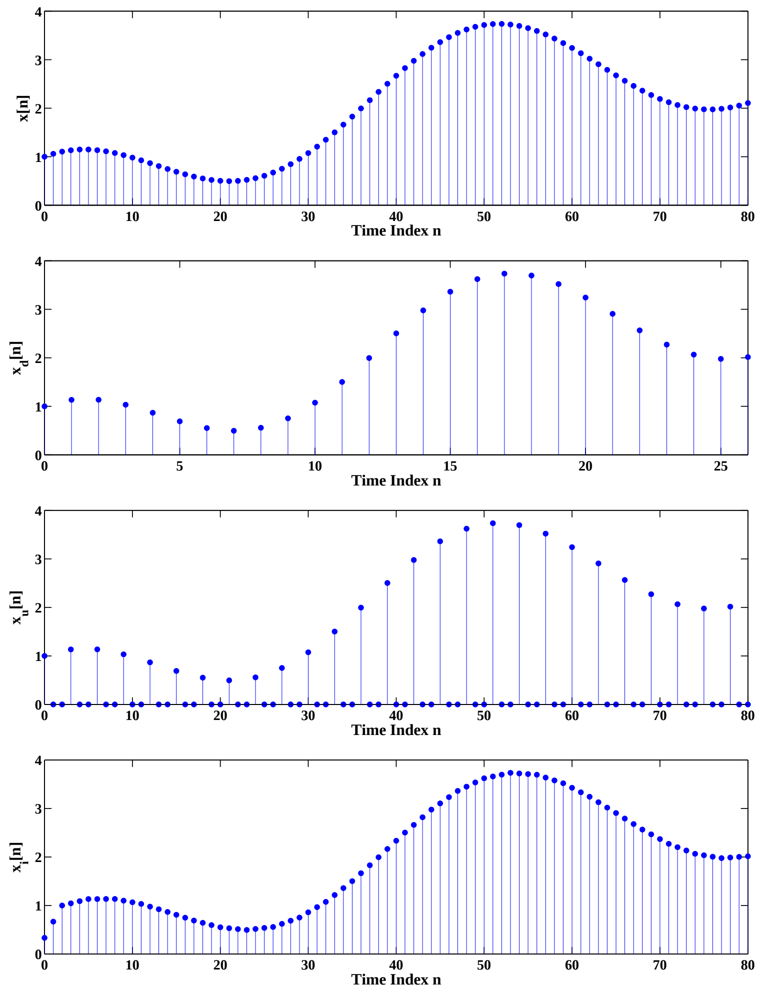

FIGURE 12.19: Stem plots of sequence $x[n]$, $x_d[n]$, $x_u[n]$ and $x_i[n]$ for $D = I = 3$.

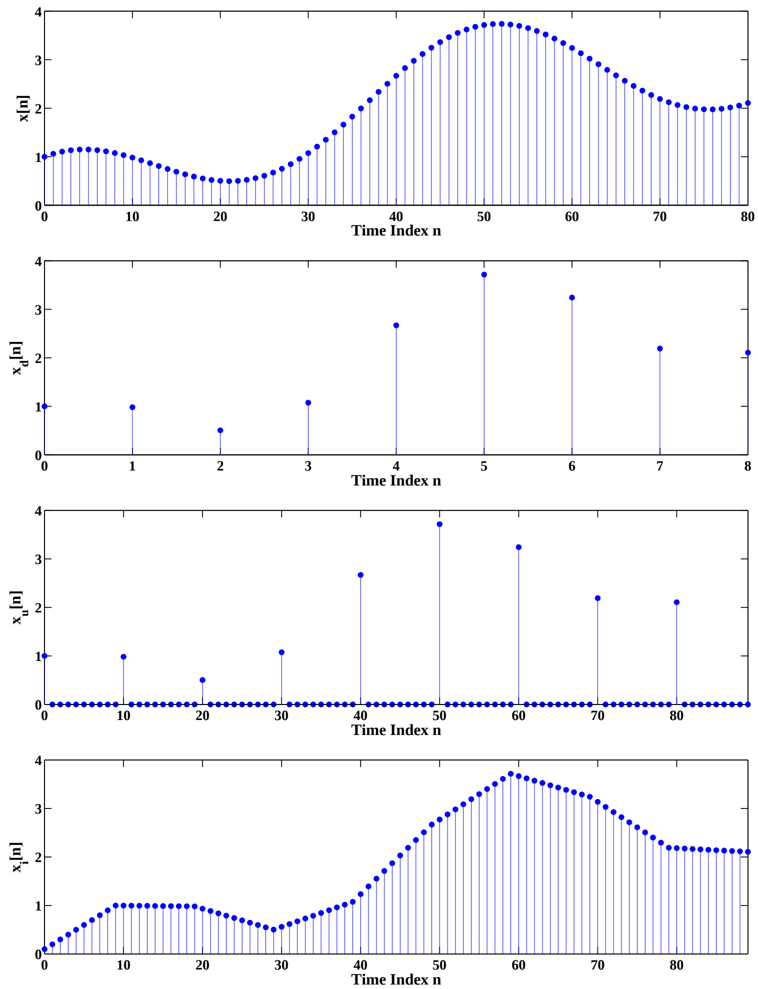

FIGURE 12.20: Stem plots of sequence $x[n]$, $x_d[n]$, $x_u[n]$ and $x_i[n]$ for $D = I = 5$.

10. Proof:

Given (12.89), that is

$$H(z) = \frac{1}{K} + \sum_{k=1}^{K-1} z^{-k} P_k\left(z^K\right)$$

we have

$$\begin{aligned} H\left(zW_K^p\right) &= \frac{1}{K} + \sum_{k=1}^{K-1} \left(zW_K^p\right)^{-k} P_k\left((zW_K^p)^K\right) \\ &= \frac{1}{K} + \sum_{k=1}^{K-1} z^{-k} W_K^{p-k} P_k(z^K) \end{aligned}$$

Hence,

$$\begin{aligned} \sum_{p=0}^{K-1} H\left(zW_K^p\right) &= \sum_{p=0}^{K-1} \left(\frac{1}{K} + \sum_{k=1}^{K-1} z^{-k} W_K^{p-k} P_k(z^K)\right) \\ &= \sum_{p=0}^{K-1} \frac{1}{K} + \sum_{p=0}^{K-1}\sum_{k=1}^{K-1} z^{-k} W_K^{p-k} P_k(z^K) \\ &= 1 + \sum_{k=1}^{K-1} z^{-k} W_K^{-k} P_k(z^K) \left(\sum_{p=0}^{K-1} W_K^p\right) \\ &= 1 \end{aligned}$$

Substitute $z = \mathrm{e}^{\mathrm{j}\omega}$, $W_K = \mathrm{e}^{-\mathrm{j}2\pi/K}$ into (12.90), we have

$$\sum_{k=0}^{K-1} H\left(\mathrm{e}^{\mathrm{j}\omega} \cdot \mathrm{e}^{-\mathrm{j}\frac{2\pi}{K}k}\right) = \sum_{k=0}^{K-1} H\left(\mathrm{e}^{\mathrm{j}(\omega - \frac{2k\pi}{K})}\right) = 1$$

11. Solution:

Step I:

Suppose $I = I_1 I_2$. A single interpolation of I can be implemented by a two stage process of I_1 and I_2, that is

$$x[n] \longrightarrow \boxed{\uparrow I_1} \longrightarrow \boxed{H_1(z)} \longrightarrow \boxed{\uparrow I_2} \longrightarrow \boxed{H_2(z)} \longrightarrow x_{\mathrm{I}}[n]$$

where $\omega_c^{(1)} = \pi/I_1$ of $H_1(z)$, and $\omega_c^{(2)} = \pi/I_2$ of $H_2(z)$.

Step II:

Interchange the order of lowpass filters $H_1(z)$ and upsampler $\uparrow I_2$ by the multirate identity for the sampling. We obtain that

$$x[n] \longrightarrow \boxed{\uparrow I_1} \longrightarrow \boxed{\uparrow I_2} \longrightarrow \boxed{H_1(z^{I_2})} \longrightarrow \boxed{H_2(z)} \longrightarrow x_{\mathrm{I}}[n]$$

Step III:
Combining the two upsamplers and two filters yields the equivalent single-stage interpolator as follows. The equivalent single-stage interpolator has a factor of $I = I_1 I_2$ and a lowpass filter with system function $H(z) = H_1(z^{I_2})H_2(z)$.

$$x[n] \longrightarrow \boxed{\uparrow (I_1 I_2)} \longrightarrow \boxed{H(z)} \longrightarrow x_{\mathrm{I}}[n]$$

12. See plot below

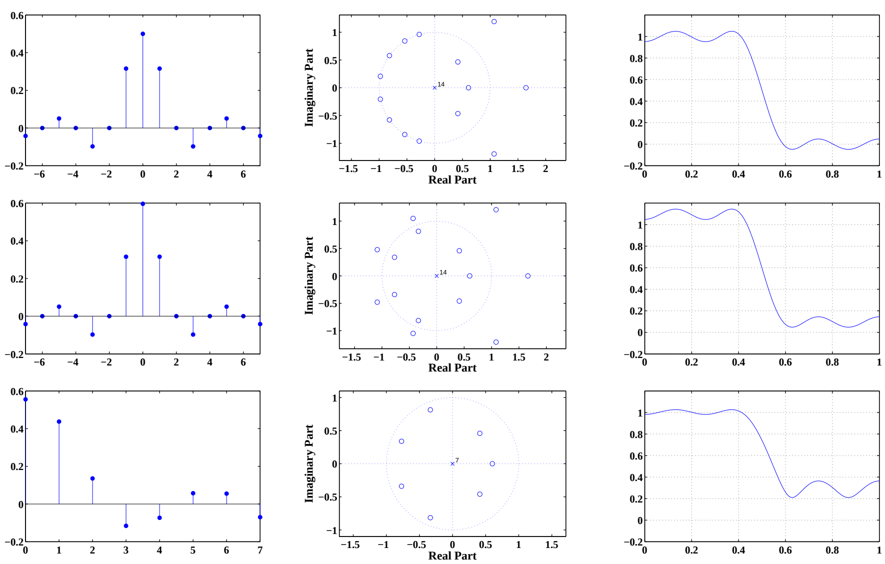

FIGURE 12.21: Illustration of the modified design process for conjugate quadrature filter banks using the Parks-McClellan algorithm.

13. (a) $I = 2$, and $D = 3$.
    (b) tba
    (c) tba
    (d) tba

14. Solution:
    Complexity:
    (1) The upsamplers of the two structure are of the same complexity.
    (2) $H(z)$ and $H(z^I)$ has same number of nonzero coefficients if we omit the multiplications by zero which is trivial.
    Hence, the two structures have the same complexity.

    Rate:
    (1) Figure 12.25(a) has I time higher rate after upsampler before subband filter and adders.
    (2) Figure 12.25(b) only takes higher rate before adders.

15. tba

16. tba

17. Solution:

$$H(z) = \sum_{m=0}^{3} z^{-m} P_m(z^4)$$

$$P_m(z) = \sum_{n=0}^{\infty} p_k[4n+m] z^{-n}$$

$$H_k(z) = \sum_{m=0}^{3} z^{-m} W_4^{-km} P_m(z^4 W_4^{4k}) = \sum_{m=0}^{3} z^{-m} W_4^{-km} P_m(z^4)$$

$$\begin{bmatrix} H_0(z) \\ H_1(z) \\ H_2(z) \\ H_3(z) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & W_4^1 & W_4^2 & W_4^3 \\ 1 & W_4^2 & W_4^4 & W_4^6 \\ 1 & W_4^3 & W_4^6 & W_4^9 \end{bmatrix} \begin{bmatrix} P_0(z^4) \\ z^{-1}P_1(z^4) \\ z^{-2}P_2(z^4) \\ z^{-3}P_3(z^4) \end{bmatrix}$$

    The plot will be available shortly.

18. tba

Basic Problems

19. (a) See plot below.

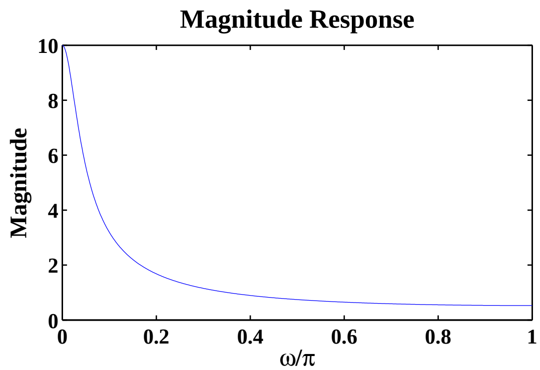

FIGURE 12.22: Magnitude spectra of $x[n]$.

(b) See plot below.

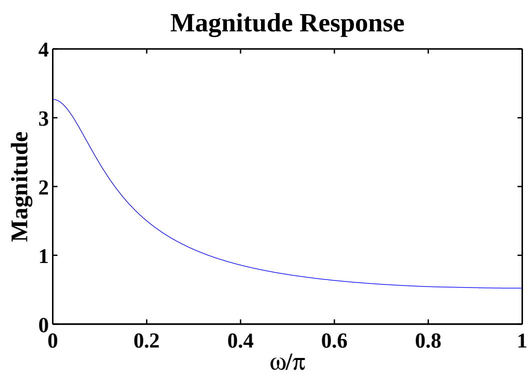

FIGURE 12.23: Magnitude spectra of $x_{\mathrm{D}}[n]$.

(c) tba.

MATLAB script:

```
% P1219: Decimation; Frequency Investigation
close all; clc
L = 101; n = 0:L-1;
xn = 0.9.^n;
w = linspace(0,1,501)*pi;
```

```
Hx = freqz(xn,1,w); Hxmag = abs(Hx);
D = 3;
yn = decimate(xn,D);
Hy = freqz(yn,1,w); Hymag = abs(Hy);
%% Plot
hfa = figconfg('P1219a','small');
plot(w/pi,Hxmag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
hfb = figconfg('P1219b','small');
plot(w/pi,Hymag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
```

20. Solution:

$$y[n] = \sum_{m=-\infty}^{\infty} x[3m]g_{\mathrm{r}}[n-5m]$$

21. (a) See plot below.
    (b) $x[n] = \cos(0.3\pi n)$, $0 \le n \le 60$, $D = 3$, $k = 0$, and $k = 1$.
    (c) See plot below.
    (d) See plot below.
    (e) See plot below.

    MATLAB script:

```
% P1221: Illustrating function "downsample"
close all; clc
%% Part a:
n = 0:50; D = 4;
k = 0;
% k = 2;
xn = sin(0.2*pi*n);

%% Part b:
% n = 0:60; D = 3;
```

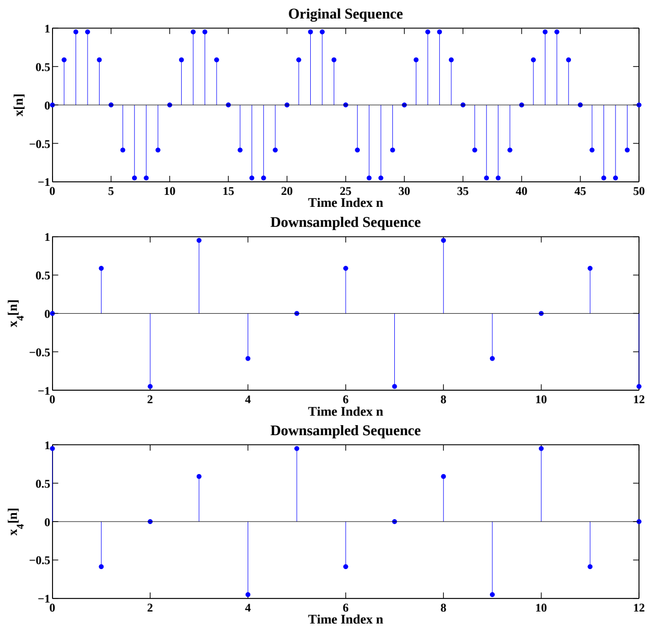

FIGURE 12.24: Stem plots of $x[n] = \sin(0.2\pi n)$ and downsampled sequences for $D = 4$, $k = 0$, and $k = 2$.

```
% k = 0;
% % k = 1;
% xn = cos(0.3*pi*n);

%% Part c:
% n = 0:100; D = 5;
% k = 0;
% % k = 3;
% xn = 0.2*n;

%% Part d:
% n = 0:32; D = 4;
% k = 0;
% % k = 2;
% xn = sin(0.25*pi*n);

%% Part e:
% n = 0:100; D = 2;
```

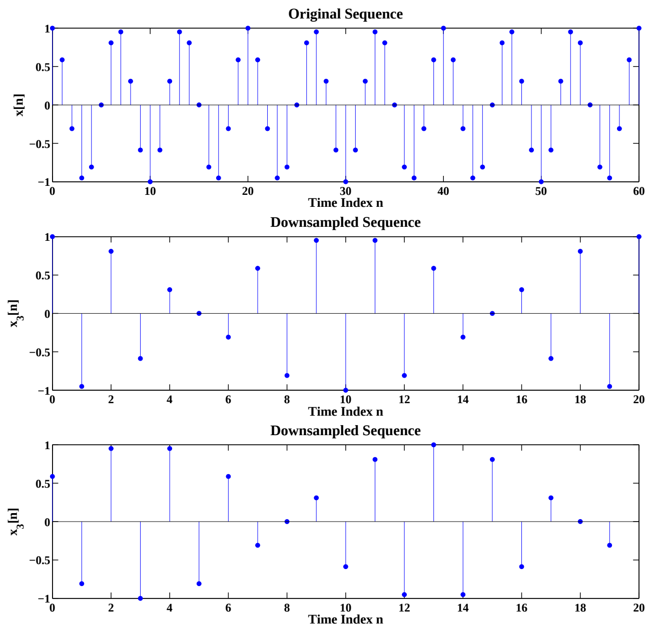

FIGURE 12.25: Stem plots of $x[n] = \cos(0.3\pi n)$ and downsampled sequences for $D = 3$, $k = 0$, and $k = 1$.

```
% k = 1;
% xn = 1 - cos(0.25*pi*n);

yn = downsample(xn,D,k);
%% Plot
hfa = figconfg('P1221a','long');
stem(n,xn,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel('x[n]','fontsize',LFS);
title('Original Sequence','fontsize',TFS);
hfb = figconfg('P1221b','long');
stem(0:length(yn)-1,yn,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel(['x_',num2str(D),'[n]'],'fontsize',LFS);
title('Downsampled Sequence','fontsize',TFS);
```

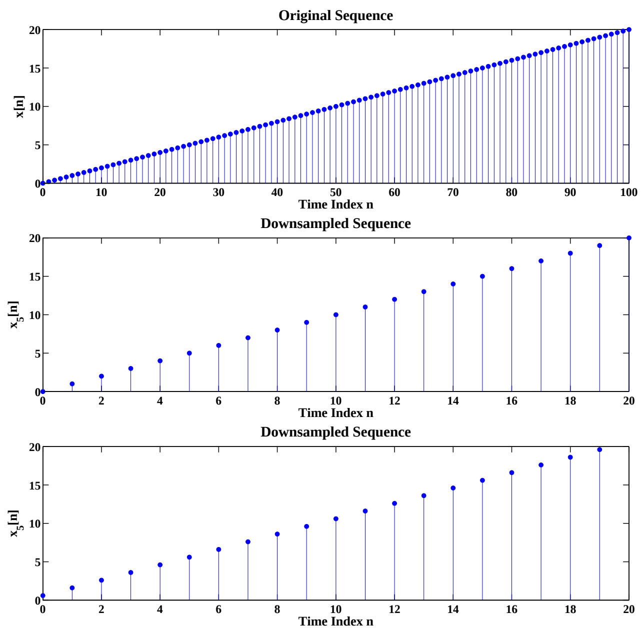

FIGURE 12.26: Stem plots of $x[n] = 0.2n$ and downsampled sequences for $D = 5$, $k = 0$, and $k = 3$.

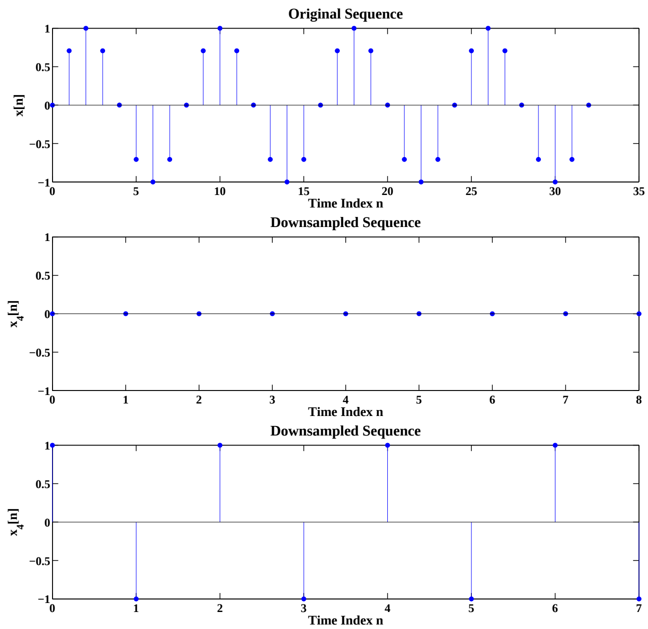

FIGURE 12.27: Stem plots of $x[n] = \sin(0.25\pi n)$ and downsampled sequences for $D = 4$, $k = 0$, and $k = 2$.

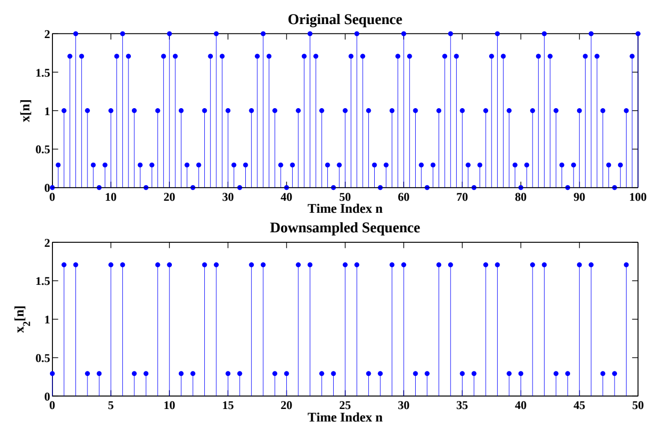

FIGURE 12.28: Stem plots of $x[n] = 1 - \cos(0.6\pi n)$ and downsampled sequences for $D = 2$, $k = 1$.

22. (a) See plot below.

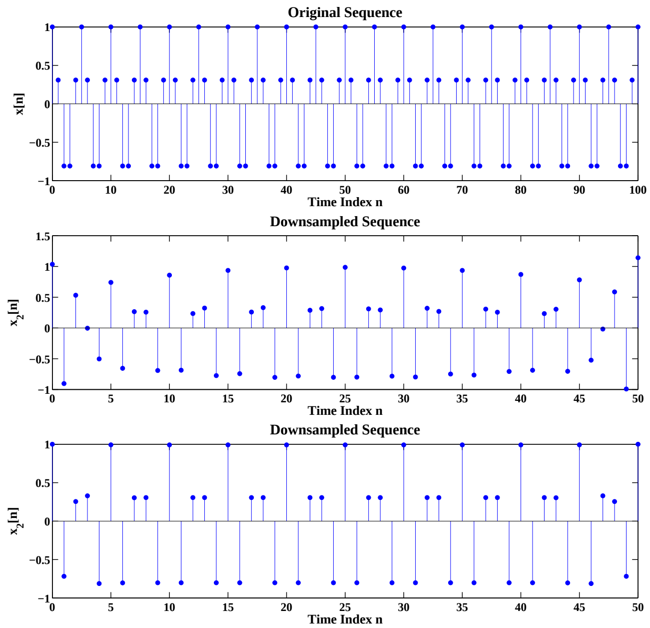

FIGURE 12.29: Stem plots of $x[n] = \cos(0.4\pi n)$ and downsampled sequences for $D = 2$ using both the default IIR and FIR decimation filters.

(b) See plot below.

(c) See plot below.

(d) See plot below.

(e) See plot below.

MATLAB script:

```
% P1222: Illustrating function "decimate"
close all; clc
%% Part a:
n = 0:100; D = 2;
xn = cos(0.4*pi*n);

%% Part b:
% n = 0:100; D = 3;
% xn = sin(0.15*pi*n);
```

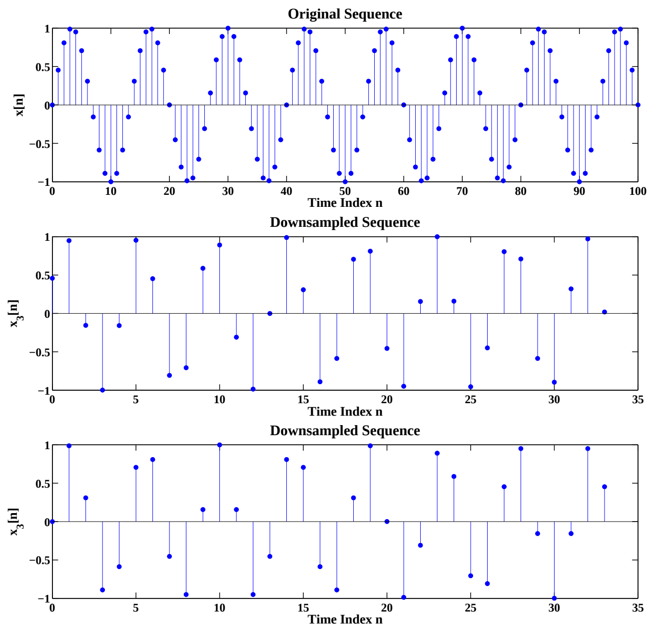

FIGURE 12.30: Stem plots of $x[n] = \sin(0.15\pi n)$ and downsampled sequences for $D = 3$ using both the default IIR and FIR decimation filters.

```
%% Part c:
% n = 0:150; D = 5;
% xn = cos(0.05*pi*n) + 2*sin(0.001*pi*n);

%% Part d:
% n = 0:100; D = 4;
% xn = cos(0.25*pi*n);

%% Part e:
% n = 0:100; D = 5;
% xn = 1 - sin(0.01*pi*n);

yn = decimate(xn,D); % default IIR
% yn = decimate(xn,D,'fir'); % default FIR
%% Plot
hfa = figconfg('P1222a','long');
stem(n,xn,'filled')
xlabel('Time Index n','fontsize',LFS);
```

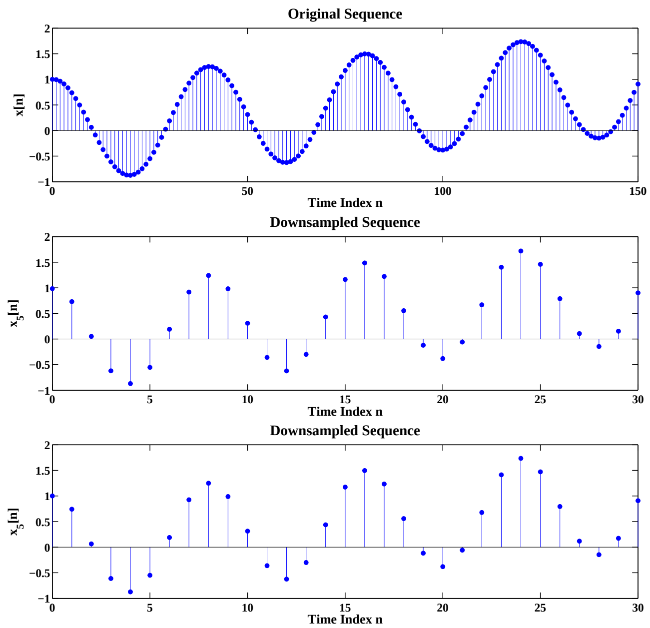

FIGURE 12.31: Stem plots of $x[n] = \cos(0.05\pi n) + 2\sin 0.001\pi n$ and downsampled sequences for $D = 5$ using both the default IIR and FIR decimation filters.

```
ylabel('x[n]','fontsize',LFS);
title('Original Sequence','fontsize',TFS);

hfb = figconfg('P1222b','long');
stem(0:length(yn)-1,yn,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel(['x_',num2str(D),'[n]'],'fontsize',LFS);
title('Downsampled Sequence','fontsize',TFS);
```

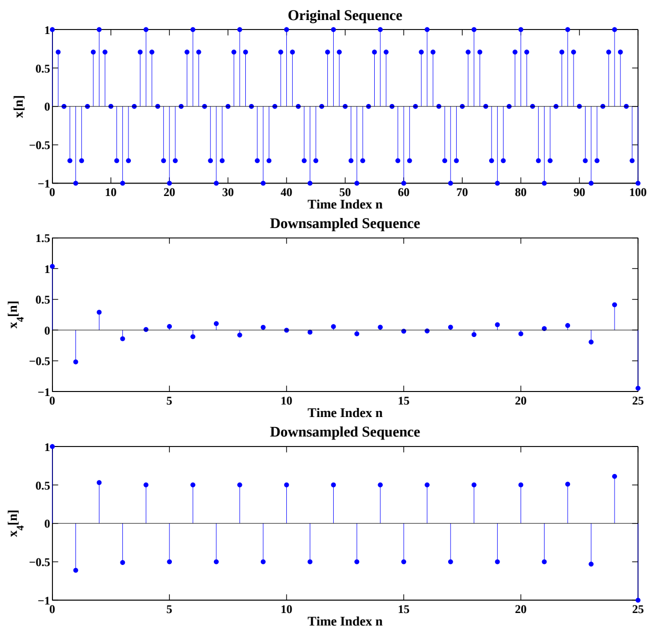

FIGURE 12.32: Stem plots of $x[n] = \cos(0.25\pi n)$ and downsampled sequences for $D = 4$ using both the default IIR and FIR decimation filters.

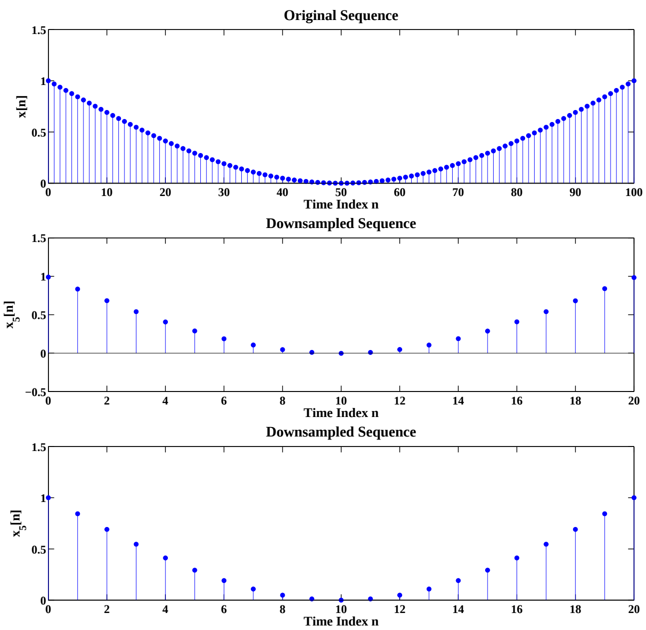

FIGURE 12.33: Stem plots of $x[n] = 1 - \sin(0.01\pi n)$ and downsampled sequences for $D = 5$ using both the default IIR and FIR decimation filters.

23. (a) See script below.
    (b) See plot below.

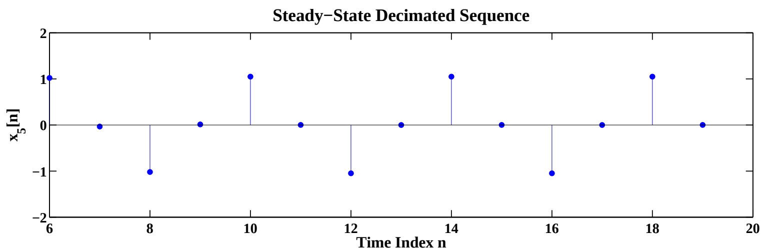

FIGURE 12.34: Steady-state values of $x_{\mathrm{d}}[n]$ by the decimator of Figure 12.5.

    (c) See plot below.

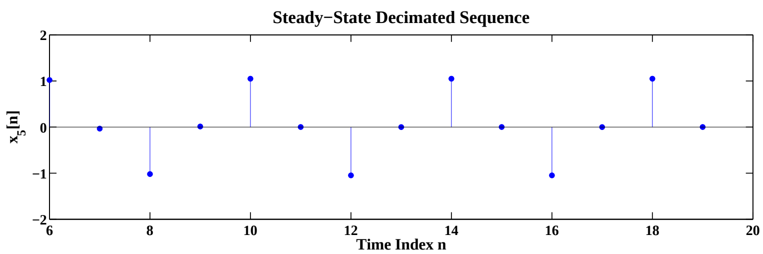

FIGURE 12.35: Steady-state values of $x_{\mathrm{d}}[n]$ by the decimator using the `firdec` function.

    (d) See plot below.
    (e) See plot below.
    (f) tba.

MATLAB script:

```
% P1223: Decimation functions comparison
close all; clc
N = 100;
n = 0:N-1;
om0 = 0.1*pi;
xn = sin(om0*n);
D = 5;
Ap = 1; As = 50;
%% Part a: Lowpass filter
```

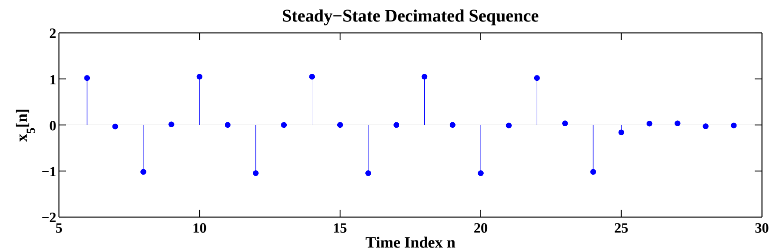

FIGURE 12.36: Steady-state values of $x_{\mathrm{d}}[n]$ by the decimator using the `upfirdn` function.

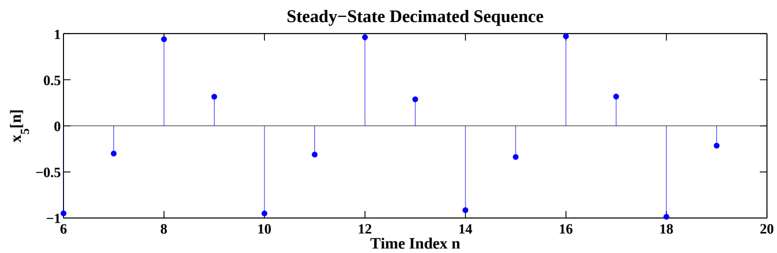

FIGURE 12.37: Steady-state values of $x_{\mathrm{d}}[n]$ by the decimator using the `decimate` function.

```
[deltap, deltas] = spec_convert(Ap,As,'rel','abs');
[M,fo,ao,W] = firpmord([0.2,0.3],[1,0],[deltap,deltas]);
[hn,delta] = firpm(M,fo,ao,W);
vn = filter(hn,1,xn);
%% Part b:
ynb = src(vn,D);
%% Part c:
ync = firdec(hn,xn,D);
%% Part d:
ynd = upfirdn(xn,hn,1,D);
%% Part e:
% yne = decimate(xn,D,M,'fir');
yne = decimate(xn,D);

%% Plot
yn = ynb; % part b
% yn = ync; % part c
% yn = ynd; % part d
```

```
% yn = yne; % part e
hfa = figconfg('P1223a','long');
Lp = length(yn); Ls = 7;
stem(Ls-1:Lp-1,yn(Ls:end),'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel(['x_',num2str(D),'[n]'],'fontsize',LFS);
title('Steady-State Decimated Sequence','fontsize',TFS);
```

24. (a) See plot below.

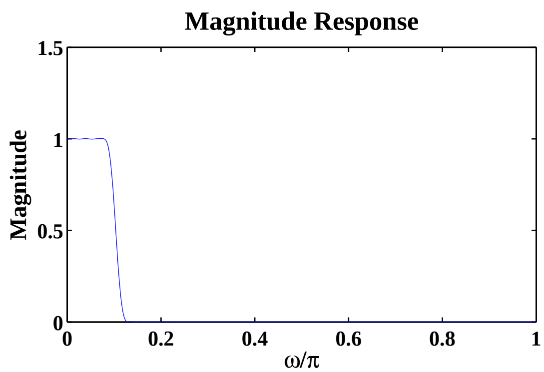

FIGURE 12.38: Magnitude spectra of $x[n]$.

(b) See plot below.

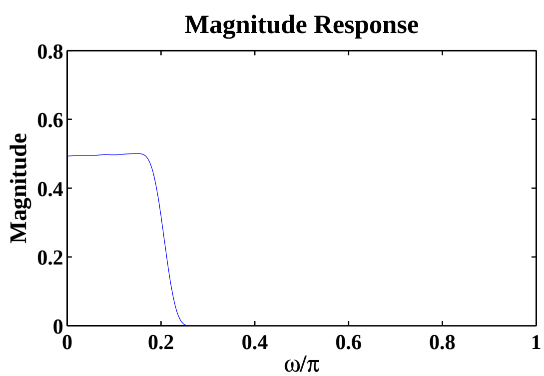

FIGURE 12.39: Magnitude spectra of decimated signal using $D = 2$.

(c) See plot below.

(d) See plot below.

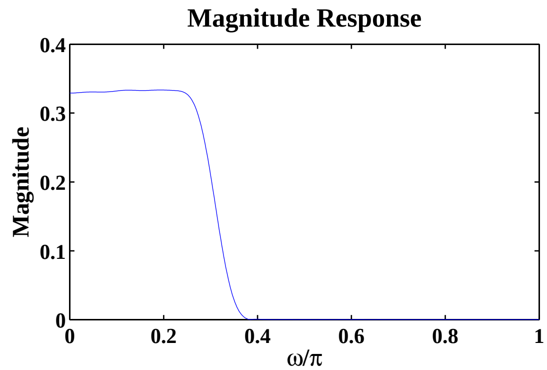

FIGURE 12.40: Magnitude spectra of decimated signal using $D = 3$.

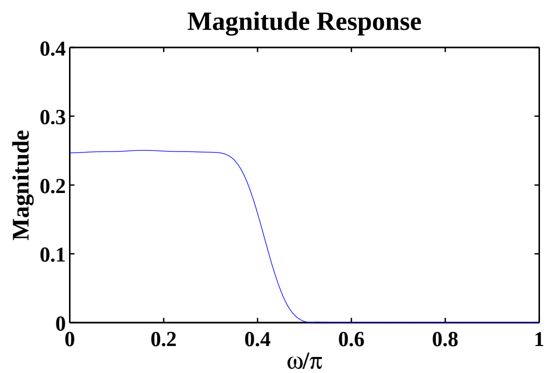

FIGURE 12.41: Magnitude spectra of decimated signal using $D = 4$.

(e) tba.

MATLAB script:

```
% P1224: Decimation; Frequency Investigation
close all; clc
L = 151; M = L - 1;
xn = fir2(M,[0,0.05,0.1,0.11,1],[1,1,1,0,0]);
w = linspace(0,1,501)*pi;
Hx = freqz(xn,1,w); Hxmag = abs(Hx);
D = 2;
% D = 3;
% D = 4;
yn = decimate(xn,D);
```

```
Hy = freqz(yn,1,w); Hymag = abs(Hy);
%% Plot
hfa = figconfg('P1224a','small');
plot(w/pi,Hxmag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
hfb = figconfg('P1224b','small');
plot(w/pi,Hymag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
```

25. (a) See plot below.

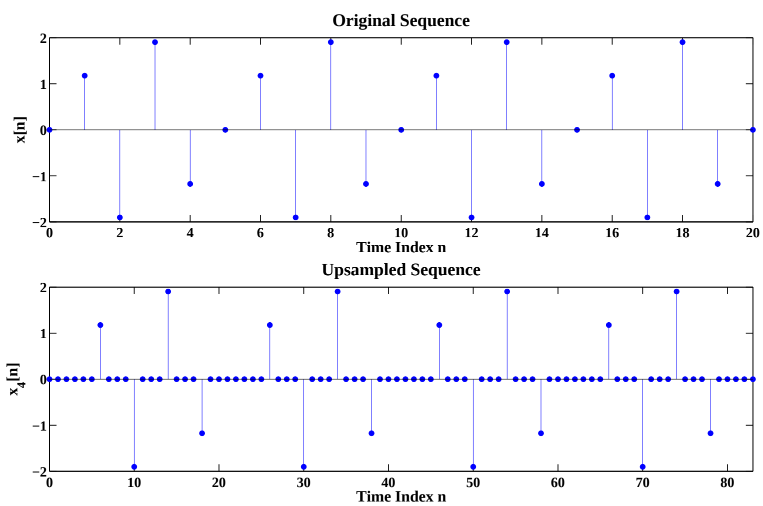

FIGURE 12.42: Stem plots of $x[n] = 2\sin(0.8\pi n)$ and upsampled sequences for $I = 4$.

(b) See plot below.

(c) See plot below.

(d) See plot below.

(e) See plot below.

MATLAB script:

```
% P1225: Illustrating function "upsample"
```

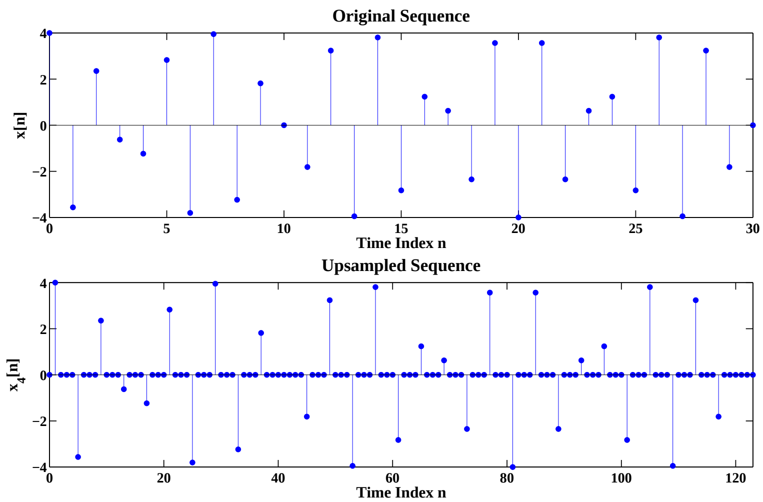

FIGURE 12.43: Stem plots of $x[n] = 4\cos(0.0.85\pi n)$ and upsampled sequences for $I = 4$.

```
close all; clc
%% Part a:
n = 0:20;
k = 2;
xn = 2*sin(0.8*pi*n);

%% Part b:
% n = 0:30;
% k = 1;
% xn = 4*cos(0.85*pi*n);

%% Part c:
% n = 0:25;
% k = 0;
% xn = 5*cos(0.5*pi*n);

%% Part d:
% n = 0:40;
% k = 2;
% xn = 3*sin(0.65*pi*n);

%% Part e:
```

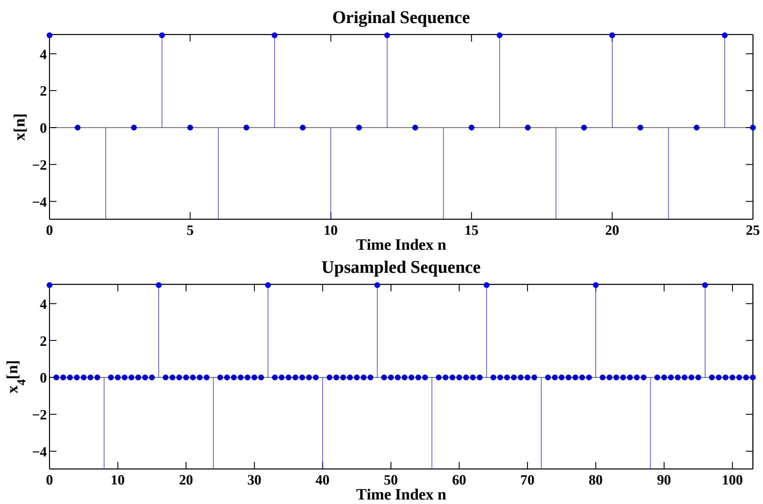

FIGURE 12.44: Stem plots of $x[n] = 5\cos(0.5\pi n)$ and upsampled sequences for $I = 4$.

```
% n = 0:10;
% k = 1;
% xn = sin(0.45*pi*n);

I = 4;
yn = upsample(xn,I,k);
%% Plot
hfa = figconfg('P1225a','long');
stem(n,xn,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel('x[n]','fontsize',LFS);
title('Original Sequence','fontsize',TFS);

hfb = figconfg('P1225b','long');
stem(0:length(yn)-1,yn,'filled')
xlim([0 length(yn)-1])
xlabel('Time Index n','fontsize',LFS);
ylabel(['x_',num2str(I),'[n]'],'fontsize',LFS);
title('Upsampled Sequence','fontsize',TFS);
```

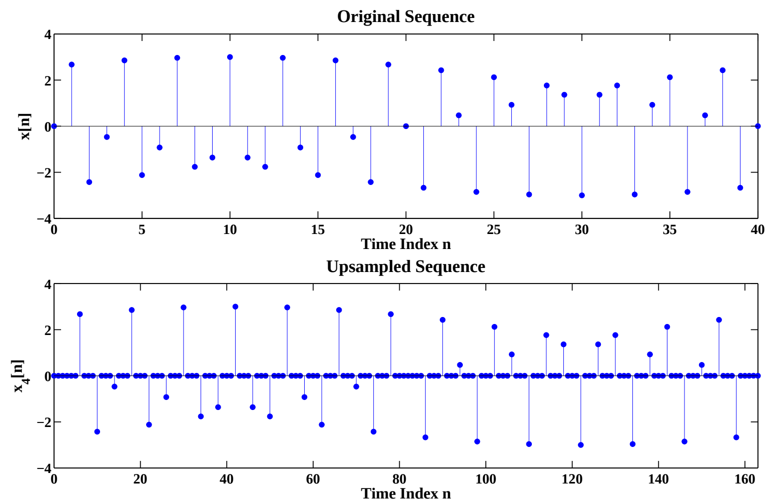

FIGURE 12.45: Stem plots of $x[n] = 3\sin(0.65\pi n)$ and upsampled sequences for $I = 4$.

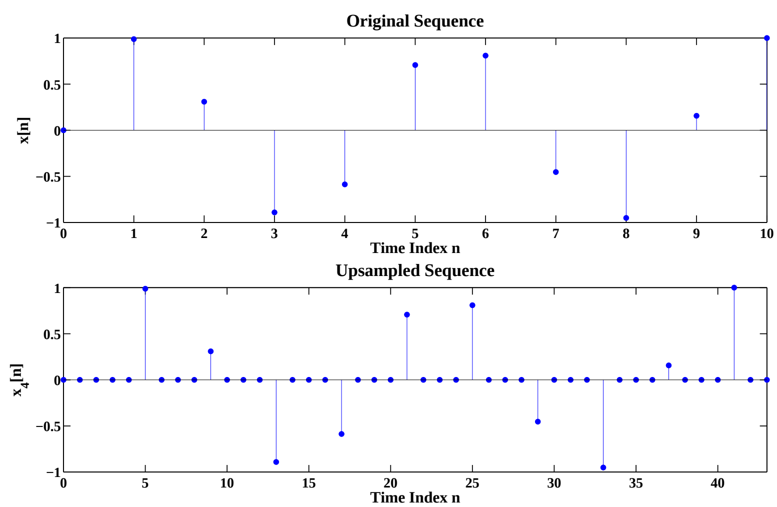

FIGURE 12.46: Stem plots of $x[n] = \sin(0.45\pi n)$ and upsampled sequences for $I = 4$.

26. (a) See plot below.

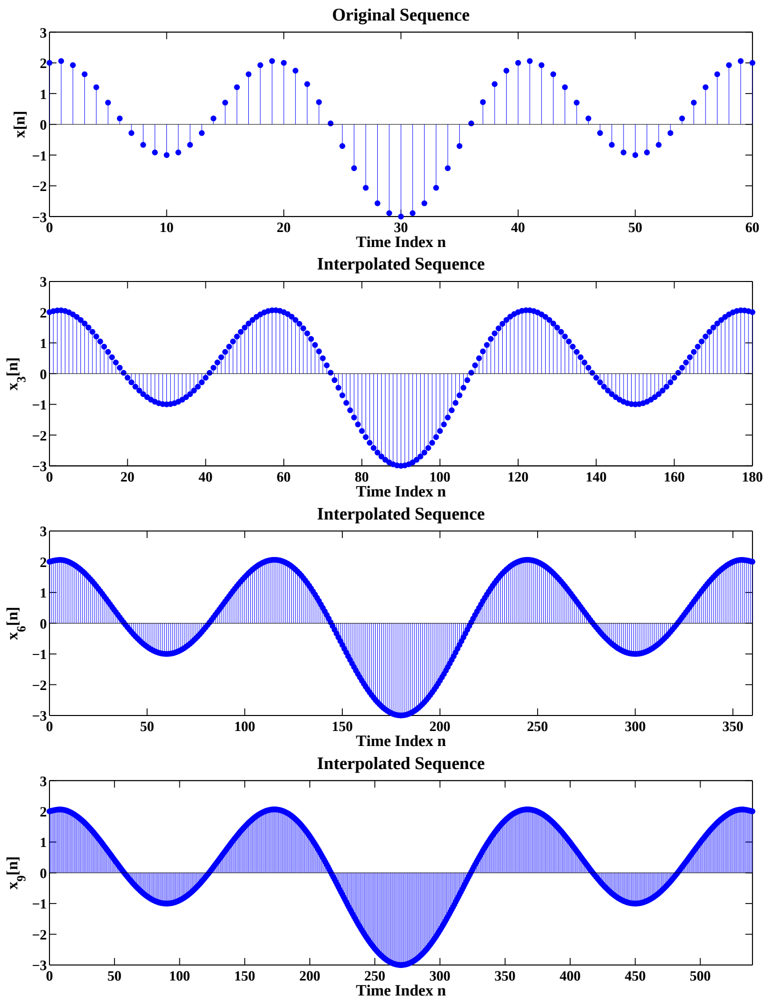

FIGURE 12.47: Stem plots of the original and interpolated signals for $I = 3$, $I = 6$, and $I = 9$.

(b) See plot below.

MATLAB script:

```
% P1226: Interpolation function "interp"
close all; clc
n = 0:60;
xn = 2*cos(0.1*pi*n)+sin(0.05*pi*n);
```

```
% I = 3;
% I = 6;
I = 9;
[yn b] = interp(xn,I);
%% Plot
hfa = figconfg('P1226a','long');
stem(n,xn,'filled')
ylim([-3 3]);
xlabel('Time Index n','fontsize',LFS);
ylabel('x[n]','fontsize',LFS);
title('Original Sequence','fontsize',TFS);

hfb = figconfg('P1226b','long');
stem(0:length(yn)-1,yn,'filled')
ylim([-3 3]); xlim([0 60*I])
xlabel('Time Index n','fontsize',LFS);
ylabel(['x_',num2str(I),'[n]'],'fontsize',LFS);
title('Interpolated Sequence','fontsize',TFS);

w = linspace(0,1,501)*pi;
H = freqz(b,1,w); Hmag = abs(H);
hfc = figconfg('P1226c','small');
plot(w/pi,Hmag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
```

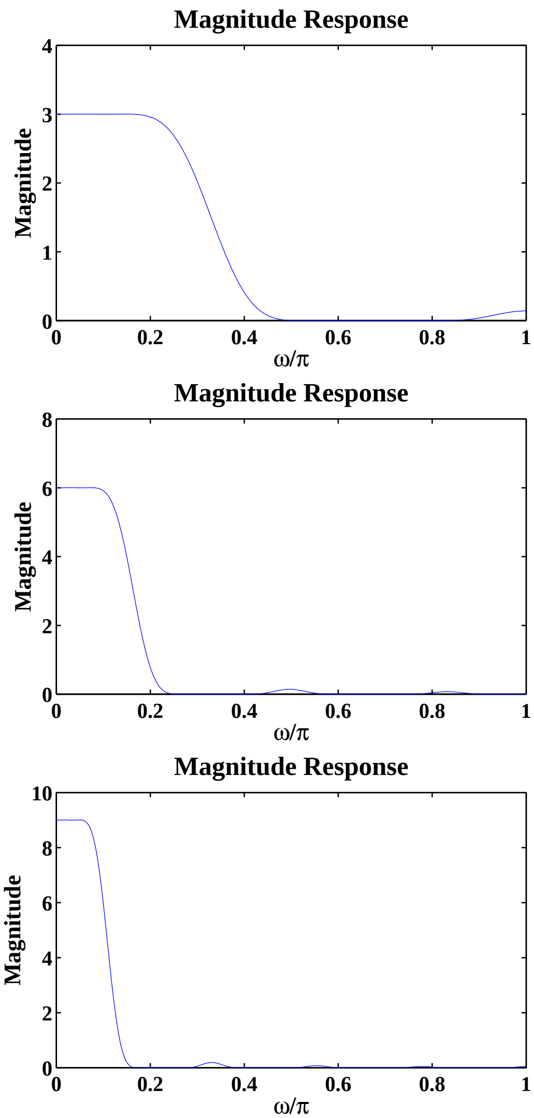

FIGURE 12.48: Magnitude responses of the lowpass filters used in interpolations for $I = 3$, $I = 6$, and $I = 9$.

27. (a) See plot below.

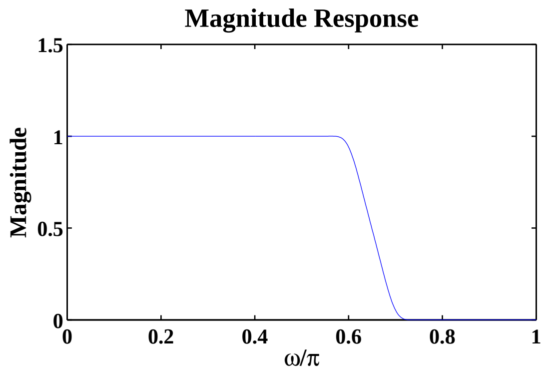

FIGURE 12.49: Magnitude responses of $x[n]$.

(b) See plot below.

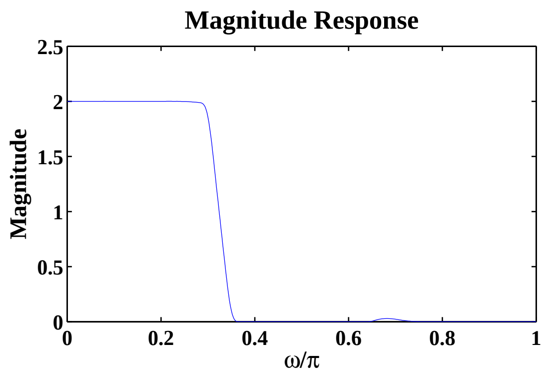

FIGURE 12.50: Magnitude responses of the upsampled signal using $I = 2$.

(c) See plot below.

(d) See plot below.

(e) tba.

MATLAB script:

```
% P1227: Interpolation; Frequency Investigation
close all; clc
L = 101; M = L - 1;
xn = fir2(M,[0,0.1,0.2,0.6,0.65,0.7,1],[1,1,1,1,0.5,0,0]);
```

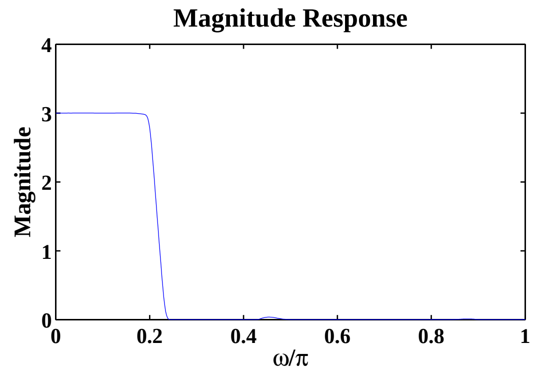

FIGURE 12.51: Magnitude responses of the upsampled signal using $I = 3$.

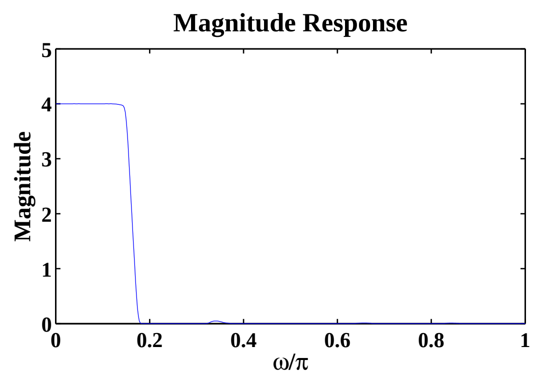

FIGURE 12.52: Magnitude responses of the upsampled signal using $I = 4$.

```
w = linspace(0,1,501)*pi;
Hx = freqz(xn,1,w); Hxmag = abs(Hx);
% I = 2;
% I = 3;
I = 4;
yn = interp(xn,I);
Hy = freqz(yn,1,w); Hymag = abs(Hy);
%% Plot
hfa = figconfg('P1227a','small');
plot(w/pi,Hxmag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
```

```
hfb = figconfg('P1227b','small');
plot(w/pi,Hymag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
```

28. (a) See script below.
    (b) See plot below.

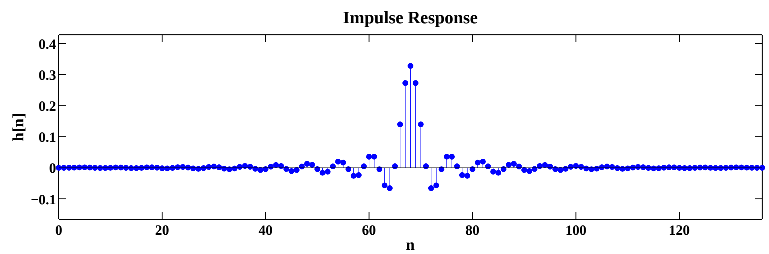

FIGURE 12.53: Stem plots of the impulse response of the designed filter.

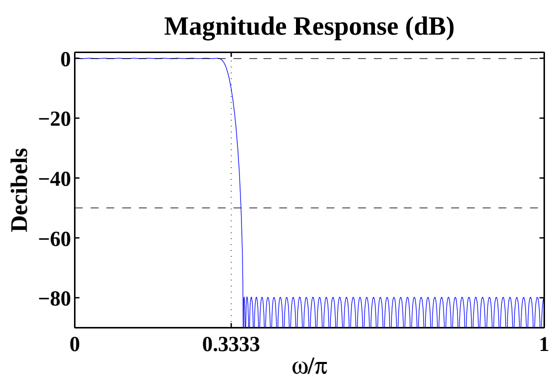

FIGURE 12.54: Log-magnitude response of the designed filter.

    (c) tba
    (d) See plot below.

MATLAB script:

```
% P1228: Interpolator design using Parks-McClellan
close all; clc
I = 3; Ap = 0.1; As = 50; dw = 0.05*pi;
```

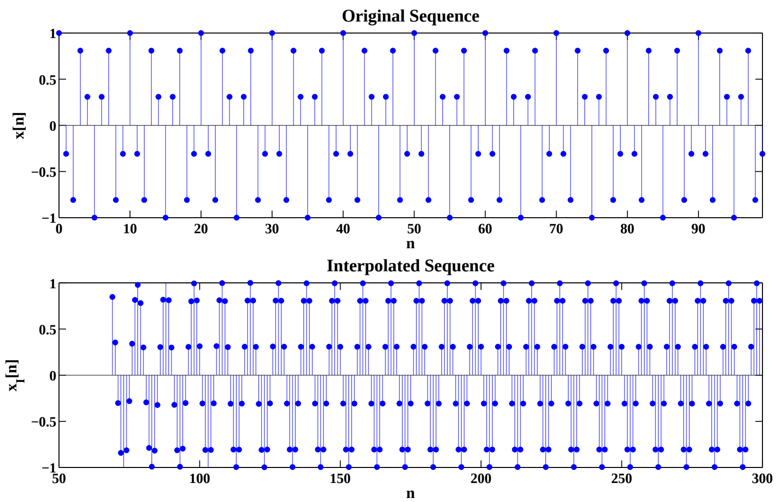

FIGURE 12.55: Stem plots of the original signal $x[n] = \cos(0.6\pi n)$ and interpolated signal for $I = 3$.

```
wp = pi/I-dw/2; ws = pi/I + dw/2;
% FIR lowpass filter design by Parks-McClellan
[deltap, deltas] = spec_convert(Ap,As,'rel','abs');
[M,fo,ao,W] = firpmord([wp,ws]/pi,[1,0],[deltap,deltas]);
M = M + 3;
[h,delta] = firpm(M,fo,ao,W);
w = linspace(0,1,1001)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
% Interpolation
N = 100; n = 0:N-1;
xn = cos(0.6*pi*n);
xu = sre(xn,I);
xi = filter(h,1,xu)*I;

%% Plot:
hfa = figconfg('P1228a','long');
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('P1228b','small');
plot(w/pi,Hdb);hold on
plot(w/pi,-As*ones(1,length(w)),'--','color','k')
plot(w/pi,-Ap*ones(1,length(w)),'--','color','k')
ylim([-90 2])
set(gca,'XTick',[0 pi/I pi]/pi,'Xgrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1228c','long');
stem(n,xn,'filled');
xlim([0 N-1])
xlabel('n','fontsize',LFS)
ylabel('x[n]','fontsize',LFS)
title('Original Sequence','fontsize',TFS)

hfd = figconfg('P1228d','long');
nss = 70;
stem(nss-1:length(xi)-1,xi(nss:end),'filled');
ylim([-1 1])
xlabel('n','fontsize',LFS)
ylabel('x_I[n]','fontsize',LFS)
title('Interpolated Sequence','fontsize',TFS)
```

29. (a) See plot below.

    (b) tba

    MATLAB script:

```
% P1229: Interpolation Investigation
close all; clc
N = 32; m = 0:N; D = 2; L = 2;
xD = sin(pi*m/2);
n = 0:D*N;
GL = bsxfun(@minus,n,m(:)*D);
ind = GL >= L*D | GL <= -L*D;
```

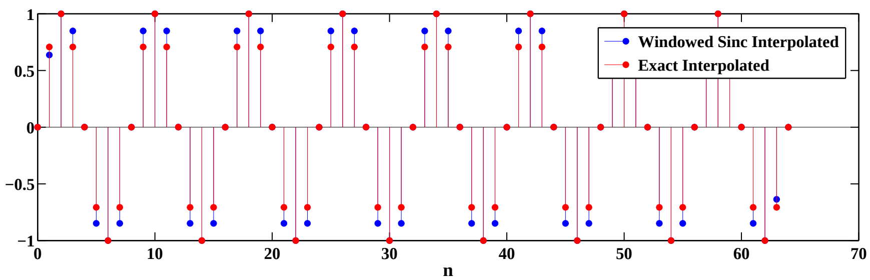

FIGURE 12.56: Stem plots of the interpolated signals by windowed sinc interpolation function compared with the exact interpolated sequence $x[n]$.

```
GL = sinc(GL/D);
GL(ind) = 0;
xn = xD*GL;
xn_ref = sin(pi*n/2/D);
%% Plot:
hfa = figconfg('P1229a','long');
stem(n,xn,'filled'); hold on
stem(n,xn_ref,'filled','r');
xlabel('n','fontsize',LFS)
legend('Windowed Sinc Interpolated','Exact Interpolated','location','best')
```

30. (a) See script below.

(b) See plot below.

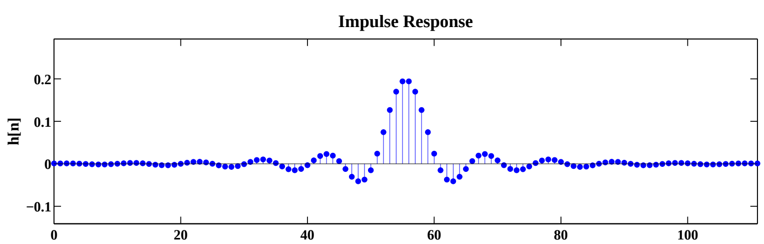

FIGURE 12.57: Impulse response of the designed filter.

(c) tba.

(d) See plot below.

MATLAB script:

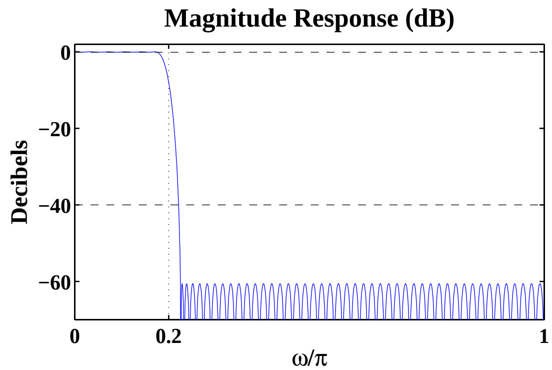

FIGURE 12.58: Log-magnitude response of the designed filter.

```
% P1230: Sampling rate converter design using Parks-McClellan
close all; clc
I = 2; D = 5; Ap = 0.1; As = 40; dw = 0.05*pi;
wp = pi/5-dw/2; ws = pi/5 + dw/2;
% FIR lowpass filter design by Parks-McClellan
[deltap, deltas] = spec_convert(Ap,As,'rel','abs');
[M,fo,ao,W] = firpmord([wp,ws]/pi,[1,0],[deltap,deltas]);
M = M + 2;
[h,delta] = firpm(M,fo,ao,W);
w = linspace(0,1,1001)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
% Sampling rate conversion
N = 500; n = 0:N-1;
xn = sin(0.3*pi*n) + 2*cos(0.4*pi*n);
xu = sre(xn,I);
xi = filter(h,1,xu);
xD = src(xi,D);
%% Plot:
hfa = figconfg('P1230a','long');
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)
```

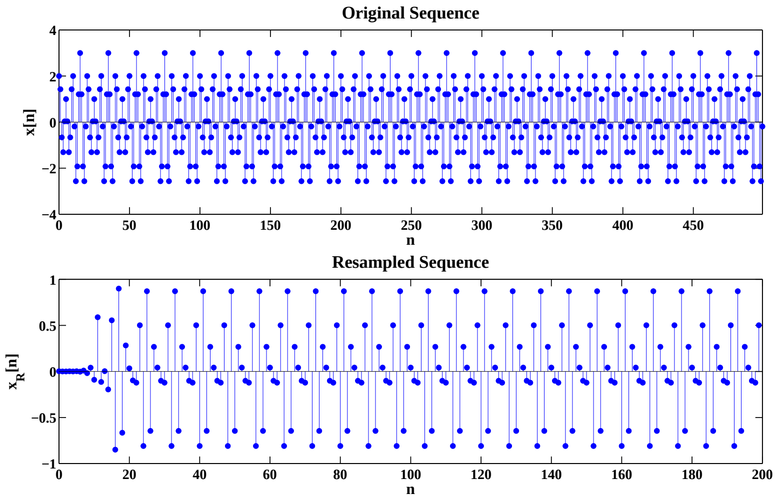

FIGURE 12.59: Stem plots of original sequence of $x[n] = \sin(0.3\pi n) + 2\cos(0.4\pi n)$ and resampled sequence $x_{\mathrm{R}}[m]$ by $2/5$.

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

hfb = figconfg('P1230b','small');
plot(w/pi,Hdb);hold on
plot(w/pi,-As*ones(1,length(w)),'--','color','k')
plot(w/pi,-Ap*ones(1,length(w)),'--','color','k')
ylim([-70 2])
set(gca,'XTick',[0 pi/5 pi]/pi,'Xgrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)

hfc = figconfg('P1230c','long');
stem(n,xn,'filled');
xlim([0 N-1])
xlabel('n','fontsize',LFS)
ylabel('x[n]','fontsize',LFS)
title('Original Sequence','fontsize',TFS)

hfd = figconfg('P1230d','long');
stem(0:length(xD)-1,xD,'filled');
xlabel('n','fontsize',LFS)
```

```
ylabel('x_R[n]','fontsize',LFS)
title('Resampled Sequence','fontsize',TFS)
```

31. tba

32. (a) See plot below.

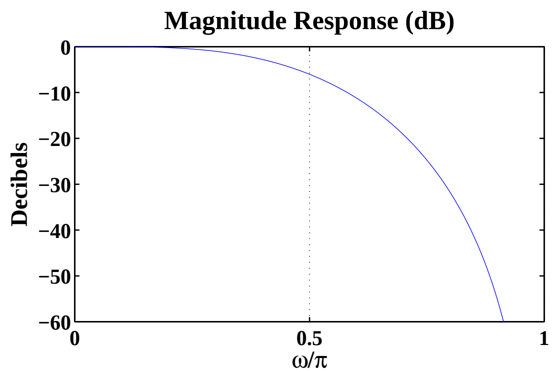

FIGURE 12.60: Log-magnitude response of the filter $H(z)$.

MATLAB script:

```
% P1232: Half-band lowpass filter
close all; clc
hn = [1 0 -9 -16 -9 0 1];
w = linspace(0,1,1001)*pi;
H = freqz(hn,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
%% Plot
hfa = figconfg('P1232a','small');
plot(w/pi,Hdb);hold on
ylim([-60 0])
set(gca,'XTick',[0 pi/2 pi]/pi,'Xgrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)
```

(b) tba.

33. See plot below.

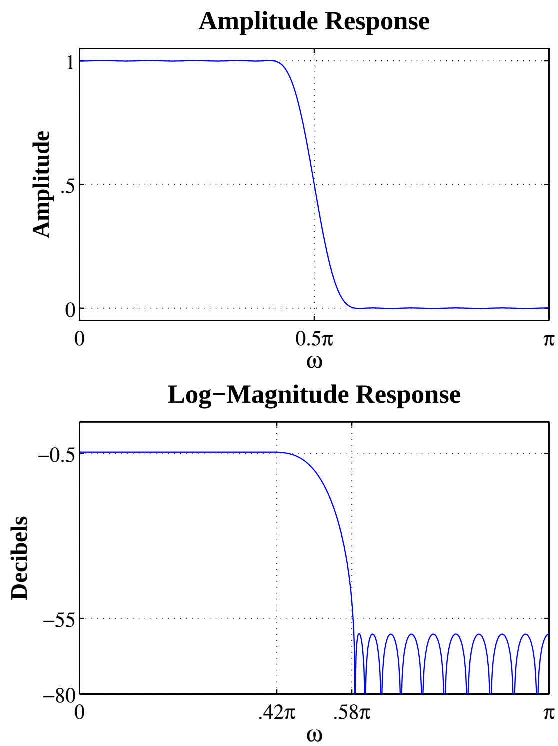

FIGURE 12.61: Amplitude response and log-magnitude response of the designed half-band filter.

MATLAB script:

```
% P1233: Half-band lowpass filter design
close all; clc
% Frequency Response parameters
om = linspace(0,pi,1001);
% Given Halfband Filter Sepcifications
omegas = 0.58*pi; omegap = pi - omegas; Ap = 0.5; As = 55;
% Step-1: Determine order M so that is is equal to 4*p-2
deltap = (10^(Ap/20)-1)/(10^(Ap/20)+1);
deltas = (1+deltap)/(10^(As/20)); delta = min(deltap,deltas);
f = [2*omegap,pi]/pi; A = [1,0]; dev = 2*[delta,delta];
[M,fo,Ao,W] = firpmord(f,A,dev);
M = ceil((M+2)/4)*4-2;
```

```
% Step-2: PM Design
[g,delta] = firpm(M/2,fo,Ao); delta
M = M+4; [g,delta] = firpm(M/2,fo,Ao); delta
% Step-3: Halfband Lowpass Filter Design
h = upsample(0.5*g,2); h(M/2+1) = 0.5; h = h(1:M+1);
% Frequency Response
H = freqz(h,1,om); Hmag = abs(H); HdB = 20*log10(Hmag/max(Hmag));
Hz = zerophase(h,1,om);

%% Plot
hfa = figconfg('P1233a','small');
plot(om/pi,Hz,'b','linewidth',0.9);
axis([0,1,-0.05,1.05]);
title('Amplitude Response','fontsize',TFS);
ylabel('Amplitude','fontsize',LFS);
xlabel('\omega','fontsize',LFS);
set(gca,'Xtick',[0,0.5,1]);
set(gca,'XTickLabel','0|0.5p|p');
set(gca,'FontName','Symbol');
set(gca,'ytick',[0,0.5,1],'yticklabel','0|.5|1'); grid;

hfb = figconfg('P1233b','small');
plot(om/pi,HdB,'b','linewidth',0.9);
axis([0,1,-80,10]);
title('Log-Magnitude Response','fontsize',TFS);
ylabel('Decibels','fontsize',LFS);
xlabel('\omega','fontsize',LFS);
set(gca,'Xtick',[0,omegap/pi,omegas/pi,1]);
set(gca,'XTickLabel','0|.42p|.58p|p');
set(gca,'FontName','Symbol');
set(gca,'ytick',[-80,-As,-Ap]); grid;
```

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

MATLAB script:

```
% P1234: Two-stage Decimation
close all; clc
```

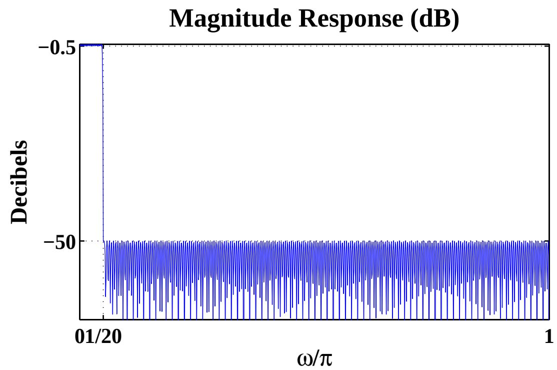

FIGURE 12.62: Log-magnitude response of the lowpass FIR filter of single-stage decimator.

```
%% Given Parameters
FH = 1000; D1 = 5; D2 = 4; D = D1*D2;
FL = 50; F1 = FH/D1;
fs = 1/D; fp = fs-fs/D; Ap = 0.5; As = 50;
%% Single-stage filter design
deltap = (10^(Ap/20)-1)/(10^(Ap/20)+1);
deltas = (1+deltap)/(10^(As/20));
f = [fp,fs]; A = [1,0]; dev = [deltap,deltas];
[M,fo,Ao,W] = firpmord(f,A,dev);
M = M + 13;
[h delta] = firpm(M,fo,Ao,W);
%% Filter F(z) Design for L=5
fpF = fp*L; fsF = fs*L; ApF = Ap/2; AsF = As;
deltapF = (10^(ApF/20)-1)/(10^(ApF/20)+1);
deltasF = (1+deltapF)/(10^(AsF/20));
fF = [fpF,fsF]; AF = [1,0]; devF = [deltapF,deltasF];
[MF,foF,AoF,WF] = firpmord(fF,AF,devF);
MF = MF+3;
[hF deltaF] = firpm(MF,foF,AoF,WF);
hFL = upsample(hF,L); hFL = hFL(1:end-L+1);
%% Filter G(z) Design
fpG = fp; fsG = 2/L-fs; ApG = Ap/2; AsG = As;
deltapG = (10^(ApG/20)-1)/(10^(ApG/20)+1);
deltasG = (1+deltapG)/(10^(AsG/20));
fG = [fpG,fsG]; AG = [1,0]; devG = [deltapG,deltasG];
```

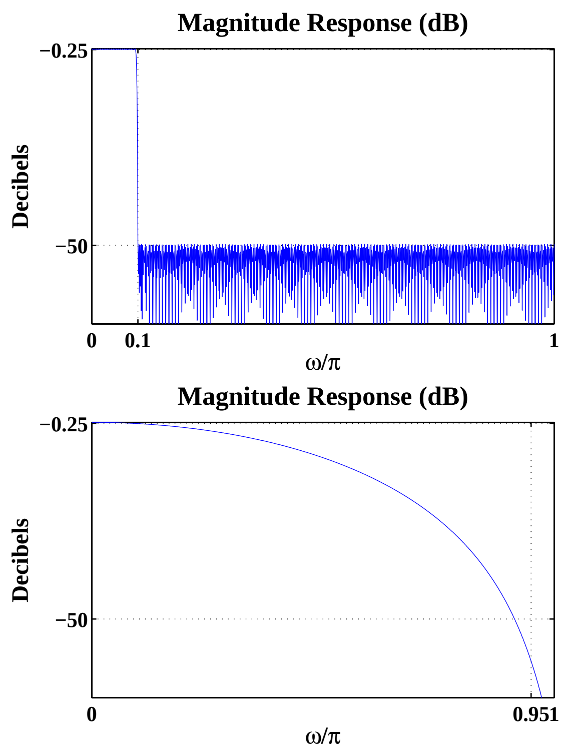

FIGURE 12.63: Log-magnitude responses of both filters of the two-stage decimator.

```
[MG,foG,AoG,WG] = firpmord(fG,AG,devG);
MG = MG+3;
[hG deltaG] = firpm(MG,foG,AoG,WG);
%% Equivalent Filter hGF = hG * hL
hGF = conv(hG,hFL);

%% Computational Complexity: Mults/sec (multrate)
filtlenA = length(h),       % Approach-A
filtlenB = length(hG), % Approach-B
filtlenC = length(hF), % Approach-B

multrateA = length(h)*FH/D,      % Approach-A
multrateB = length(hGF)*FH/D, % Approach-B
multrateC1 = length(hG)*FH/D1,  % Approach-C1
multrateC2 = length(hF)*F1/D2,   % Approach-C2
```

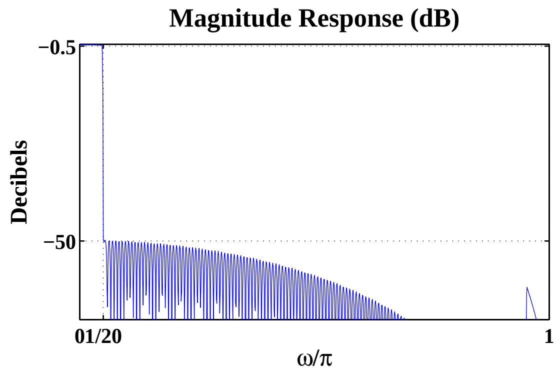

FIGURE 12.64: Log-magnitude response of the lowpass FIR filter of the equivalent single-stage filter from (b).

```
multrateC = multrateC1+multrateC2, % Approach-C

%% Plot:
w = linspace(0,1,1001)*pi;
H = freqz(h,1,w);
Hmag = abs(H);
Hdb = 20*log10(Hmag./max(Hmag));
hfa = figconfg('P1234a','small');
plot(w/pi,Hdb);hold on
ylim([-70 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)
set(gca,'XTick',[0 pi/D pi]/pi,'Xgrid','on','Xticklabel','0|1/20|1')
set(gca,'YTick',[-As -Ap],'Ygrid','on')

HF = freqz(hF,1,w);
HFmag = abs(HF); HFdb = 20*log10(HFmag./max(HFmag));
hfb = figconfg('P1248b','small');
plot(w/pi,HFdb);hold on
ylim([-70 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)
set(gca,'XTick',[0 pi*fsF pi]/pi,'Xgrid','on')
```

```
set(gca,'YTick',[-AsF -ApF],'Ygrid','on')

HG = freqz(hG,1,w);
HGmag = abs(HG); HGdb = 20*log10(HGmag./max(HGmag));
hfc = figconfg('P1248c','small');
plot(w/pi,HGdb);hold on
ylim([-70 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)
set(gca,'XTick',[0 pi*fsG pi]/pi,'Xgrid','on')
set(gca,'YTick',[-AsG -ApG],'Ygrid','on')

HGF = freqz(hGF,1,w);
HGFmag = abs(HGF); HGFdb = 20*log10(HGFmag./max(HGFmag));
hfd = figconfg('P1248d','small');
plot(w/pi,HGFdb);hold on
ylim([-70 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)
set(gca,'XTick',[0 pi/D pi]/pi,'Xgrid','on','Xticklabel','0|1/20|1')
set(gca,'YTick',[-As -Ap],'Ygrid','on')
```

Assessment Problems

35. (a) See plot below.

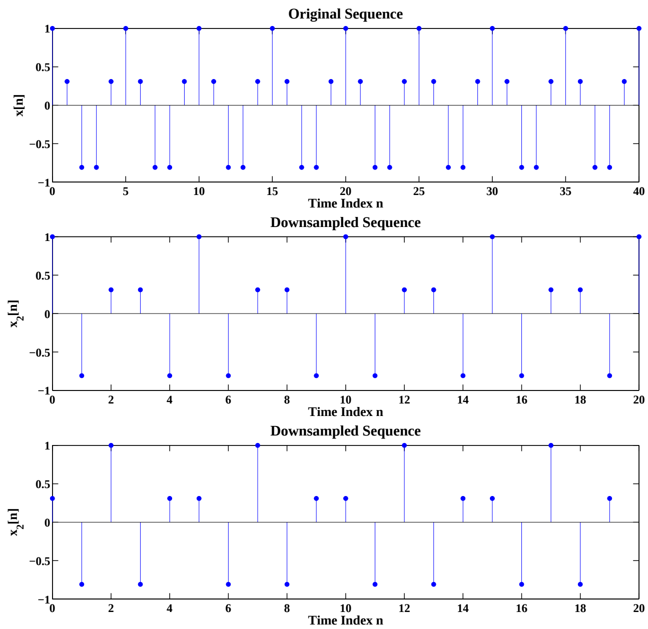

FIGURE 12.65: Stem plots of $x[n] = \cos(0.4\pi n)$ and downsampled sequences for $D = 2$, $k = 0$, and $k = 1$.

(b) See plot below.

(c) See plot below.

(d) See plot below.

(e) See plot below.

MATLAB script:

```
% P1235: Illustrating function "src"
close all; clc
%% Part a:
% n = 0:40; D = 2;
% % k = 0;
% k = 1;
% xn = cos(0.4*pi*n);
```

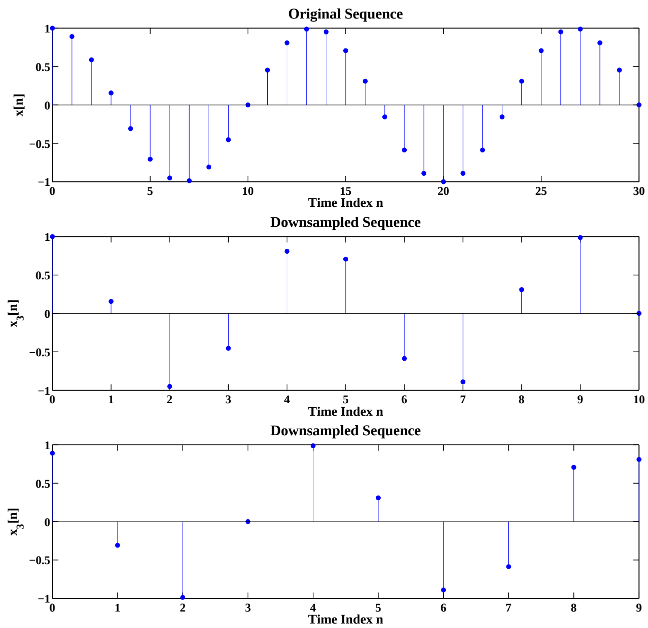

FIGURE 12.66: Stem plots of $x[n] = \cos(0.15\pi n)$ and downsampled sequences for $D = 3$, $k = 0$, and $k = 1$.

```
%% Part b:
% n = 0:30; D = 3;
% k = 0;
% % k = 1;
% xn = cos(0.15*pi*n);

%% Part c:
% n = 0:100; D = 3;
% k = 0;
% % k = 2;
% xn = n - 2*n.*(n>=20) + (n>=40);

%% Part d:
% n = 0:90; D = 2;
% k = 0;
% % k = 1;
% xn = cos(0.45*pi*n);
```

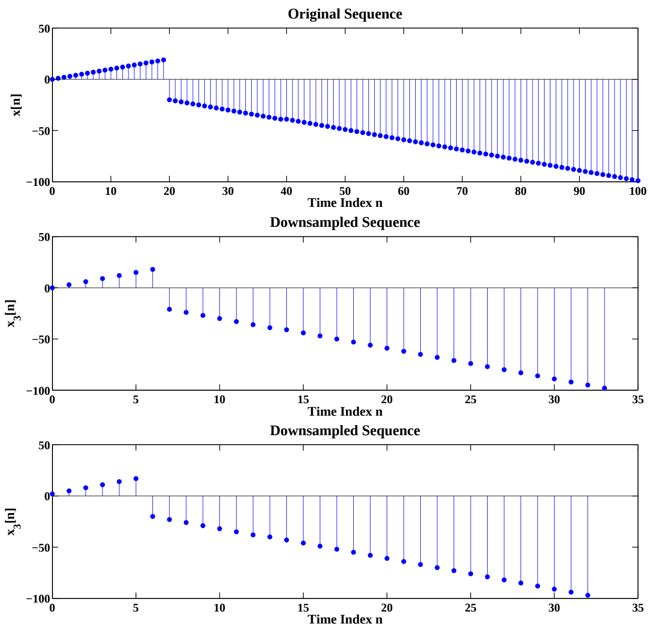

FIGURE 12.67: Stem plots of $x[n] = nu[n] - 2nu[n-20] + u[n-40]$ and downsampled sequences for $D = 3$, $k = 0$, and $k = 2$.

```
%% Part e:
n = 0:100; D = 5;
k = 1;
% k = 3;
xn = 1 - cos(0.05*pi*n);

yn = src(xn(1+k:end),D);
%% Plot
hfa = figconfg('P1235a','long');
stem(n,xn,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel('x[n]','fontsize',LFS);
title('Original Sequence','fontsize',TFS);

hfb = figconfg('P1235b','long');
stem(0:length(yn)-1,yn,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel(['x_',num2str(D),'[n]'],'fontsize',LFS);
```

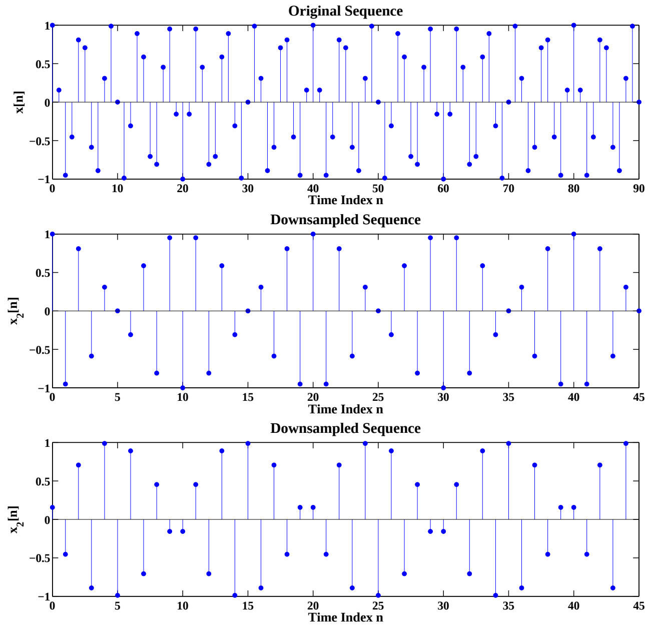

FIGURE 12.68: Stem plots of $x[n] = \cos(0.45\pi n)$ and downsampled sequences for $D = 2$, $k = 0$, and $k = 1$.

```
title('Downsampled Sequence','fontsize',TFS);
```

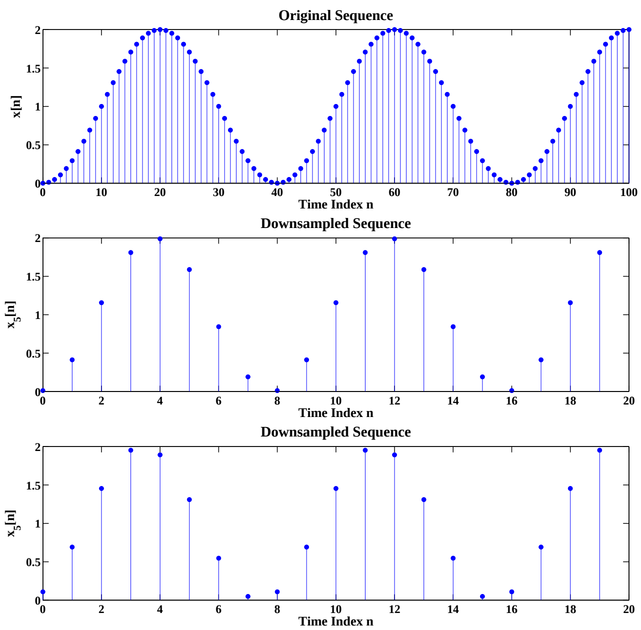

FIGURE 12.69: Stem plots of $x[n] = 1 - \cos(0.05\pi n)$ and downsampled sequences for $D = 5$, $k = 1$, and $k = 3$.

36. (a) See plot below.

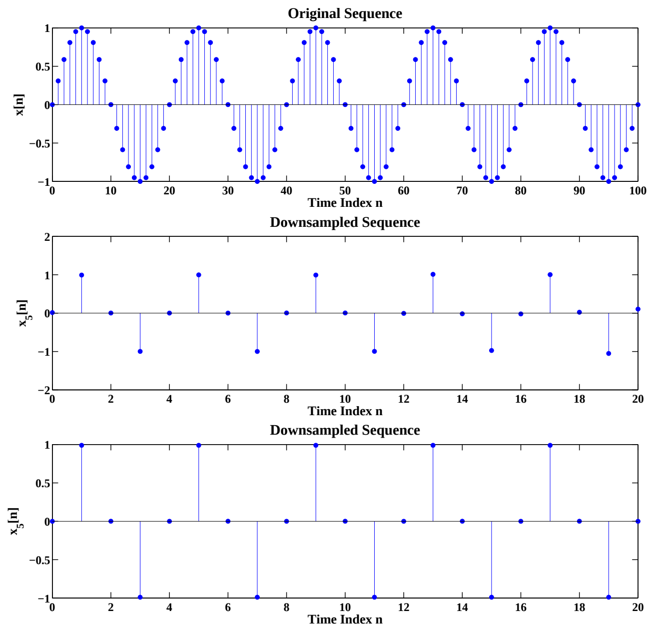

FIGURE 12.70: Stem plots of $x[n] = \sin(0.1\pi n)$ and downsampled sequences for $D = 5$ using both the default IIR and FIR decimation filters.

(b) See plot below.

(c) See plot below.

(d) See plot below.

(e) See plot below.

MATLAB script:

```
% P1236: Illustrating function "decimate"
close all; clc
%% Part a:
n = 0:100; D = 5;
xn = sin(0.1*pi*n);

%% Part b:
% n = 0:100; D = 10;
% xn = cos(0.015*pi*n);
```

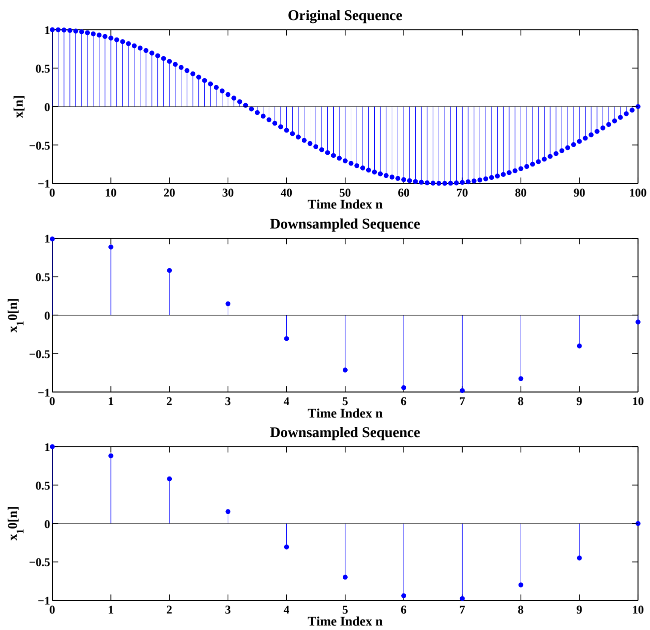

FIGURE 12.71: Stem plots of $x[n] = \cos(0.015\pi n)$ and downsampled sequences for $D = 10$ using both the default IIR and FIR decimation filters.

```
%% Part c:
% n = 0:150; D = 6;
% xn = sin(n/11) + 2*cos(n/31);

%% Part d:
% n = 0:100; D = 8;
% xn = sin(0.025*pi*n);

%% Part e:
% n = 0:64; D = 2;
% xn = repmat([1 2 3 4 3 2 1 0],1,ceil(length(n)/8));
% xn = xn(1:length(n));

yn = decimate(xn,D); % default IIR
% yn = decimate(xn,D,'fir'); % default FIR
%% Plot
hfa = figconfg('P1236a','long');
stem(n,xn,'filled')
```

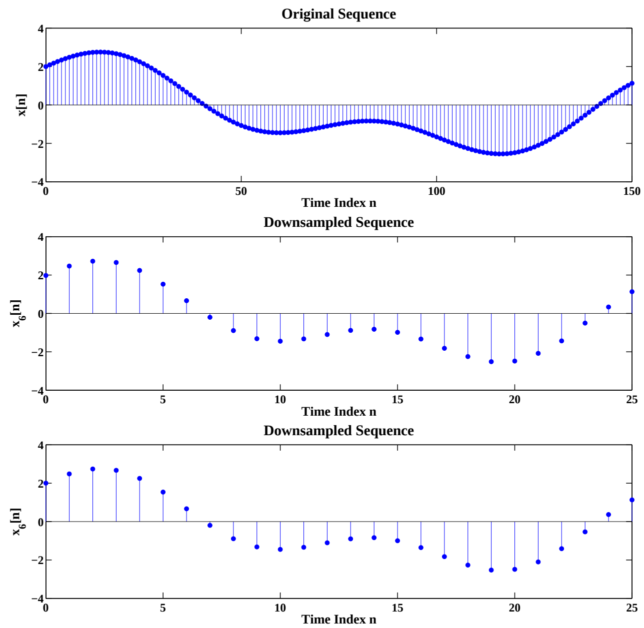

FIGURE 12.72: Stem plots of $x[n] = \sin(n/11) + 2\cos n/31$ and downsampled sequences for $D = 6$ using both the default IIR and FIR decimation filters.

```
xlabel('Time Index n','fontsize',LFS);
ylabel('x[n]','fontsize',LFS);
title('Original Sequence','fontsize',TFS);

hfb = figconfg('P1236b','long');
stem(0:length(yn)-1,yn,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel(['x_',num2str(D),'[n]'],'fontsize',LFS);
title('Downsampled Sequence','fontsize',TFS);
```

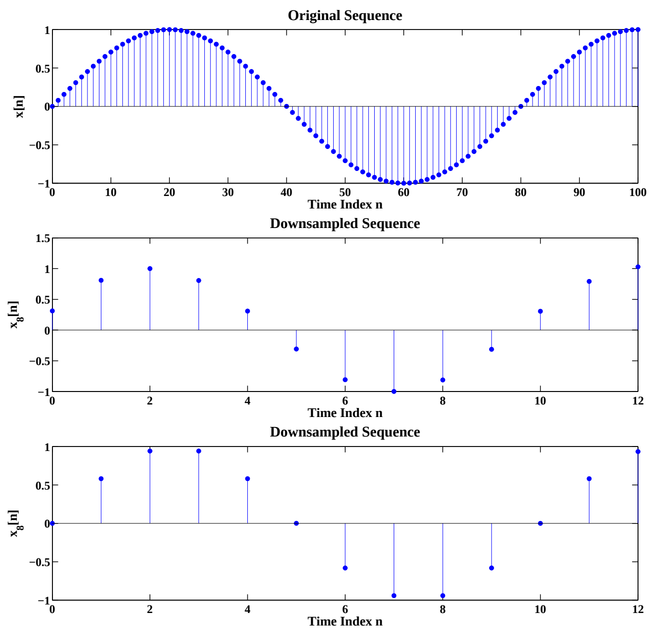

FIGURE 12.73: Stem plots of $x[n] = \sin(0.025\pi n)$ and downsampled sequences for $D = 8$ using both the default IIR and FIR decimation filters.

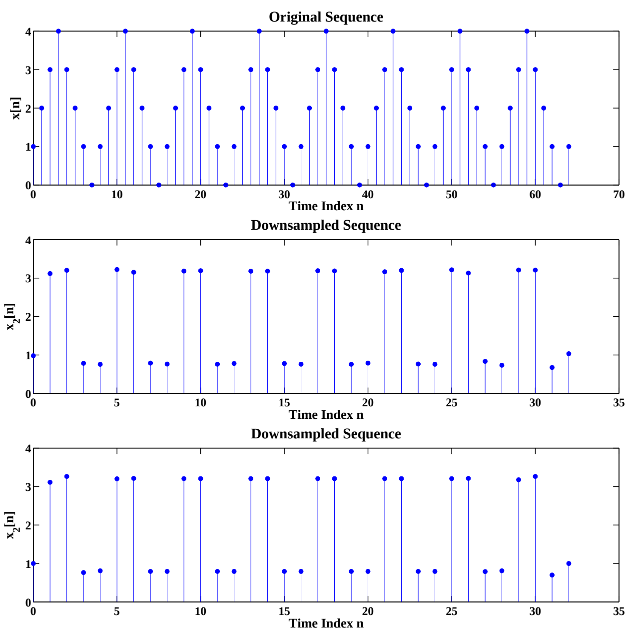

FIGURE 12.74: Stem plots of $x[n] = 1, 2, 3, 4, 3, 2, 1, 0$, periodic with period 8, $0 \leq n \leq 64$ and downsampled sequences for $D = 2$ using both the default IIR and FIR decimation filters.

37. (a) See plot below.

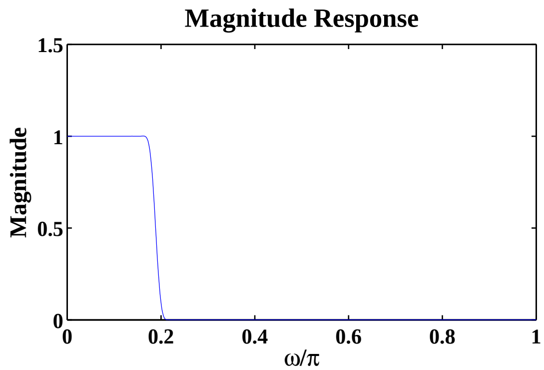

FIGURE 12.75: Magnitude spectra of $x[n]$.

(b) See plot below.

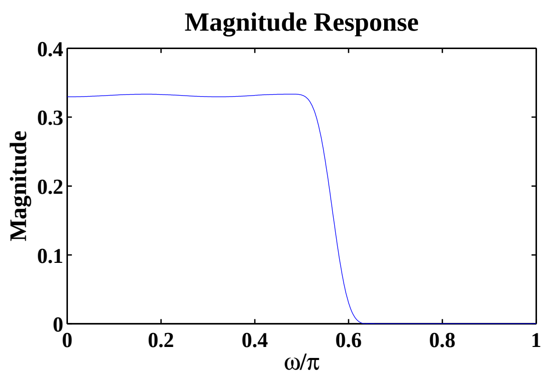

FIGURE 12.76: Magnitude spectra of decimated signal using $D = 3$.

(c) See plot below.

(d) See plot below.

(e) tba.

MATLAB script:

```
% P1237: Decimation; Frequency Investigation
close all; clc
L = 201; M = L - 1;
xn = fir2(M,[0,0.1,0.18,0.2,1],[1,1,1,0,0]);
```

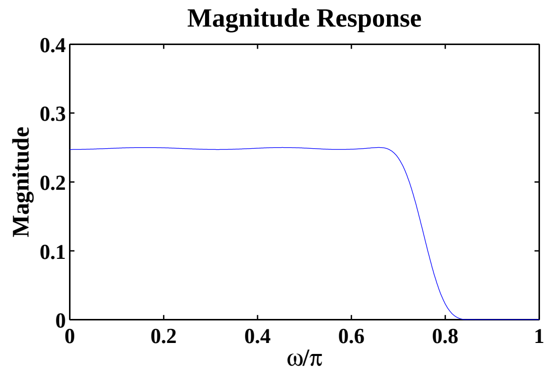

FIGURE 12.77: Magnitude spectra of decimated signal using $D = 4$.

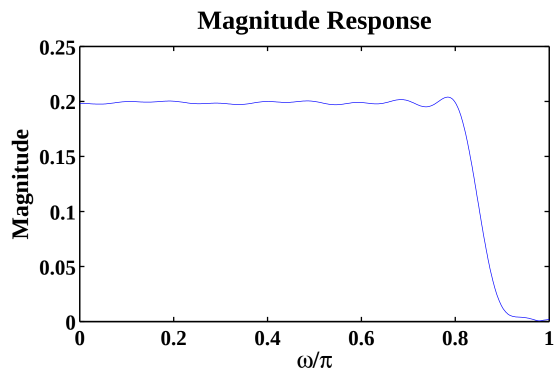

FIGURE 12.78: Magnitude spectra of decimated signal using $D = 5$.

```
w = linspace(0,1,501)*pi;
Hx = freqz(xn,1,w); Hxmag = abs(Hx);
% D = 3;
% D = 4;
D = 5;
yn = decimate(xn,D);
Hy = freqz(yn,1,w); Hymag = abs(Hy);
%% Plot
hfa = figconfg('P1237a','small');
plot(w/pi,Hxmag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
```

```
hfb = figconfg('P1237b','small');
plot(w/pi,Hymag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
```

38. tba

39. (a) See script below.
    (b) See plot below.

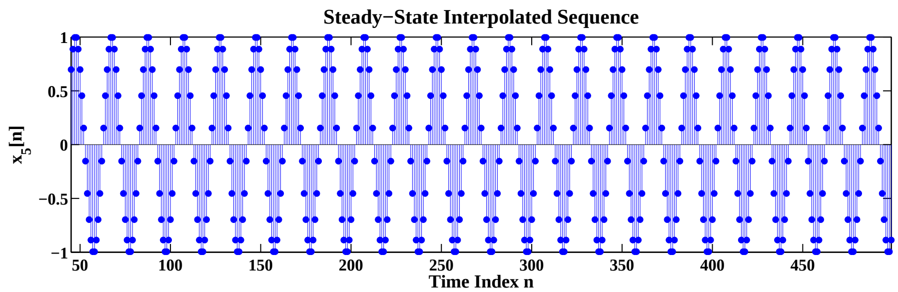

FIGURE 12.79: Steady-state values of $x_{\mathrm{I}}[n]$ by interpolator using the `sre` function.

    (c) See plot below.

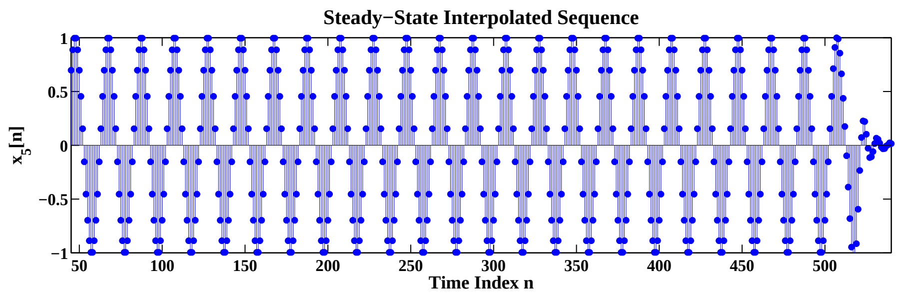

FIGURE 12.80: Steady-state values of $x_{\mathrm{I}}[n]$ by interpolator using the `upfirdn` function.

    (d) See plot below.
    (e) tba.

MATLAB script:

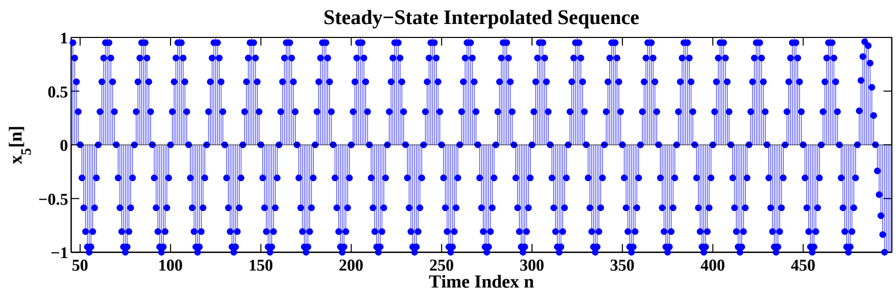

FIGURE 12.81: Steady-state values of $x_{\mathrm{I}}[n]$ by interpolator using the `interp` function.

```
% P1239: Interpolation functions comparison
close all; clc
N = 100;
n = 0:N-1;
% om0 = pi;
om0 = 0.5*pi;
xn = sin(om0*n);
I = 5;
%% Part a: Lowpass filter
M = 45;
hn = firpm(M,[0 0.2 0.3 1],[1 1 0 0],[1 1]);
hn = hn*I;
w = linspace(0,1,501)*pi;
H = freqz(hn,1,w); Hmag = abs(H);
figure, plot(w/pi,Hmag)

vn = sre(xn,I);
%% Part b:
ynb = filter(hn,1,vn);
%% Part c:
ync = upfirdn(xn,hn,I,1);
%% Part d:
ynd = interp(xn,I);
%% Plot
% yn = ynb; % part b
% yn = ync; % part c
yn = ynd; % part d
```

```
hfa = figconfg('P1239a','long');
Lp = length(yn); Ls = length(hn);
stem(Ls-1:Lp-1,yn(Ls:end),'filled')
ylim([-1 1]); xlim([Ls-1 Lp-1])
xlabel('Time Index n','fontsize',LFS);
ylabel(['x_',num2str(I),'[n]'],'fontsize',LFS);
title('Steady-State Interpolated Sequence','fontsize',TFS);
```

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

    MATLAB script:

```
% P1240: Interpolation function "interp"
close all; clc
n = 0:80;
xn = cos(0.65*pi*n);
% I = 5;
% I = 10;
I = 15;
[yn b] = interp(xn,I);
%% Plot
hfa = figconfg('P1240a','long');
stem(n,xn,'filled')
ylim([-1 1]);
xlabel('Time Index n','fontsize',LFS);
ylabel('x[n]','fontsize',LFS);
title('Original Sequence','fontsize',TFS);
hfb = figconfg('P1240b','long');
stem(0:length(yn)-1,yn,'filled')
ylim([-1 1]); xlim([0 80*I])
xlabel('Time Index n','fontsize',LFS);
ylabel(['x_',num2str(I),'[n]'],'fontsize',LFS);
title('Interpolated Sequence','fontsize',TFS);
w = linspace(0,1,501)*pi;
H = freqz(b,1,w); Hmag = abs(H);
hfc = figconfg('P1240c','small');
plot(w/pi,Hmag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
```

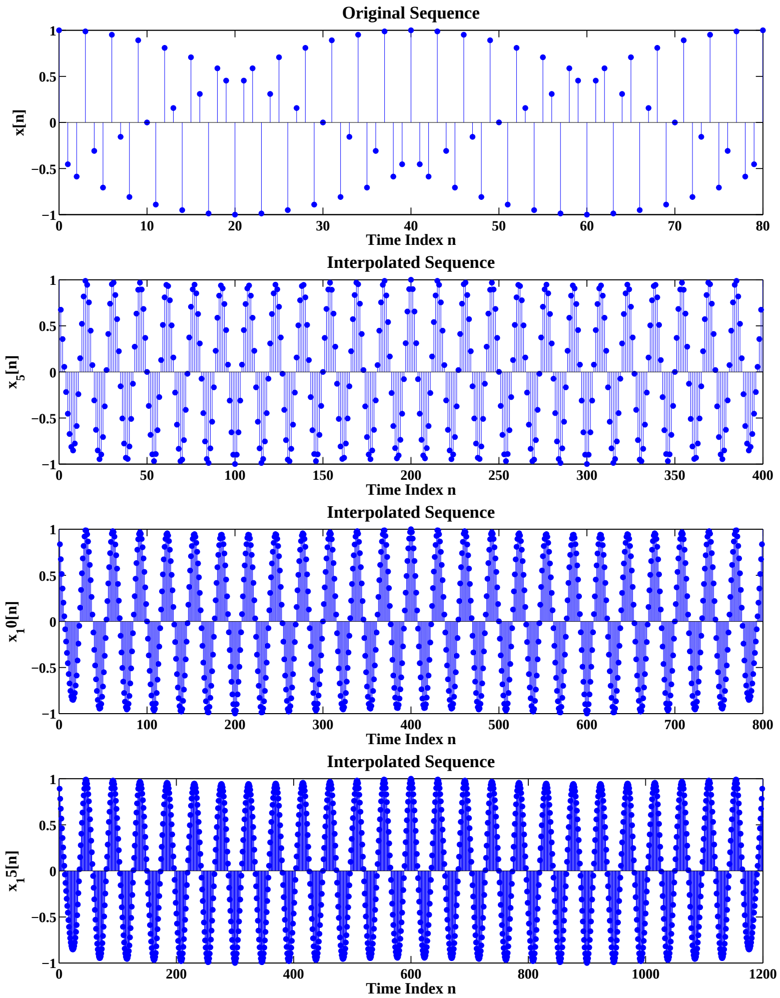

FIGURE 12.82: Stem plots of the original and interpolated signals for $I = 5$, $I = 10$, and $I = 15$.

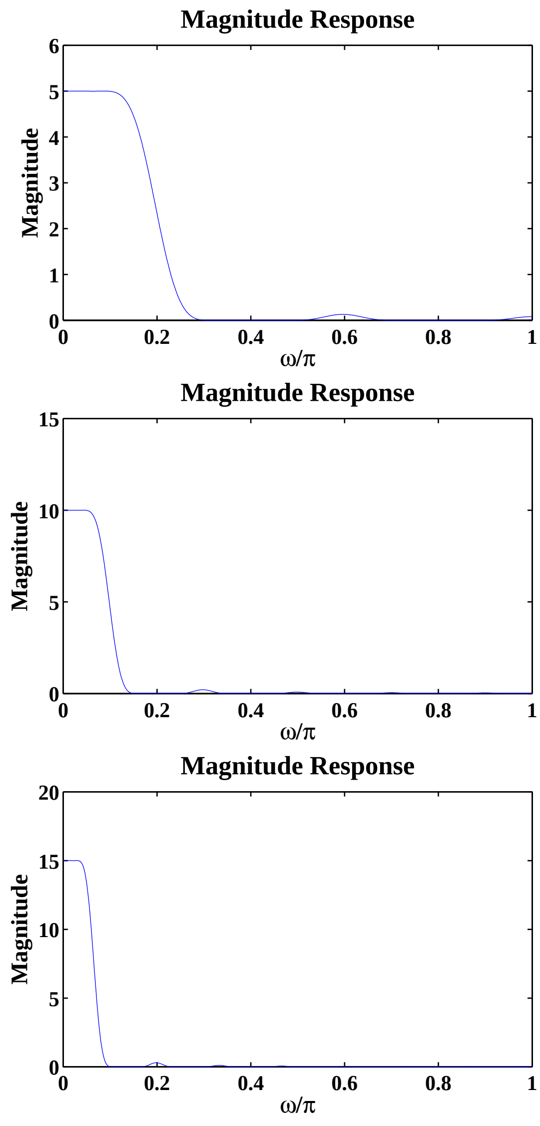

FIGURE 12.83: Magnitude responses of the lowpass filters used in interpolations for $I = 5$, $I = 10$, and $I = 15$.

41. (a) See plot below.

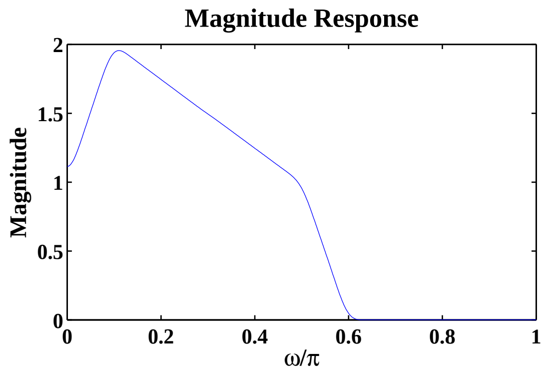

FIGURE 12.84: Magnitude responses of $x[n]$.

(b) See plot below.

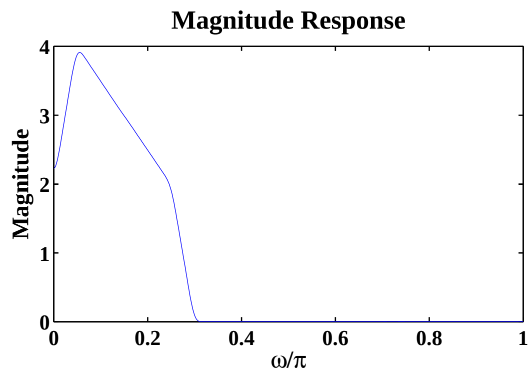

FIGURE 12.85: Magnitude responses of the upsampled signal using $I = 2$.

(c) See plot below.

(d) See plot below.

(e) tba.

MATLAB script:

```
% P1241: Interpolation; Frequency Investigation
close all; clc
L = 101; M = L - 1;
xn = fir2(M,[0,0.1,0.3,0.5,0.55,0.6,1],[1,2,1.5,1,0.5,0,0]);
```

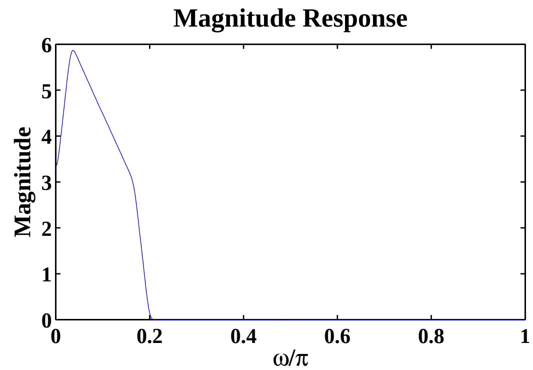

FIGURE 12.86: Magnitude responses of the upsampled signal using $I = 3$.

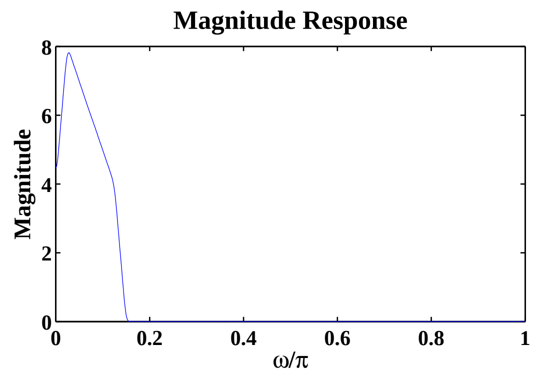

FIGURE 12.87: Magnitude responses of the upsampled signal using $I = 4$.

```
w = linspace(0,1,501)*pi;
Hx = freqz(xn,1,w); Hxmag = abs(Hx);
% I = 2;
% I = 3;
I = 4;
yn = interp(xn,I);
Hy = freqz(yn,1,w); Hymag = abs(Hy);
%% Plot
hfa = figconfg('P1241a','small');
plot(w/pi,Hxmag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
```

```
hfb = figconfg('P1241b','small');
plot(w/pi,Hymag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
```

42. (a) See plot below.

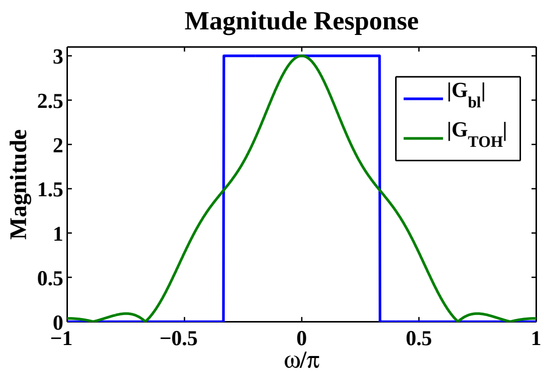

FIGURE 12.88: Magnitude responses of the ideal and TOH interpolators for $I = 3$.

(b) See plot below.

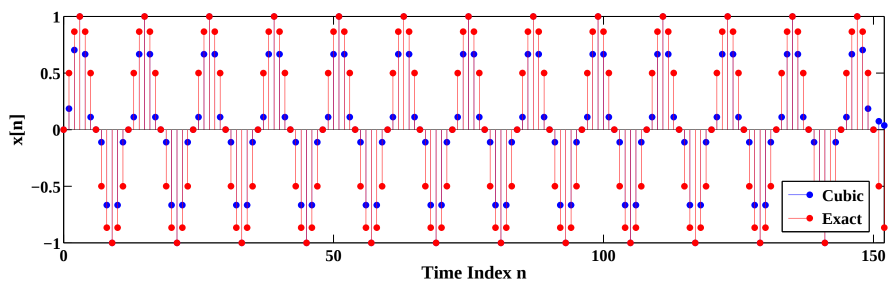

FIGURE 12.89: Stem plots of the exact interpolated and cubic interpolated sequences.

(c) See plot below.

MATLAB script:

```
% P1242: Third-order-hold (TOH) Interpretor
close all; clc
```

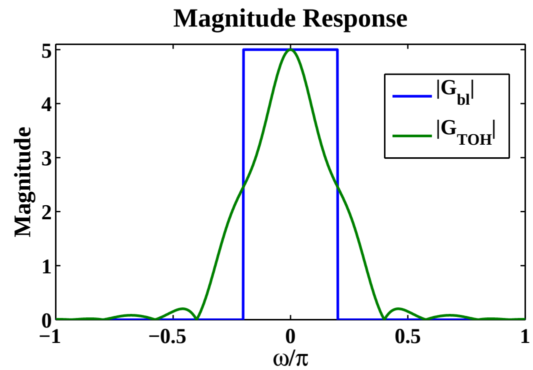

FIGURE 12.90: Magnitude responses of the ideal and TOH interpolators for $I = 5$.

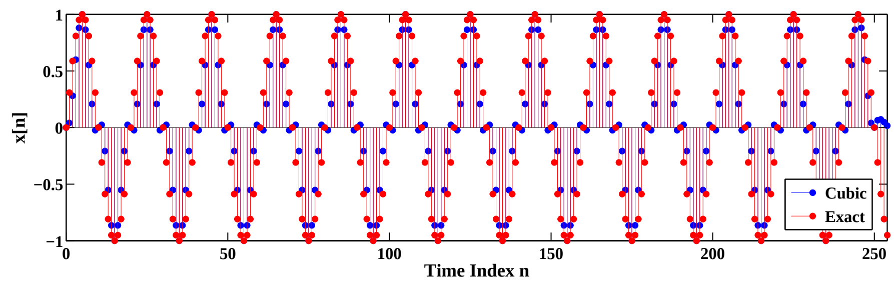

FIGURE 12.91: Stem plots of the exact interpolated and cubic interpolated sequences.

```
w = linspace(-1,1,1001)*pi;
% I = 3; % Part a
I = 5; % Part c
G_bl = zeros(size(w));
ind = (abs(w) <= pi/I);
G_bl(ind) = I; magG_bl = abs(G_bl);
n = -2*I:2*I;
a = 0.5;
% a = 0.1;
g_TOH = (a+2)*abs((n/I).^3) - (a+3)*abs((n/I).^2) + 1;
ind = abs(n) > I;
g_TOH(ind) = a*abs((n(ind)/I).^3) - 5*a*abs((n(ind)/I).^2) + ...
    8*a*abs(n(ind)/I) - 4*a;
G_TOH = g_TOH*exp(-1j*n'*w); magG_TOH = abs(G_TOH);
```

```
nn = 0:50;
xDn = sin(0.5*pi*nn);
xn = conv(g_TOH,upsample(xDn,I));
xn = xn(2*I+1:end-2*I);
xn_ref = sin(0.5*pi*(0:length(xn)-1)/I);

%% Plot:
hfa = figconfg('P1242a','small');
plot(w/pi,[magG_bl;magG_TOH],'linewidth',2)
ylim([0 I+0.1])
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
legend('|G_{bl}|','|G_{TOH}|','location','best')

hfb = figconfg('P1242b','long');
stem(0:length(xn)-1,xn,'filled'); hold on
stem(0:length(xn)-1,xn_ref,'filled','r');
xlim([0 length(xn)-1])
xlabel('Time Index n','fontsize',LFS);
ylabel('x[n]','fontsize',LFS);
legend('Cubic','Exact','location','best')
```

43. (a) See plot below.
    (b) See plot below.
    (c) tba.
    (d) See plot below.

    MATLAB script:

```
% P1243: Illustrating function "resample"
close all; clc
n = -20:20;
x1 = zeros(size(n));
ind = (20 - abs(n) > 0);
x1(ind) = 20 - abs(n(ind));
x2 = 20*ones(size(n));
ind = (abs(n)<20);
x2(ind) = abs(n(ind));
```

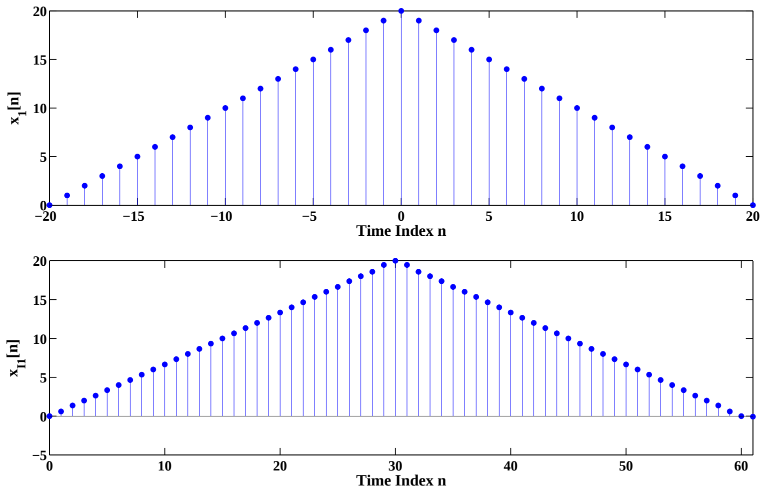

FIGURE 12.92: Stem plots of the original signal $x_1[n]$ and resampled sequence $x_{\mathrm{I}_1}[m]$.

```
[xI1 b1] = resample(x1,3,2); % Part a
[xI2 b2] = resample(x2,3,2); % Part b

w = linspace(0,1,501)*pi;
H1 = freqz(b1,1,w); H1mag = abs(H1);
H2 = freqz(b2,1,w); H2mag = abs(H2);

%% Plot
hfa = figconfg('P1243a','long');
stem(n,x1,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel('x_1[n]','fontsize',LFS);

hfb = figconfg('P1243b','long');
stem(0:length(xI1)-1,xI1,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel('x_{I1}[n]','fontsize',LFS);
xlim([0 length(xI1)-1])

hfc = figconfg('P1243c','long');
stem(n,x2,'filled')
xlabel('Time Index n','fontsize',LFS);
```

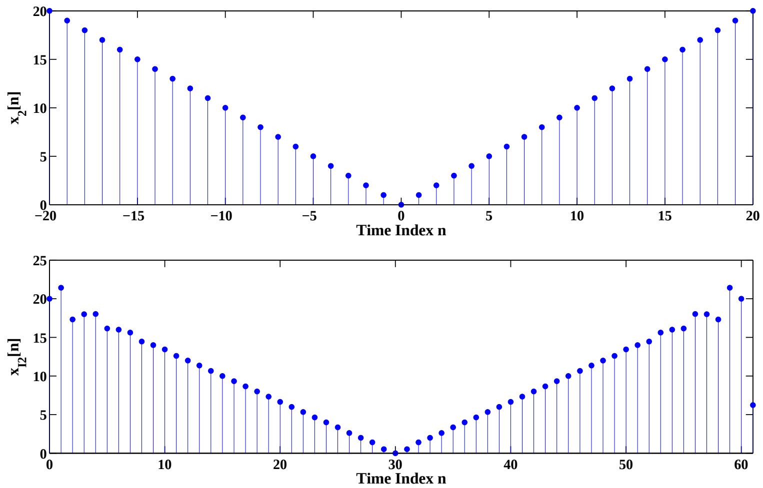

FIGURE 12.93: Stem plots of the original signal $x_2[n]$ and resampled sequence $x_{\mathrm{I}_2}[m]$.

```
ylabel('x_2[n]','fontsize',LFS);

hfd = figconfg('P1243d','long');
stem(0:length(xI2)-1,xI2,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel('x_{I2}[n]','fontsize',LFS);
xlim([0 length(xI2)-1])

hfe = figconfg('P1243e','small');
plot(w/pi,H1mag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);

hff = figconfg('P1243f','small');
plot(w/pi,H2mag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
```

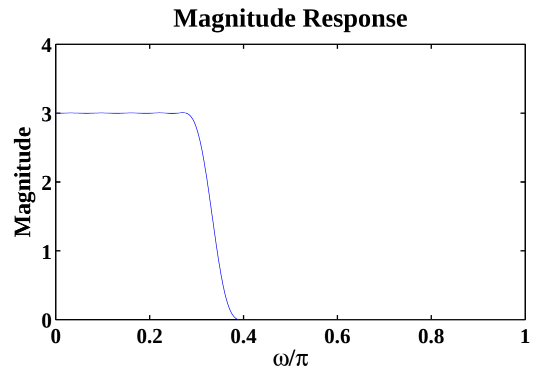

FIGURE 12.94: Magnitude response of the lowpass filter used in resampling $x_1[n]$.

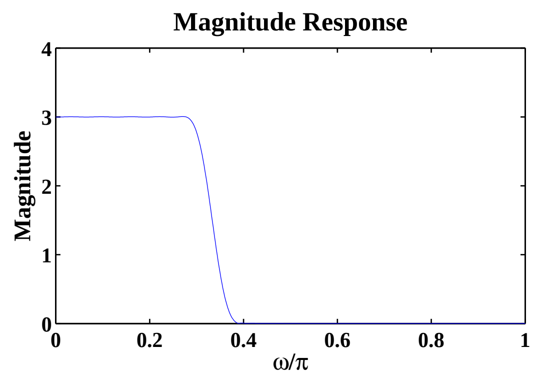

FIGURE 12.95: Magnitude response of the lowpass filter used in resampling $x_2[n]$.

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

    MATLAB script:

```
% P1244: Illustrating function "resample"
close all; clc
n = 0:100;
xn = cos(0.4*pi*n) + cos(0.6*pi*n);
xI1 = resample(xn,4,5); % Part a
xI2 = resample(xn,5,4); % Part b
xI3 = resample(xn,2,3); % Part c
```

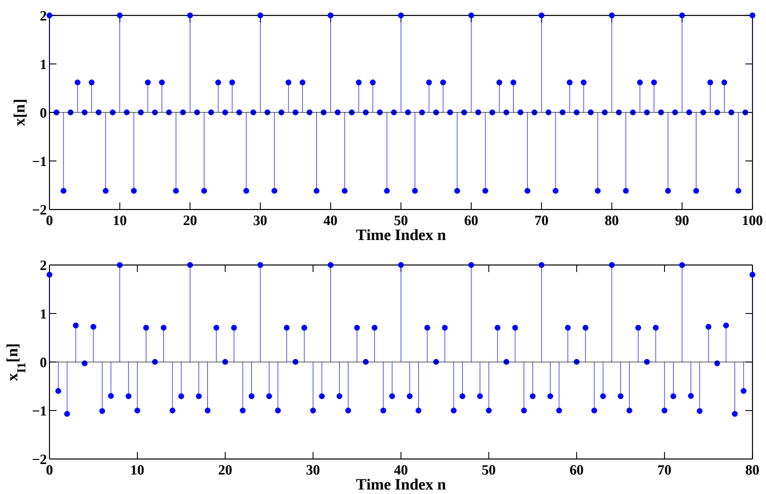

FIGURE 12.96: Stem plots of original sequence $x[n]$ and resampled sequence $x_{\mathrm{I}_1}[m]$.

```
%% Plot
hfa = figconfg('P1244a','long');
stem(n,xn,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel('x[n]','fontsize',LFS);

hfb = figconfg('P1244b','long');
stem(0:length(xI1)-1,xI1,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel('x_{I1}[n]','fontsize',LFS);
xlim([0 length(xI1)-1])

hfc = figconfg('P1244c','long');
stem(0:length(xI2)-1,xI2,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel('x_{I2}[n]','fontsize',LFS);
xlim([0 length(xI2)-1])

hfd = figconfg('P1244d','long');
stem(0:length(xI3)-1,xI3,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel('x_{I3}[n]','fontsize',LFS);
```

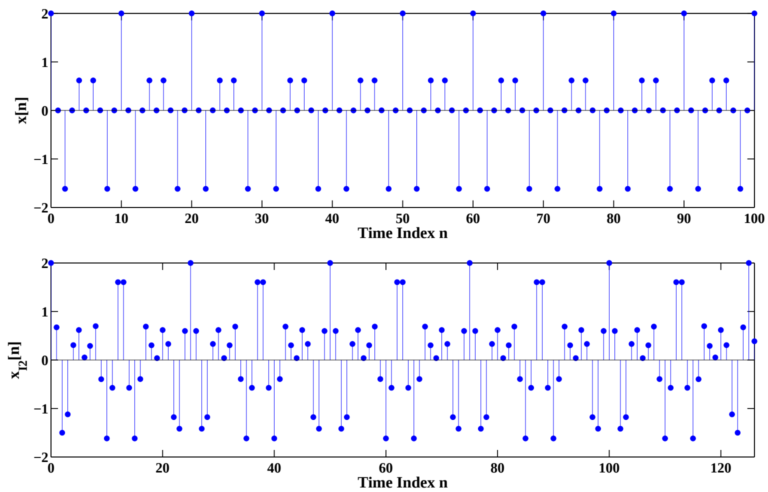

FIGURE 12.97: Stem plots of original sequence $x[n]$ and resampled sequence $x_{\mathrm{I}_2}[m]$.

```
xlim([0 length(xI3)-1])
```

45. (a) See plot below.
    (b) See plot below.
    (c) See plot below.
    (d) See plot below.
    (e) tba.

MATLAB script:

```
% P1245: Illustrating function "resample"
close all; clc
L = 101;
xn = fir2(L-1,[0,0.1,0.2,0.5,0.55,0.6,1],[0,0.5,1,1,0.5,0,0]);
w = linspace(0,1,501)*pi;
H = freqz(xn,1,w); Hmag = abs(H); % Part a
% p = 4; q = 3; % Part b
% p = 3; q = 4; % Part c
p = 3; q = 5; % Part d
xI = resample(xn,p,q);
HI = freqz(xI,1,w); HImag = abs(HI);
```

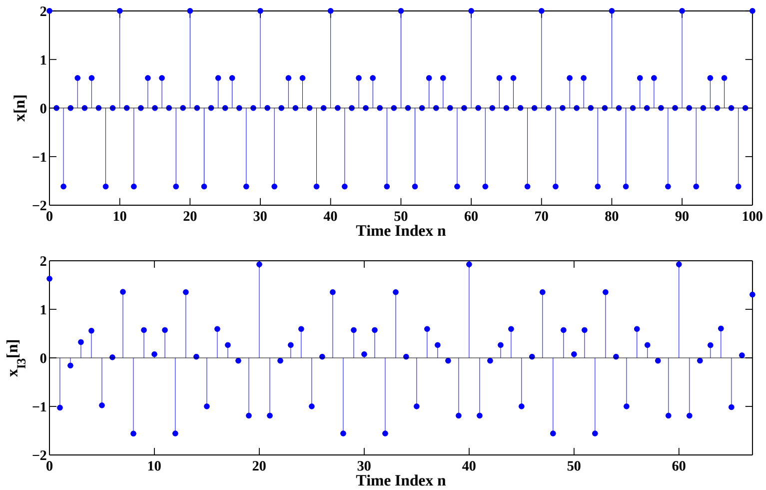

FIGURE 12.98: Stem plots of original sequence $x[n]$ and resampled sequence $x_{\mathrm{I}_3}[m]$.

```
%% Plot
hfa = figconfg('P1245a','long');
stem(0:length(xn)-1,xn,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel('x[n]','fontsize',LFS);

hfb = figconfg('P1245b','small');
plot(w/pi,Hmag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);

hfc = figconfg('P1245c','long');
stem(0:length(xI)-1,xI,'filled')
xlabel('Time Index n','fontsize',LFS);
ylabel('x_{I}[n]','fontsize',LFS);
xlim([0 length(xI)-1])

hfd = figconfg('P1245d','small');
plot(w/pi,HImag)
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
```

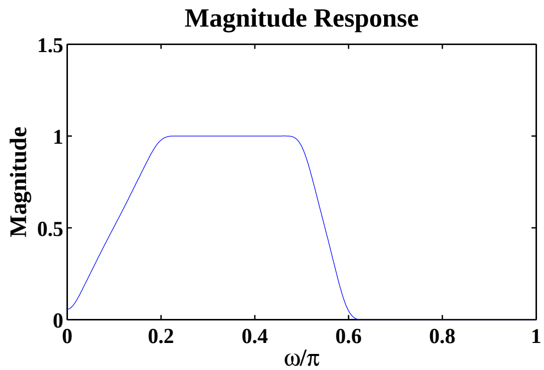

FIGURE 12.99: Magnitude spectra of $x[n]$.

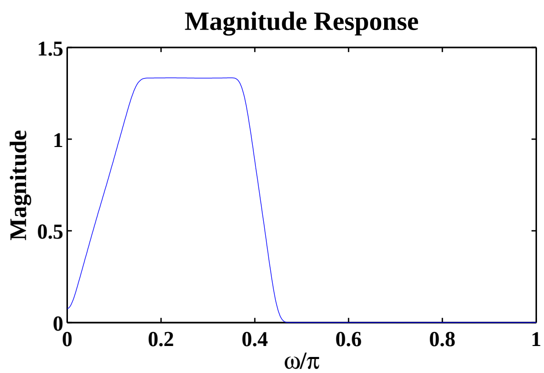

FIGURE 12.100: Magnitude spectra of the resampled sequence by a factor of $4/3$.

```
title('Magnitude Response','fontsize',TFS);
```

46. (a) See plot below.

    (b) tba.

    MATLAB script:

```
% P1246: Half-band lowpass filter
close all; clc
hn = [3 0 -19 -32 -19 0 3];
w = linspace(0,1,1001)*pi;
H = freqz(hn,1,w);
% H = 3 - 19*exp(-2j*w) - 32*exp(-3j*w) - 19*exp(-4j*w) + 3*exp(-6j*w);
Hmag = abs(H);
```

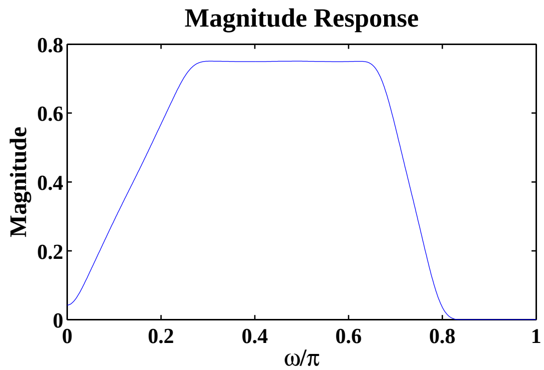

FIGURE 12.101: Magnitude spectra of the resampled sequence by a factor of $3/4$.

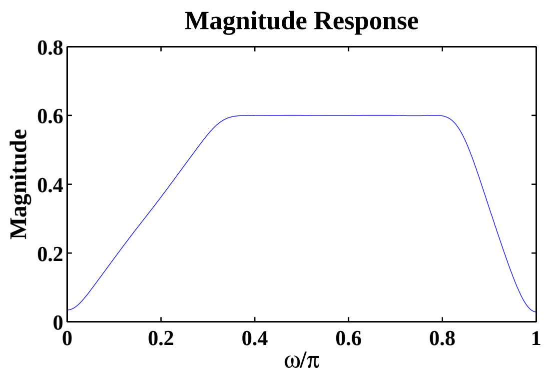

FIGURE 12.102: Magnitude spectra of the resampled sequence by a factor of $3/5$.

```
Hdb = 20*log10(Hmag./max(Hmag));
%% Plot
hfa = figconfg('P1246a','small');
plot(w/pi,Hdb);hold on
ylim([-60 0])
set(gca,'XTick',[0 pi/2 pi]/pi,'Xgrid','on')
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)
```

47. See plot below

    MATLAB script:

```
% P1247: Half-band lowpass filter design
```

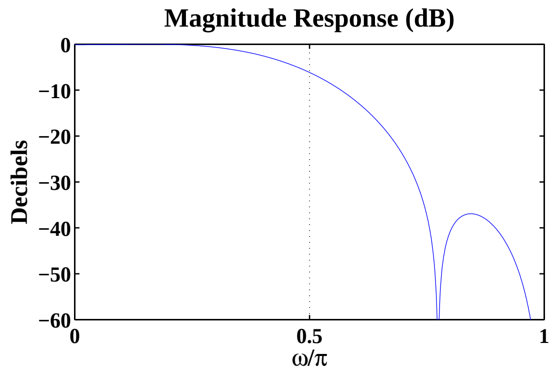

FIGURE 12.103: Magnitude spectra of the filter.

```
close all; clc
% Frequency Response parameters
om = linspace(0,pi,1001);
% Given Halfband Filter Sepcifications
omegas = 0.6*pi; omegap = pi - omegas; Ap = 0.2; As = 60;
% Step-1: Determine order M so that is is equal to 4*p-2
deltap = (10^(Ap/20)-1)/(10^(Ap/20)+1);
deltas = (1+deltap)/(10^(As/20)); delta = min(deltap,deltas);
f = [2*omegap,pi]/pi; A = [1,0]; dev = 2*[delta,delta];
[M,fo,Ao,W] = firpmord(f,A,dev);
M = ceil((M+2)/4)*4-2;
% Step-2: PM Design
[g,delta] = firpm(M/2,fo,Ao); delta
M = M+8; [g,delta] = firpm(M/2,fo,Ao); delta
% Step-3: Halfband Lowpass Filter Design
h = upsample(0.5*g,2); h(M/2+1) = 0.5; h = h(1:M+1);
% Frequency Response
H = freqz(h,1,om); Hmag = abs(H); HdB = 20*log10(Hmag/max(Hmag));
Hz = zerophase(h,1,om);
%% Plot
hfa = figconfg('P1247a','small');
plot(om/pi,Hz,'b','linewidth',0.9);
axis([0,1,-0.05,1.05]);
title('Amplitude Response','fontsize',TFS);
ylabel('Amplitude','fontsize',LFS);
xlabel('\omega','fontsize',LFS);
```

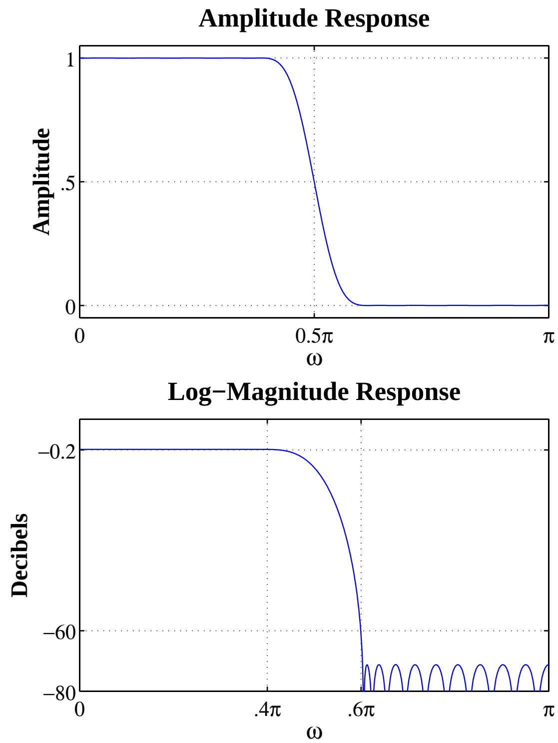

FIGURE 12.104: Amplitude response and log-magnitude response of the designed half-band filter.

```
set(gca,'Xtick',[0,0.5,1]);
set(gca,'XTickLabel','0|0.5p|p');
set(gca,'FontName','Symbol');
set(gca,'ytick',[0,0.5,1],'yticklabel','0|.5|1'); grid;

hfb = figconfg('P1247b','small');
plot(om/pi,HdB,'b','linewidth',0.9);
axis([0,1,-80,10]);
title('Log-Magnitude Response','fontsize',TFS);
ylabel('Decibels','fontsize',LFS);
xlabel('\omega','fontsize',LFS);
set(gca,'Xtick',[0,omegap/pi,omegas/pi,1]);
set(gca,'XTickLabel','0|.4p|.6p|p');
set(gca,'FontName','Symbol');
set(gca,'ytick',[-80,-As,-Ap]); grid;
```

48. (a) See plot below.

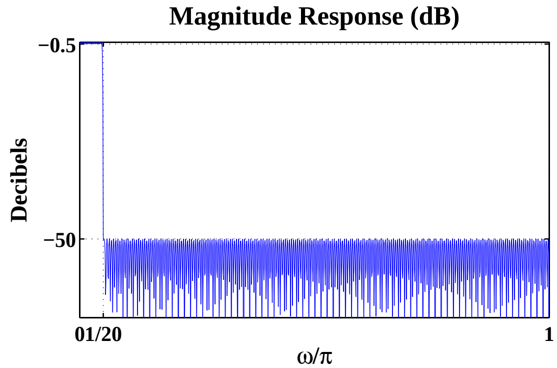

FIGURE 12.105: Log-magnitude response of the lowpass FIR filter of single-stage decimator.

(b) See plot below.

(c) See plot below.

MATLAB script:

```
% P1248: Two-stage Decimation
close all; clc
%% Given Parameters
FH = 1500; D1 = 5; D2 = 3; D = D1*D2;
FL = 100; F1 = FH/D1;
fs = 1/D; fp = fs-fs/D; Ap = 0.5; As = 50;
%% Single-stage filter design
deltap = (10^(Ap/20)-1)/(10^(Ap/20)+1);
deltas = (1+deltap)/(10^(As/20));
f = [fp,fs]; A = [1,0]; dev = [deltap,deltas];
[M,fo,Ao,W] = firpmord(f,A,dev);
M = M + 15;
[h delta] = firpm(M,fo,Ao,W);
%% Filter F(z) Design for L=5
L = D1;
fpF = fp*L; fsF = fs*L; ApF = Ap/2; AsF = As;
deltapF = (10^(ApF/20)-1)/(10^(ApF/20)+1);
deltasF = (1+deltapF)/(10^(AsF/20));
fF = [fpF,fsF]; AF = [1,0]; devF = [deltapF,deltasF];
[MF,foF,AoF,WF] = firpmord(fF,AF,devF);
```

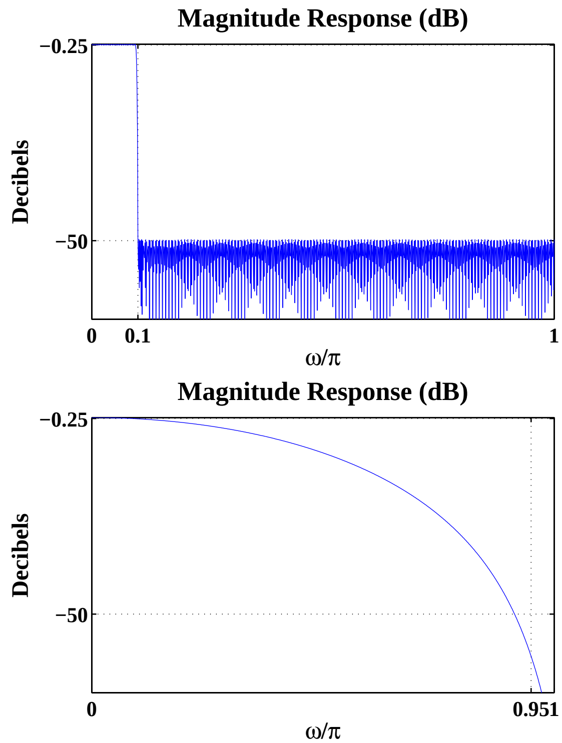

FIGURE 12.106: Log-magnitude responses of both filters of the two-stage decimator.

```
MF = MF+1;
[hF deltaF] = firpm(MF,foF,AoF,WF);
hFL = upsample(hF,L); hFL = hFL(1:end-L+1);
%% Filter G(z) Design
fpG = fp; fsG = 2/L-fs; ApG = Ap/2; AsG = As;
deltapG = (10^(ApG/20)-1)/(10^(ApG/20)+1);
deltasG = (1+deltapG)/(10^(AsG/20));
fG = [fpG,fsG]; AG = [1,0]; devG = [deltapG,deltasG];
[MG,foG,AoG,WG] = firpmord(fG,AG,devG);
MG = MG+3;
[hG deltaG] = firpm(MG,foG,AoG,WG);
%% Equivalent Filter hGF = hG * hL
hGF = conv(hG,hFL);

%% Computational Complexity: Mults/sec (multrate)
```

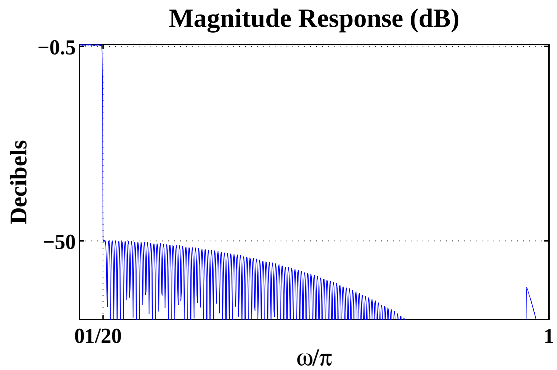

FIGURE 12.107: Log-magnitude response of the lowpass FIR filter of the equivalent single-stage filter from (b).

```
filtlenA = length(h),      % Approach-A
filtlenB = length(hG), % Approach-B
filtlenC = length(hF), % Approach-B

multrateA = length(h)*FH/D,     % Approach-A
multrateB = length(hGF)*FH/D, % Approach-B
multrateC1 = length(hG)*FH/D1,  % Approach-C1
multrateC2 = length(hF)*F1/D2,   % Approach-C2
multrateC = multrateC1+multrateC2, % Approach-C

%% Plot:
w = linspace(0,1,1001)*pi;
H = freqz(h,1,w);
Hmag = abs(H); Hdb = 20*log10(Hmag./max(Hmag));
hfa = figconfg('P1248a','small');
plot(w/pi,Hdb);hold on
ylim([-70 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)
set(gca,'XTick',[0 pi/D pi]/pi,'Xgrid','on','Xticklabel','0|1/15|1')
set(gca,'YTick',[-As -Ap],'Ygrid','on')

HF = freqz(hF,1,w);
HFmag = abs(HF); HFdb = 20*log10(HFmag./max(HFmag));
```

```
hfb = figconfg('P1248b','small');
plot(w/pi,HFdb);hold on
ylim([-70 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)
set(gca,'XTick',[0 pi*fsF pi]/pi,'Xgrid','on')
set(gca,'YTick',[-AsF -ApF],'Ygrid','on')

HG = freqz(hG,1,w);
HGmag = abs(HG); HGdb = 20*log10(HGmag./max(HGmag));
hfc = figconfg('P1248c','small');
plot(w/pi,HGdb);hold on
ylim([-70 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)
set(gca,'XTick',[0 pi*fsG pi]/pi,'Xgrid','on')
set(gca,'YTick',[-AsG -ApG],'Ygrid','on')

HGF = freqz(hGF,1,w);
HGFmag = abs(HGF); HGFdb = 20*log10(HGFmag./max(HGFmag));
hfd = figconfg('P1248d','small');
plot(w/pi,HGFdb);hold on
ylim([-70 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)
set(gca,'XTick',[0 pi/D pi]/pi,'Xgrid','on','Xticklabel','0|1/15|1')
set(gca,'YTick',[-As -Ap],'Ygrid','on')
```

Review Problems

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

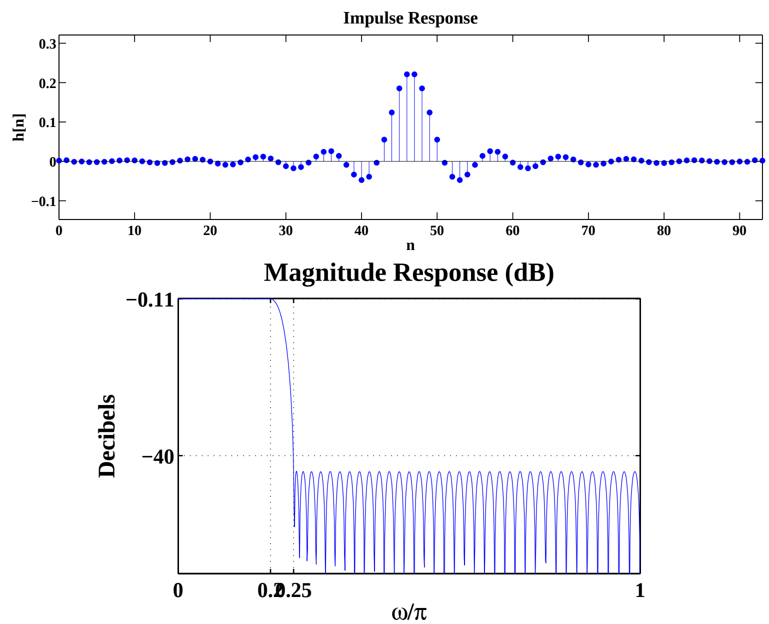

FIGURE 12.108: Impulse and log-magnitude responses of the designed FIR filter.

    (c) tba.
    (d) See plot below.

MATLAB script:

```
% P1249: Resampling
close all; clc
I = 3; D = 2;
ws = 0.25*pi; wp = 0.2*pi; As = 40; Ap = 0.11;
deltap = (10^(Ap/20)-1)/(10^(Ap/20)+1);
deltas = (1+deltap)/(10^(As/20));
[M,fo,Ao,W] = firpmord([wp ws]/pi,[1 0],[deltap deltas]);
M = M + 10;
[h delta] = firpm(M,fo,Ao,W);
N = 101;
xn = fir2(N-1,[0 0.3 0.7 0.75 0.8 1],[0.7 1 1 0.5 0 0]);
```

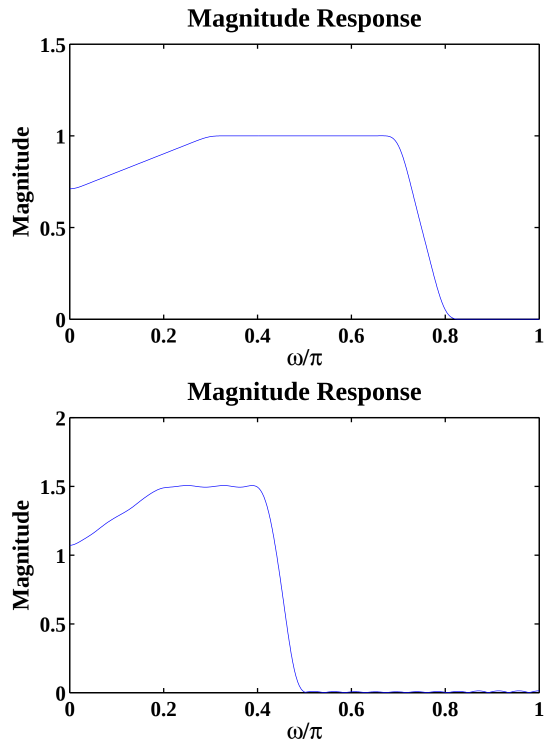

FIGURE 12.109: Magnitude spectra of original sequence $x[n]$ and resampled sequence $x_{\mathrm{R}}[m]$.

```
xu = sre(xn,I);
xi = filter(h,1,xu)*I/D;
xR = src(xi,D); xR = xR*D;

w = linspace(0,1,1001)*pi;
H = freqz(h,1,w); Hmag = abs(H); Hdb = 20*log10(Hmag./max(Hmag));
X = freqz(xn,1,w); Xmag = abs(X);
XR = freqz(xR,1,w); XRmag = abs(XR);

%% Plot
hfa = figconfg('P1249a','long');
stem(0:length(h)-1,h,'filled');
xlim([0 length(h)-1])
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('P1249b','small');
plot(w/pi,Hdb);hold on
ylim([-70 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)
set(gca,'XTick',[0 wp ws pi]/pi,'Xgrid','on')
set(gca,'YTick',[-As -Ap],'Ygrid','on')

hfc = figconfg('P1249c','small');
plot(w/pi,Xmag);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Magnitude','fontsize',LFS)
title('Magnitude Response','fontsize',TFS)

hfd = figconfg('P1249d','small');
plot(w/pi,XRmag);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Magnitude','fontsize',LFS)
title('Magnitude Response','fontsize',TFS)
```

50. (a) See script below.
    (b) See plot below.
    (c) tba.
    (d) See plot below.

    MATLAB script:

```
% P1250: Resampling
close all; clc
I = 3; D = 8;
ws = 0.12*pi; wp = 0.1*pi; As = 50; Ap = 0.5;
deltap = (10^(Ap/20)-1)/(10^(Ap/20)+1);
deltas = (1+deltap)/(10^(As/20));
[M,fo,Ao,W] = firpmord([wp ws]/pi,[1 0],[deltap deltas]);
M = M + 8;
[h delta] = firpm(M,fo,Ao,W);
```

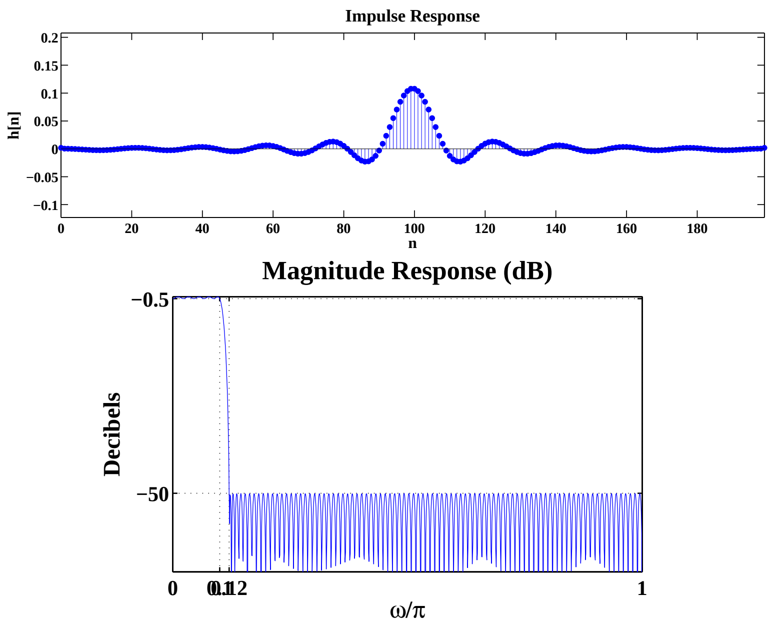

FIGURE 12.110: Impulse and log-magnitude responses of the designed FIR filter.

```
N = 101;
xn = fir2(N-1,[0 0.25 0.5 0.55 0.6 1],[1 1 1 0.5 0 0]);
xu = sre(xn,I);
xi = filter(h,1,xu)*I/D;
xR = src(xi,D); xR = xR*D;

w = linspace(0,1,1001)*pi;
H = freqz(h,1,w); Hmag = abs(H); Hdb = 20*log10(Hmag./max(Hmag));
X = freqz(xn,1,w); Xmag = abs(X);
XR = freqz(xR,1,w); XRmag = abs(XR);

%% Plot
hfa = figconfg('P1250a','long');
stem(0:length(h)-1,h,'filled');
xlim([0 length(h)-1])
ylim([min(h)-0.1 max(h)+0.1])
xlabel('n','fontsize',LFS)
ylabel('h[n]','fontsize',LFS)
title('Impulse Response','fontsize',TFS)
```

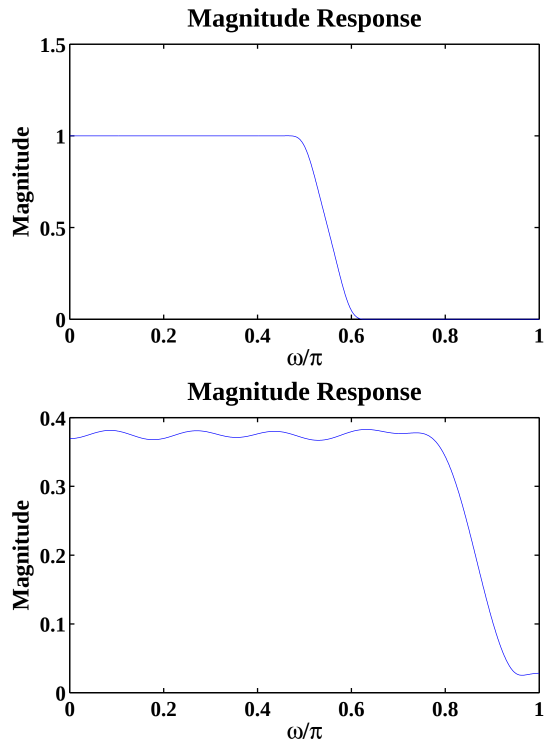

FIGURE 12.111: Magnitude spectra of original sequence $x[n]$ and resampled sequence $x_{\mathrm{R}}[m]$.

```
hfb = figconfg('P1250b','small');
plot(w/pi,Hdb);hold on
ylim([-70 0])
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Decibels','fontsize',LFS)
title('Magnitude Response (dB)','fontsize',TFS)
set(gca,'XTick',[0 wp ws pi]/pi,'Xgrid','on')
set(gca,'YTick',[-As -Ap],'Ygrid','on')

hfc = figconfg('P1250c','small');
plot(w/pi,Xmag);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Magnitude','fontsize',LFS)
title('Magnitude Response','fontsize',TFS)
```

```
hfd = figconfg('P1250d','small');
plot(w/pi,XRmag);
xlabel('\omega/\pi','fontsize',LFS)
ylabel('Magnitude','fontsize',LFS)
title('Magnitude Response','fontsize',TFS)
```