CHAPTER 11

Design of IIR Filters

Tutorial Problems

1. (a) Solution:
   The frequency response is:

$$H\left(e^{j\omega}\right) = H(z)|_{z=e^{j\omega}} = \frac{e^{j\omega}}{(e^{j\omega}-0.8)(1-0.8e^{j\omega})} = \frac{1}{1.64-1.6\cos\omega}$$

   (b) Solution:
   Apply partial fraction expansion to system function:

$$H(z) = \frac{-1.25z^{-1}}{(1-0.8^{-1})(1-1.25z^{-1})} = \frac{25/9}{1-0.8z^{-1}} + \frac{-25/9}{1-1.25z^{-1}}$$

   where $0.8 \le |z| \le 1.25$, hence the impulse response is:

$$h[n] = \frac{25}{9}\cdot 0.8^n u[n] + \frac{25}{9}\cdot 1.25^n u[-n-1] = \frac{25}{9}\cdot 0.8^{|n|}$$

   (c) See plot below.
   MATLAB script:

```
% P1101: Illustration of usage of function ’filtfilt’
close all; clc
N = 30;
n = -N:N;
% Analytical Result:
hn1 = zeros(size(n));
ind = n >= 0;
hn1(ind) = 25/9*0.8.^n(ind);
ind = n < 0;
```

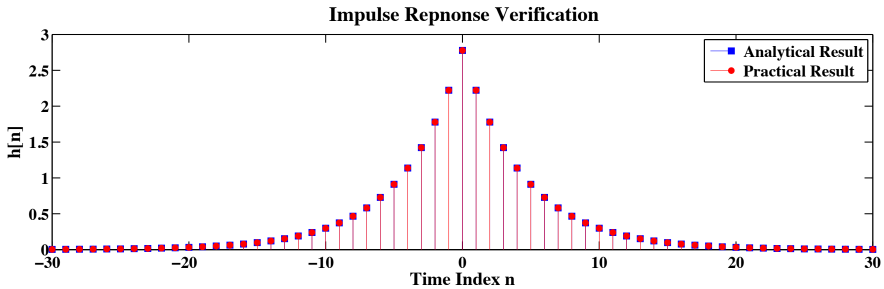

FIGURE 11.1: MATLAB verification of the impulse response of the filter using the `filtfilt` function.

```
hn1(ind) = 25/9*1.25.^n(ind);
% Practical Result:
deltan = zeros(size(n)); deltan(ceil(length(n)/2)) = 1;
b = [0 1];
a = [1 -0.8];
hn2 = filtfilt(b,a,deltan);
%% plot
hfa = figconfg('P1101a','long');
stem(n,hn1,'filled','marker','s','markersize',8); hold on
stem(n,hn2,'r','filled')
xlabel('Time Index n','fontsize',LFS)
ylabel('h[n]','fontsize',LFS)
title('Impulse Repnonse Verification','fontsize',TFS)
legend('Analytical Result','Practical Result','location','northeast')
```

2. (a) Solution:
   Pole locations of $H_c(s)$: $s_k = \sigma_k + \mathrm{j}\Omega_s$, that is

   $$\begin{cases} \sigma_k = \Omega_c \cos\theta_k, \\ \Omega_k = \Omega_c \sin\theta_k. \end{cases} \quad \text{where } \theta_k = \frac{\pi}{2} + \frac{2k-1}{2N}\pi, k = 1, 2, \ldots, 2N$$

   $\Omega_c = 40\pi$ rad/s, $N = 7$.

   (b) See plot below.

   (c) Solution:
   The frequencies are 27.77, 32.76, and 38.61 rad/s at which the attenuation is 20 dB, 30 dB, and 40 dB.

MATLAB script:

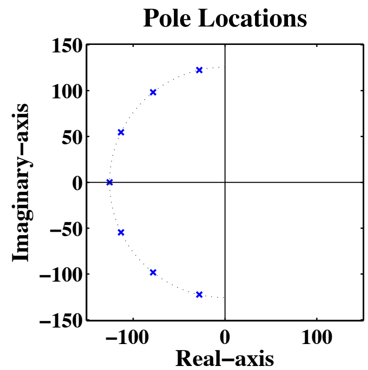

FIGURE 11.2: Pole locations of $H_c(s)$

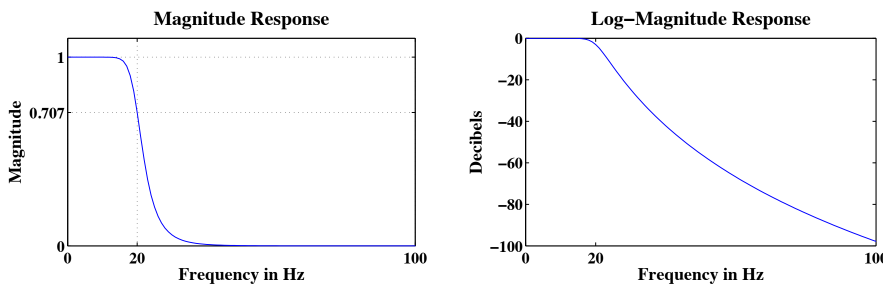

FIGURE 11.3: Magnitude and log-magnitude responses over $[0, 100]$ Hz range.

```
% P1102: Seventh order Butterworth low-pass filter
close all; clc
N = 7;
% Determine cutoff frequency
Hc = 20;
Omegac = Hc*2*pi;
% Determine zero locations
k = 1:N; thetak = pi/2+(2*k-1)*pi/2/N;
sigmak = Omegac*cos(thetak); Omegak = Omegac*sin(thetak);
sk = cplxpair(sigmak + 1j*Omegak);
% Compute system function
C = Omegac^N;
D = real(poly(sk));
Fmax = 100;
F = linspace(0,Fmax,101);
Om = F*2*pi;
```

```
H = freqs(C,D,F*2*pi);
Hmag = abs(H); Hpha = angle(H);
Hdb = 20*log10(Hmag);
Hgdl = -diff(unwrap(Hpha))./diff(Om); Hgdl = [Hgdl,Hgdl(end)];
% Part c:
A = [3 20 30 40];
delta = (10.^(-A/20)).^2;
disp('Frequencies where attenuation is 3db, 20db, 30db, 40db')
F3 = (1./delta-1).^(1/2/N)*Hc,
%% Plot:
hfa = figconfg('P1102a','small');
plot(sigmak,Omegak,'bx','linewidth',1.5); hold on;
ff = 1.2; pc = ff*Omegac;
plot([-pc,pc],[0,0],'k','linewidth',0.75);
plot([0,0],[-pc,pc],'k','linewidth',0.75);
plot(Omegac*cos(0.5*pi*[1:0.01:3]),Omegac*sin(0.5*pi*[1:0.01:3]),'k:');
axis([-pc,pc,-pc,pc]);
axis square;
xlabel('Real-axis','fontsize',LFS);
ylabel('Imaginary-axis','fontsize',LFS);
title('Pole Locations','fontsize',TFS);

hfb = figconfg('P1102b','small');
plot(F,Hmag,'b','linewidth',1);
axis([0,Fmax,0,1.1]);
xlabel('Frequency in Hz','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,Hc,Fmax]);
set(gca,'ytick',[0,0.707,1]); grid;

hfc = figconfg('P1102c','small');
plot(F,Hdb,'b','linewidth',1);
axis([0,Fmax,-100,0]);
xlabel('Frequency in Hz','fontsize',LFS);
ylabel('Decibels','fontsize',LFS);
title('Log-Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,Hc,Fmax]);
```

3. See plot below.

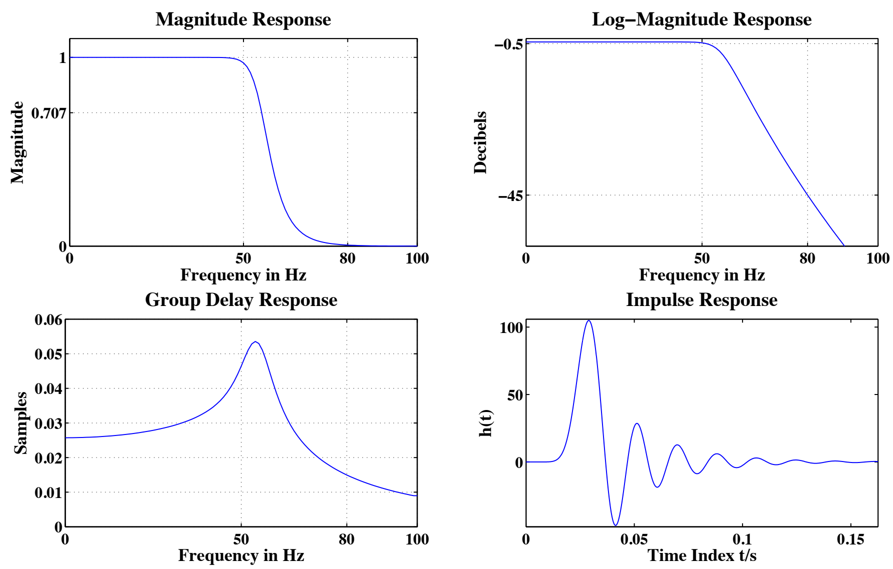

FIGURE 11.4: Plots of the magnitude, log-magnitude, group-delay, and impulse responses..

MATLAB script:

```
% P1103: Analog Butterworth lowpass filter design
clc; close all;
% Given Design Parameters
Fp = 50; Fs = 80; Ap = 0.5; As = 45;
Omegap = Fp*2*pi; Omegas = Fs*2*pi;
% Analog Design Parameters (Eq. 10.9)
epsilon = sqrt(10^(0.1*Ap)-1);
A = 10^(0.05*As);
%% Design Steps
% Step-1: Calulation of N
alpha = Omegas/Omegap;
beta = (1/epsilon)*sqrt(A^2-1);
N = log(beta)/log(alpha);
N = ceil(N);
% Step-2: Calculation of Omegac
OmegacL = Omegap/(10^(0.1*Ap)-1)^(1/(2*N));
OmegacH = Omegas/(10^(0.1*As)-1)^(1/(2*N));
```

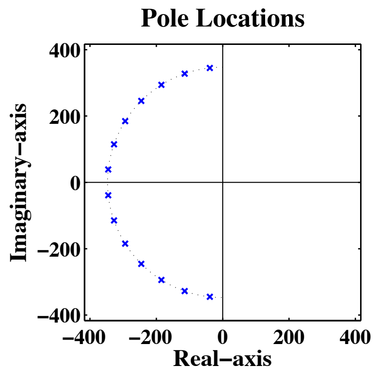

FIGURE 11.5: Pole-zero plot of the filter

```
Omegac = OmegacH;
Fc = Omegac/2/pi;
% Step-3: Calculations of Poles
k = 1:N; thetak = pi/2+(2*k-1)*pi/(2*N);
sigmak = Omegac*cos(thetak); Omegak = Omegac*sin(thetak);
sk = cplxpair(sigmak + 1j*Omegak);
% Step-4: Calculation of the system function
C = Omegac^N; D = real(poly(sk)); % Direct Form

% Design using SP Toolbox functions
% [N, Wn] = buttord(Omegap, Omegas, Ap, As, 's');
% [C,D] = butter(N,Wn,'s')

Fmax = 100;
F = linspace(0,Fmax,101);
Om = F*2*pi;
H = freqs(C,D,Om);
Hmag = abs(H); Hpha = angle(H); Hdb = 20*log10(Hmag);
Hgdl = -diff(unwrap(Hpha))./diff(Om); Hgdl = [Hgdl,Hgdl(end)];

% Impulse response:
trsys = tf(C,D);
[ht t] = impulse(trsys);

%% Design Plots
hfa = figconfg('P1103a','small'); % magnitude
```

```
plot(F,Hmag,'b','linewidth',1);
axis([0,Fmax,0,1.1]);
xlabel('Frequency in Hz','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,Fp,Fs,Fmax]);
set(gca,'ytick',[0,0.707,1]); grid;

hfb = figconfg('P1103b','small'); % Log-Magnitude Plot in dB
plot(F,Hdb,'b','linewidth',1);
axis([0,Fmax,-60,1]);
xlabel('Frequency in Hz','fontsize',LFS);
ylabel('Decibels','fontsize',LFS);
title('Log-Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,Fp,Fs,Fmax]);
set(gca,'ytick',[-As,-Ap]);grid

hfc = figconfg('P1103c','small'); % Group-Delay Plot in Samples
plot(F,Hgdl,'b','linewidth',1);
xlabel('Frequency in Hz','fontsize',LFS);
ylabel('Samples','fontsize',LFS);
title('Group Delay Response','fontsize',TFS);
set(gca,'xtick',[0,Fp,Fs,Fmax]); grid

hfd = figconfg('P1103d','small'); % Pole-zero Plot
plot(sigmak,Omegak,'bx','linewidth',1.5); hold on;
ff = 1.2; pc = ff*Omegac;
plot([-pc,pc],[0,0],'k','linewidth',0.75);
plot([0,0],[-pc,pc],'k','linewidth',0.75);
plot(Omegac*cos(0.5*pi*[1:0.01:3]),Omegac*sin(0.5*pi*[1:0.01:3]),'k:');
axis([-pc,pc,-pc,pc]);
axis square;
xlabel('Real-axis','fontsize',LFS);
ylabel('Imaginary-axis','fontsize',LFS);
title('Pole Locations','fontsize',TFS);

hfe = figconfg('P1103e','small'); % Impulse response
plot(t,ht,'linewidth',1)
axis([t(1) t(end) min(ht)-1 max(ht)+1])
xlabel('Time Index t/s','fontsize',LFS);
```

```
ylabel('h(t)','fontsize',LFS);
title('Impulse Response','fontsize',TFS);
```

4. Proof:
Repeat the definition of Chebyshev polynomial as below:

$$T_0(x) = 1, \quad T_1(x) = x, \quad T_{m+1}(x) = 2xT_m(x) - T_{m-1}(x),\ m > 1$$

Repeat $T_N(x)$ given by hyperbolic functions (11.29) as:

$$T_N(x) = \cosh(N\cosh^{-1} x), \quad |x| > 1$$

$$\cosh(x) \triangleq \frac{1}{2}(\mathrm{e}^x + \mathrm{e}^{-x}), \quad \cosh^{-1}(x) = \ln(x + \sqrt{x^2 - 1}) \qquad (11.29a)$$

$$\sinh(x) \triangleq \frac{1}{2}(\mathrm{e}^x - \mathrm{e}^{-x}), \quad \sinh^{-1}(x) = \ln(x + \sqrt{x^2 + 1}) \qquad (11.29b)$$

If $m = 0$, we have

$$T_0(x) = \cosh(0 \cdot \cosh^{-1} x) = \frac{1}{2}(\mathrm{e}^0 + \mathrm{e}{-}0) = 1.$$

If $m = 1$, we have

$$T_1(x) = \cosh(\cosh^{-1)x} = x.$$

If $m > 1$, we have

$$T_{m+1}(x) = \cosh[(m{+}1)\cosh^{-1} x] = x{\cdot}\cosh(m\cosh^{-1} x){+}\sinh(m\cosh^{-1} x)\sinh(\cosh^{-1} x)$$

$$T_{m-1}(x) = \cosh[(m{-}1)\cosh^{-1} x] = x{\cdot}\cosh(m\cosh^{-1} x){-}\sinh(m\cosh^{-1} x)\sinh(\cosh^{-1} x)$$

Hence,

$$T_{m+1}(x) + T_{m-1}(x) = 2x \cdot \cosh(m\cosh^{-1} x) = 2xT_m(x)$$

5. See plot below.

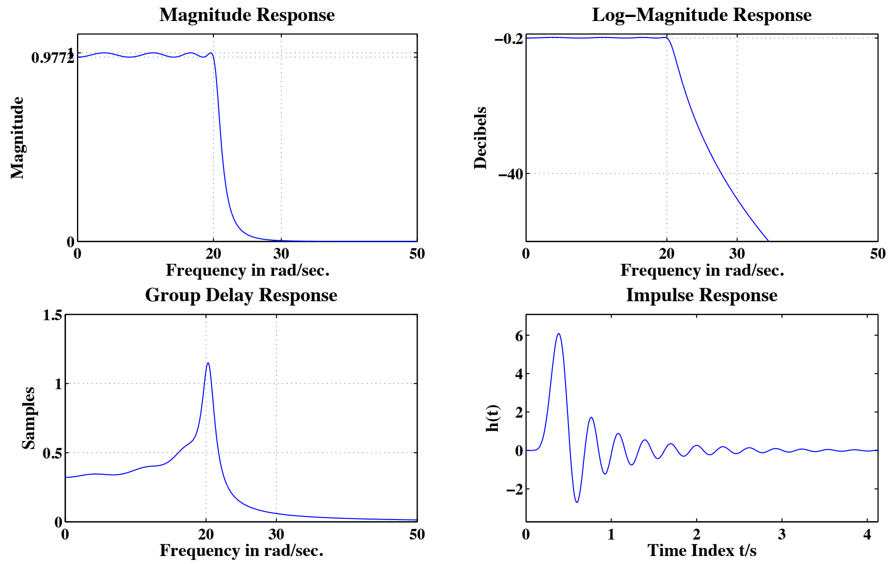

FIGURE 11.6: Plots of the magnitude, log-magnitude, group-delay, and impulse responses..

MATLAB script:

```
% P1105: Analog Chebyshev I lowpass filter design
clc; close all;
% Given Design Parameters
Omegap = 20; Omegas = 30; Ap = 0.2; As = 40;
% Analog Design Parameters (Eq. 10.9)
epsilon = sqrt(10^(0.1*Ap)-1); A = 10^(0.05*As);
Rp = 1/sqrt(1+epsilon^2);

%% Design Steps
% Step-1: Compute alpha and beta
alpha = Omegas/Omegap; beta = (1/epsilon)*sqrt(A^2-1);
% Step-2: Calulation of N
N = log(beta+sqrt(beta^2-1))/log(alpha+sqrt(alpha^2-1));
N = ceil(N);
% Step-3: Calculation of a and b
Omegac = Omegap;
gamma = (1/epsilon+sqrt(1+1/epsilon^2))^(1/N);
```

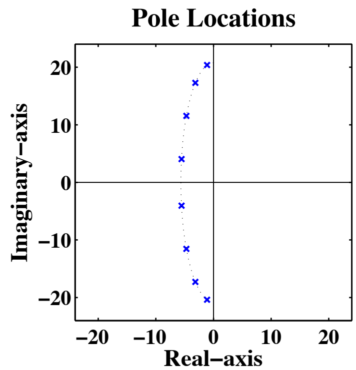

FIGURE 11.7: Pole-zero plot of the filter

```
a = 0.5*(gamma-1/gamma); b = 0.5*(gamma+1/gamma);
% Step-4: Calculations of Poles
k = 1:N; thetak = pi/2+(2*k-1)*pi/(2*N);
sigmak = (a*Omegac)*cos(thetak); Omegak = (b*Omegac)*sin(thetak);
sk = cplxpair(sigmak + 1j*Omegak);
% Step-5: Calculation of the system function
D = real(poly(sk)); % Direct Form
if mod(N,2) == 0
    G = D(end)*Rp; %1/sqrt(1+epsilon^2);
else
    G = D(end);
end
C = G;

%% Design using SP Toolbox functions
% [N, Wp] = cheb1ord(Omegap, Omegas, Ap, As, 's');
% [c,d] = cheby1(N,Ap, Wp,'s');

%% Frequency Response
Ommax = 50;
Om = linspace(0,Ommax,501);
H = freqs(C,D,Om);
Hmag = abs(H); Hpha = angle(H); Hdb = 20*log10(Hmag);
Hgdl = -diff(unwrap(Hpha))./diff(Om); Hgdl = [Hgdl,Hgdl(end)];

% Impulse response:
```

```
trsys = tf(C,D);
[ht t] = impulse(trsys);

%% Design Plots
hfa = figconfg('P1105a','small'); % magnitude
plot(Om,Hmag,'b','linewidth',1);
axis([0,Ommax,0,1.1]);
xlabel('Frequency in rad/sec.','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,Omegac,Omegas,Ommax]);
set(gca,'ytick',[0,Rp,1]); grid;

hfb = figconfg('P1105b','small'); % Log-Magnitude Plot in dB
plot(Om,Hdb,'b','linewidth',1);
axis([0,Ommax,-60,1]);
xlabel('Frequency in rad/sec.','fontsize',LFS);
ylabel('Decibels','fontsize',LFS);
title('Log-Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,Omegap,Omegas,Ommax]);
set(gca,'ytick',[-As,-Ap]);grid

hfc = figconfg('P1105c','small'); % Group-Delay Plot in Samples
plot(Om,Hgdl,'b','linewidth',1);
xlabel('Frequency in rad/sec.','fontsize',LFS);
ylabel('Samples','fontsize',LFS);
title('Group Delay Response','fontsize',TFS);
set(gca,'xtick',[0,Omegap,Omegas,Ommax]); grid

hfd = figconfg('P1105d','small'); % Pole-zero Plot
plot(sigmak,Omegak,'bx','linewidth',1.5); hold on;
ff = 1.2; pc = ff*Omegac;
plot([-pc,pc],[0,0],'k','linewidth',0.75);
plot([0,0],[-pc,pc],'k','linewidth',0.75);
plot(a*Omegac*cos(0.5*pi*[1:0.01:3]),b*Omegac*sin(0.5*pi*[1:0.01:3]),'k:');
axis([-pc,pc,-pc,pc]);
axis square;
xlabel('Real-axis','fontsize',LFS);
ylabel('Imaginary-axis','fontsize',LFS);
title('Pole Locations','fontsize',TFS);
```

```
hfe = figconfg('P1105e','small'); % Impulse response
plot(t,ht,'linewidth',1)
axis([t(1) t(end) min(ht)-1 max(ht)+1])
xlabel('Time Index t/s','fontsize',LFS);
ylabel('h(t)','fontsize',LFS);
title('Impulse Response','fontsize',TFS);
```

6. See plot below.

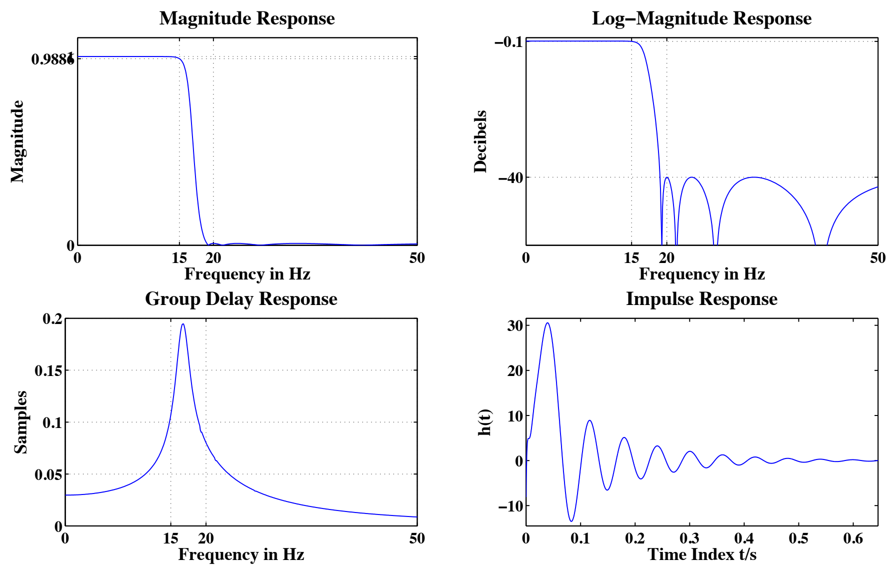

FIGURE 11.8: Plots of the magnitude, log-magnitude, group-delay, and impulse responses..

MATLAB script:

```
% P1106: Analog Chebyshev II lowpass filter design
clc; close all;
% Given Design Parameters
Fp = 15; Fs = 20; Ap = 0.1; As = 40;
Omegap = 2*pi*Fp; Omegas = 2*pi*Fs;
% Analog Design Parameters (Eq. 10.9)
epsilon = sqrt(10^(0.1*Ap)-1); A = 10^(0.05*As);
Rp = 1/sqrt(1+epsilon^2);
```

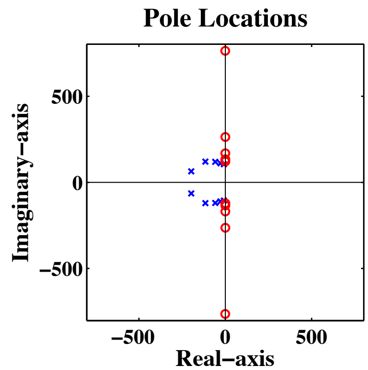

FIGURE 11.9: Pole-zero plot of the filter

```
% Plotting Parameters
Fmax = 50; Ommax = 2*pi*Fmax;
F = linspace(0,Fmax,501); Om = 2*pi*F;

% Chebyshev-II Approximation
disp('** Chebyshev-II **');
[N, Omegac] = cheb2ord(Omegap, Omegas, Ap, As, 's');
Fc = Omegac/(2*pi);
[C,D] = cheby2(N,As,Omegac,'s'); H = freqs(C,D,Om);
Hmag = abs(H); Hpha = angle(H); Hdb = 20*log10(Hmag);
Hgdl = -diff(unwrap(Hpha))./diff(Om); Hgdl = [Hgdl,Hgdl(end)];
Hgdl = medfilt1(Hgdl,3);
pk = roots(D); sigmapk = real(pk); Omegapk = imag(pk);
zk = roots(C); sigmazk = real(zk); Omegazk = imag(zk);

%% Impulse response:
trsys = tf(C,D);
[ht t] = impulse(trsys);

%% Design Plots
hfa = figconfg('P1106a','small'); % magnitude
plot(F,Hmag,'b','linewidth',1);
axis([0,Fmax,0,1.1]);
xlabel('Frequency in Hz','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
```

```
set(gca,'xtick',[0,Fp,Fs,Fmax]);
set(gca,'ytick',[0,Rp,1]); grid;

hfb = figconfg('P1106b','small'); % Log-Magnitude Plot in dB
plot(F,Hdb,'b','linewidth',1);
axis([0,Fmax,-60,1]);
xlabel('Frequency in Hz','fontsize',LFS);
ylabel('Decibels','fontsize',LFS);
title('Log-Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,Fp,Fs,Fmax]);
set(gca,'ytick',[-As,-Ap]);grid

hfc = figconfg('P1106c','small'); % Group-Delay Plot in Samples
plot(F,Hgdl,'b','linewidth',1);
xlabel('Frequency in Hz','fontsize',LFS);
ylabel('Samples','fontsize',LFS);
title('Group Delay Response','fontsize',TFS);
set(gca,'xtick',[0,Fp,Fs,Fmax]); grid

hfd = figconfg('P1106d','small'); % Pole-zero Plot
plot(sigmapk,Omegapk,'bx','linewidth',1.5); hold on;
plot(sigmazk,Omegazk,'ro','linewidth',1.5);
ff = 1.05; pc = ff*max(abs([pk(:);zk(:)]));
plot([-pc,pc],[0,0],'k','linewidth',0.75);
plot([0,0],[-pc,pc],'k','linewidth',0.75);
axis([-pc,pc,-pc,pc]);
axis square;
xlabel('Real-axis','fontsize',LFS);
ylabel('Imaginary-axis','fontsize',LFS);
title('Pole Locations','fontsize',TFS);

hfe = figconfg('P1106e','small');  % Impulse response
plot(t,ht,'linewidth',1)
axis([t(1) t(end) min(ht)-1 max(ht)+1])
xlabel('Time Index t/s','fontsize',LFS);
ylabel('h(t)','fontsize',LFS);
title('Impulse Response','fontsize',TFS);
```

7. See plot below.

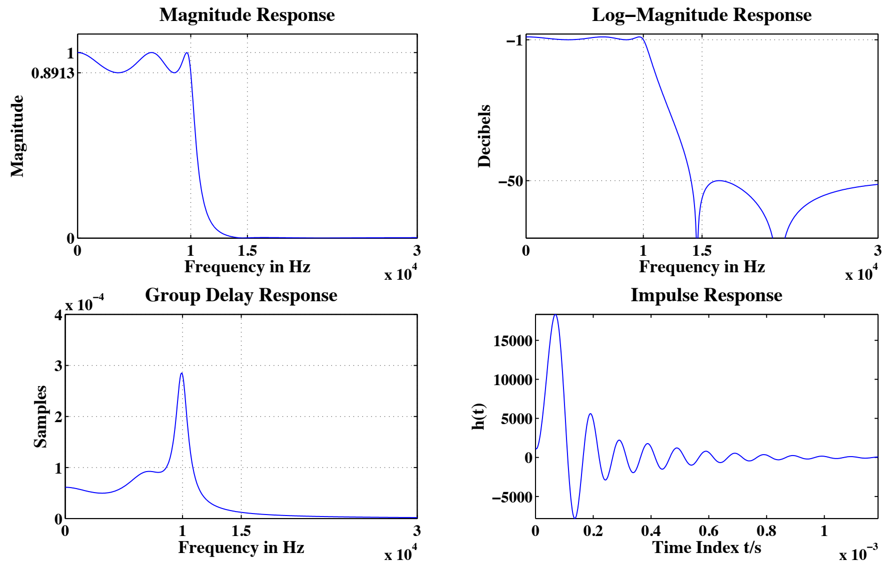

FIGURE 11.10: Plots of the magnitude, log-magnitude, group-delay, and impulse responses..

MATLAB script:

```
% P1107: Analog Elliptic low-pass filter design
clc; close all; %echo on;
% Given Design Parameters
Fp = 10e3; Fs = 15e3; Ap = 1; As = 50;
Omegap = 2*pi*Fp; Omegas = 2*pi*Fs;
% Analog Design Parameters (Eq. 10.9)
epsilon = sqrt(10^(0.1*Ap)-1); A = 10^(0.05*As);
Rp = 1/sqrt(1+epsilon^2);
% Plotting Parameters
Fmax = 30e3; Ommax = 2*pi*Fmax;
F = linspace(0,Fmax,501); Om = 2*pi*F;
% Elliptic Approximation
disp('** Elliptic **');
[N, Omegac] = ellipord(Omegap, Omegas, Ap, As, 's');
[C,D] = ellip(N,Ap,As,Omegac,'s'); H = freqs(C,D,Om);
Hmag = abs(H); Hpha = angle(H); Hdb = 20*log10(Hmag);
Hgdl = -diff(unwrap(Hpha))./diff(Om); Hgdl = [Hgdl,Hgdl(end)];
```

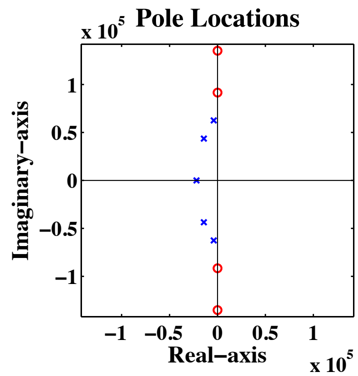

FIGURE 11.11: Pole-zero plot of the filter

```
Hgdl = medfilt1(Hgdl,3);
pk = roots(D); sigmapk = real(pk); Omegapk = imag(pk);
zk = roots(C); sigmazk = real(zk); Omegazk = imag(zk);

%% Impulse response:
trsys = tf(C,D);
[ht t] = impulse(trsys);

%% Design Plots
hfa = figconfg('P1107a','small'); % magnitude
plot(F,Hmag,'b','linewidth',1);
axis([0,Fmax,0,1.1]);
xlabel('Frequency in Hz','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,Fp,Fs,Fmax]);
set(gca,'ytick',[0,Rp,1]); grid;

hfb = figconfg('P1107b','small'); % Log-Magnitude Plot in dB
plot(F,Hdb,'b','linewidth',1);
axis([0,Fmax,-70,1]);
xlabel('Frequency in Hz','fontsize',LFS);
ylabel('Decibels','fontsize',LFS);
title('Log-Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,Fp,Fs,Fmax]);
set(gca,'ytick',[-As,-Ap]);grid
```

```
hfc = figconfg('P1107c','small'); % Group-Delay Plot in Samples
plot(F,Hgdl,'b','linewidth',1);
xlabel('Frequency in Hz','fontsize',LFS);
ylabel('Samples','fontsize',LFS);
title('Group Delay Response','fontsize',TFS);
set(gca,'xtick',[0,Fp,Fs,Fmax]); grid

hfd = figconfg('P1107d','small'); % Pole-zero Plot
plot(sigmapk,Omegapk,'bx','linewidth',1.5); hold on;
plot(sigmazk,Omegazk,'ro','linewidth',1.5);
ff = 1.05; pc = ff*max(abs([pk(:);zk(:)]));
plot([-pc,pc],[0,0],'k','linewidth',0.75);
plot([0,0],[-pc,pc],'k','linewidth',0.75);
axis([-pc,pc,-pc,pc]);
axis square;
xlabel('Real-axis','fontsize',LFS);
ylabel('Imaginary-axis','fontsize',LFS);
title('Pole Locations','fontsize',TFS);

hfe = figconfg('P1107e','small');  % Impulse response
plot(t,ht,'linewidth',1)
axis([t(1) t(end) min(ht)-1 max(ht)+1])
xlabel('Time Index t/s','fontsize',LFS);
ylabel('h(t)','fontsize',LFS);
title('Impulse Response','fontsize',TFS);
```

8. See plot below.

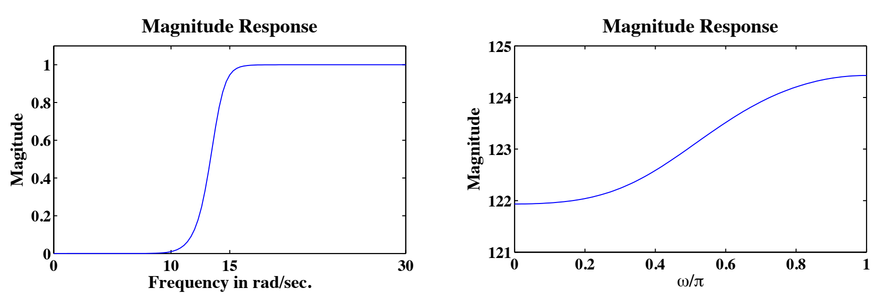

FIGURE 11.12: Plots of magnitude of analog and digital filters.

MATLAB script:

```
% P1108: High-pass analog filter by butterworth and transformation
%        using impulse invariance method
clc; close all;
%% Part a: Analog highpass filter design
Omegas = 10; Omegap = 15; As = 40; Ap = 1;
[N,Wn] = buttord(Omegap,Omegas,Ap,As,'s');
[b,a] = butter(N,Wn,'high','s');
Ommax = 30; Om = linspace(0,Ommax,101);
H = freqs(b,a,Om);
Hmag = abs(H); Hdb = 20*log10(Hmag);
%% Part b: Impulse-invariance transformation
Td = 1;
[B,A] = impinvar(b,a,1/Td);
w = linspace(0,1,101)*pi;
Hd = freqz(B,A,w);
Hdmag = abs(Hd); Hddb = 20*log10(Hdmag./max(Hdmag));

%% Design Plots
hfa = figconfg('P1108a','small'); % Magnitude Plot in dB
plot(Om,Hmag,'b','linewidth',1);
axis([0,Ommax,0,1.1]);
xlabel('Frequency in rad/sec.','fontsize',LFS);
ylabel('Magitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,Omegas,Omegap,Ommax]);

hfb = figconfg('P1108b','small'); % Magnitude Plot in dB
plot(w/pi,Hdmag,'b','linewidth',1);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
```

9. (a) See plot below.

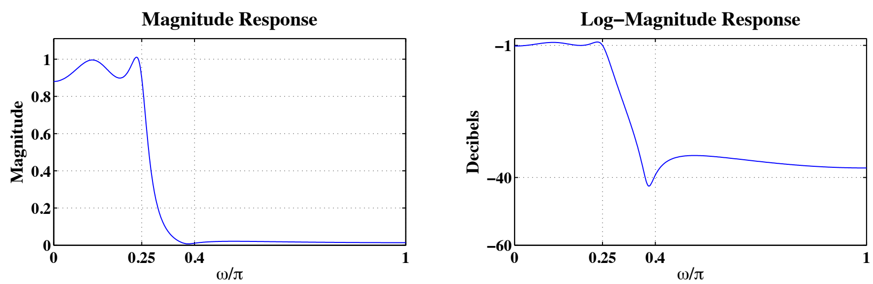

FIGURE 11.13: Plots of magnitude of analog and digital filters.

(b) See plot below.

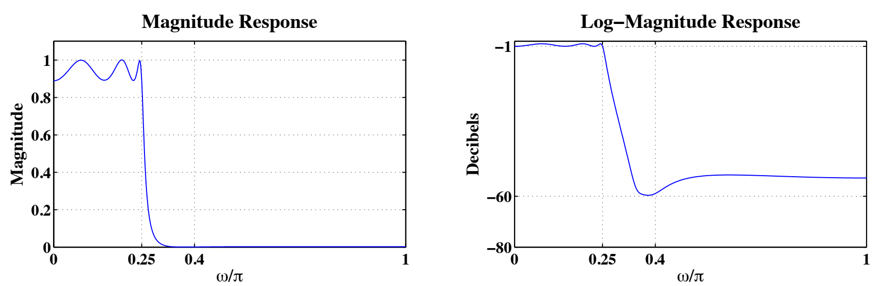

FIGURE 11.14: Plots of magnitude of analog and digital filters.

MATLAB script:

```
% P1109: Low-pass analog filter by elliptic and transformation
%         using impulse invariance method
clc; close all;
wp = 0.25*pi; ws = 0.4*pi; Ap = 1;
% As = 40; % part a
As = 60; % part b
Td = 1;
[N,Omegac] = ellipord(wp/Td,ws/Td,Ap,As,'s');
[b,a] = ellip(N,Ap,As,Omegac,'s');
[B,A] = impinvar(b,a,1/Td);
w = linspace(0,1,501)*pi;
Hd = freqz(B,A,w);
Hdmag = abs(Hd); Hddb = 20*log10(Hdmag./max(Hdmag));
```

```
%% Design Plots
hfa = figconfg('P1109a','small'); % Magnitude Plot
plot(w/pi,Hdmag,'b','linewidth',1);
axis([0,1,0,max(Hdmag)+0.1]);
set(gca,'xtick',[0 wp/pi ws/pi 1]); grid
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);

hfb = figconfg('P1109b','small'); % Log-Magnitude Plot in dB
plot(w/pi,Hddb,'b','linewidth',1);
axis([0,1,-As-20,1]);
set(gca,'ytick',[-As-20,-As,-Ap])
set(gca,'xtick',[0 wp/pi ws/pi 1]); grid
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Decibels','fontsize',LFS);
title('Log-Magnitude Response','fontsize',TFS);
```

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

    MATLAB script:

```
% P1110: Low-pass analog filter by butterworth and transformation
%        using impulse invariance method
clc; close all;
% Given Design Parameters
omegap = 0.25*pi; omegas = 0.4*pi; Ap = 1; As = 50;
% Analog Design Parameters (Eq. 10.9)
epsilon = sqrt(10^(0.1*Ap)-1); A = 10^(0.05*As);
Rp = 1/sqrt(1+epsilon^2);
%% Step by Step Impulse Invariance Design
% Step-1: Choose Td
% Td = 1; % part a
% Td = 0.1; % part b
Td = 0.01; % part c
% Step-2: Compute Analog Edge Frequencies
```

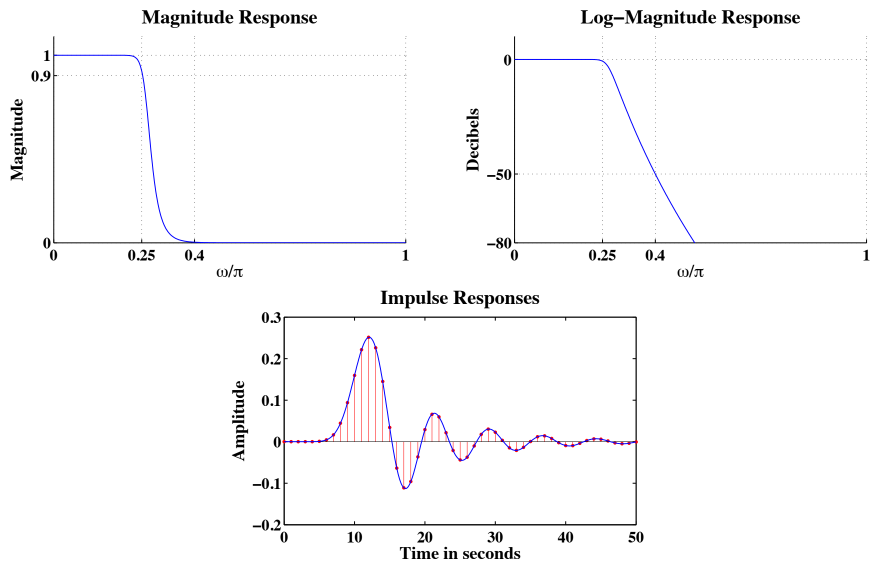

FIGURE 11.15: Plots of the magnitude, log-magnitude and impulse response of the digital filter superimposed on the impulse response of the analog prototype filter when $T_{\rm d} = 1$ sec..

```
Omegap = omegap/Td; Omegas = omegas/Td;
% Step-3: Design Analog Butterworth Approximation
[N,Omegac] = buttord(Omegap,Omegas,Ap,As,'s');
[C,D] = butter(N,Omegac,'s');
% Step-4: Obtain Digital Butterworth Filter
[B,A] = impinvar(C,D,1/Td);

% Plotting Parameters and Filter Responses
om = linspace(0,1,501)*pi; H = freqz(B,A,om);
Hmag = abs(H); Hpha = angle(H); Hdb = 20*log10(Hmag);
Hgdl = -diff(unwrap(Hpha))./diff(om); Hgdl = [Hgdl,Hgdl(end)];
Hgdl = medfilt1(Hgdl,3);
NN = 50; n = 0:NN; x = (n==0); h = filter(B,A,x);
t = linspace(0,NN*Td,501); hc = impulse(C,D,t);

%% Design Plots
hfa = figconfg('P1110a','small'); % magnitude
plot(om/pi,Hmag,'b','linewidth',1); axis([0,1,0,1.1]);
xlabel('\omega/\pi','fontsize',LFS);
```

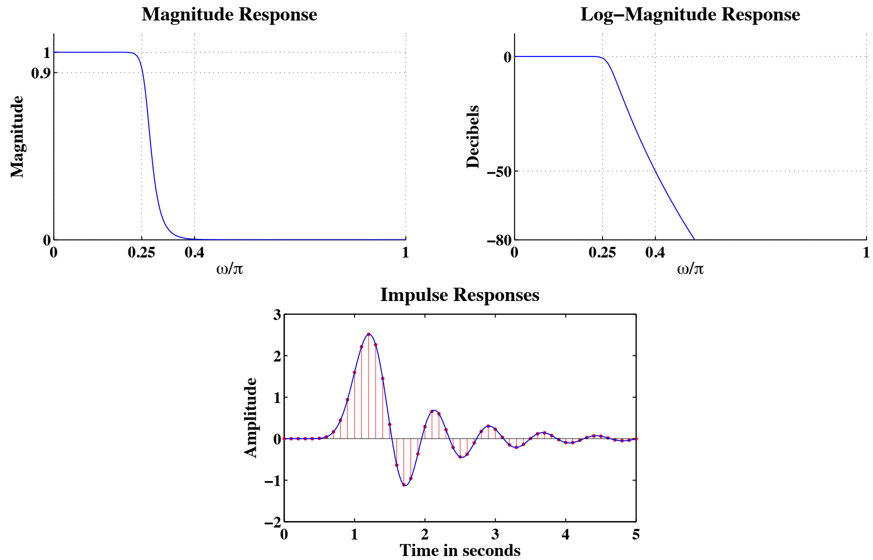

FIGURE 11.16: Plots of the magnitude, log-magnitude and impulse response of the digital filter superimposed on the impulse response of the analog prototype filter $T_{\mathrm{d}} = 0.1$ sec..

```
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,omegap,omegas,pi]/pi);
set(gca,'ytick',[0,Rp,1],'yticklabel','0|0.9|1');
grid; box off;

hfb = figconfg('P1110b','small'); % Log-Magnitude Plot in dB
plot(om/pi,Hdb,'b','linewidth',1); axis([0,1,-80,10]);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Decibels','fontsize',LFS);
title('Log-Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,omegap,omegas,pi]/pi);
set(gca,'ytick',[-80,-As,0]); grid; box off;

hfc = figconfg('P1110c','small'); % Group-Delay Plot in Samples
plot(om/pi,Hgdl,'b','linewidth',1);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Samples','fontsize',LFS);
title('Group Delay Response','fontsize',TFS);
```

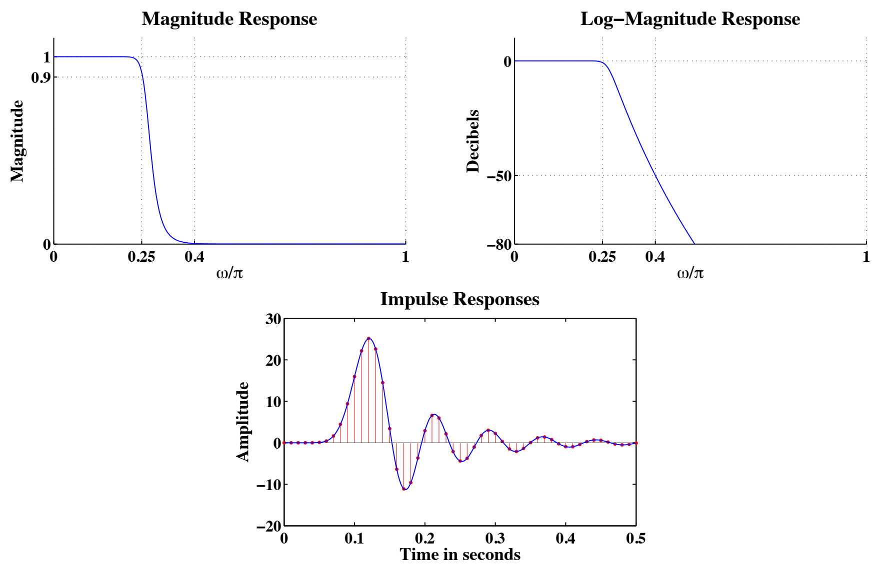

FIGURE 11.17: Plots of the magnitude, log-magnitude and impulse response of the digital filter superimposed on the impulse response of the analog prototype filter $T_{\rm d} = 0.01$ sec..

```
set(gca,'xtick',[0,omegap,omegas,pi]/pi);

hfd = figconfg('P1110d','small'); % Impulse Response Plots
stem(n*Td,h/Td,'filled','markersize',3,'color','r'); hold on;
plot(t,hc,'b','linewidth',1);
xlabel('Time in seconds','fontsize',LFS);
ylabel('Amplitude','fontsize',LFS);
title('Impulse Responses','fontsize',TFS);
```

11. See plot below.

    MATLAB script:

```
% P1111: Low-pass analog filter by Chebyshev I and transformation
%        using impulse invariance method
clc; close all;
% Given Design Parameters
omegap = 0.25*pi; omegas = 0.35*pi; Ap = 1; As = 50;
% Analog Design Parameters (Eq. 10.9)
epsilon = sqrt(10^(0.1*Ap)-1); A = 10^(0.05*As);
```

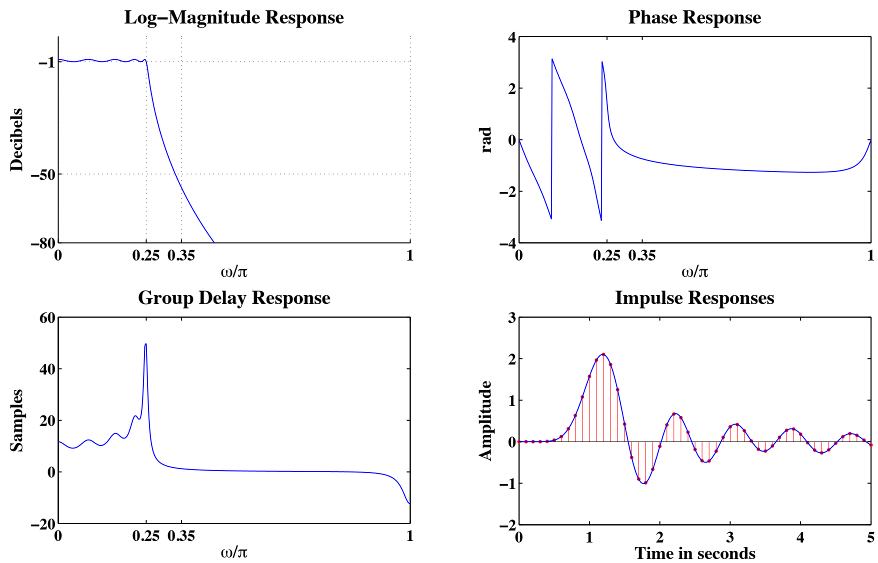

FIGURE 11.18: Plots of log-magnitude, phase, group, and impulse responses.

```
Rp = 1/sqrt(1+epsilon^2);
%% Step by Step Impulse Invariance Design
% Step-1: Choose Td
Td = 0.1;
% Step-2: Compute Analog Edge Frequencies
Omegap = omegap/Td; Omegas = omegas/Td;
% Step-3: Design Analog Chebyshev I Approximation
[N,Omegac] = cheb1ord(Omegap,Omegas,Ap,As,'s');
[C,D] = cheby1(N,Ap,Omegac,'s');
% Step-4: Obtain Digital Chebyshev I Filter
[B,A] = impinvar(C,D,1/Td);

% Plotting Parameters and Filter Responses
om = linspace(0,1,501)*pi; H = freqz(B,A,om);
Hmag = abs(H); Hpha = angle(H); Hdb = 20*log10(Hmag);
Hgdl = -diff(unwrap(Hpha))./diff(om); Hgdl = [Hgdl,Hgdl(end)];
Hgdl = medfilt1(Hgdl,3);
NN = 50; n = 0:NN; x = (n==0); h = filter(B,A,x);
t = linspace(0,NN*Td,501); hc = impulse(C,D,t);

%% Design Plots
```

```
hfa = figconfg('P1111a','small'); % Log-Magnitude Response in dB
plot(om/pi,Hdb,'b','linewidth',1); axis([0,1,-80,10]);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Decibels','fontsize',LFS);
title('Log-Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,omegap,omegas,pi]/pi);
set(gca,'ytick',[-80,-As,-Ap]); grid; box off;

hfb = figconfg('P1111b','small'); % Phase Plot
plot(om/pi,Hpha,'b','linewidth',1);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('rad','fontsize',LFS);
title('Phase Response','fontsize',TFS);
set(gca,'xtick',[0,omegap,omegas,pi]/pi);

hfc = figconfg('P1111c','small'); % Group-Delay Plot in Samples
plot(om/pi,Hgdl,'b','linewidth',1);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Samples','fontsize',LFS);
title('Group Delay Response','fontsize',TFS);
set(gca,'xtick',[0,omegap,omegas,pi]/pi);

hfd = figconfg('P1111d','small'); % Impulse Response Plots
stem(n*Td,h/Td,'filled','markersize',3,'color','r'); hold on;
plot(t,hc,'b','linewidth',1);
xlabel('Time in seconds','fontsize',LFS);
ylabel('Amplitude','fontsize',LFS);
title('Impulse Responses','fontsize',TFS);
```

12. See plot below.

    MATLAB script:

```
% P1112: Lowpass filter design by Butterworth and tranformation
%        using bilinear method
clc; close all;
% Given Design Parameters
omegap = 0.25*pi; omegas = 0.35*pi; Ap = 1; As = 50;
% Analog Design Parameters (Eq. 10.9)
epsilon = sqrt(10^(0.1*Ap)-1); A = 10^(0.05*As);
Rp = 1/sqrt(1+epsilon^2);
```

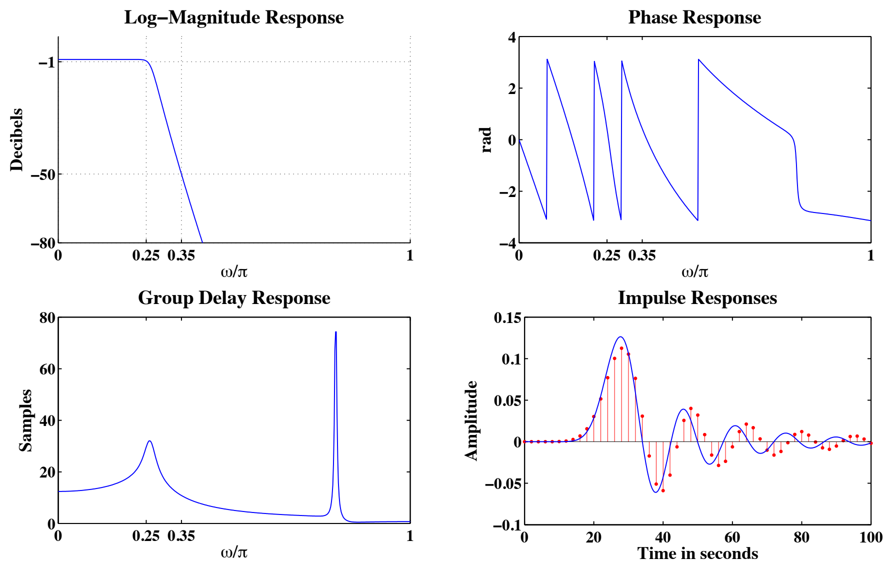

FIGURE 11.19: Plots of log-magnitude, phase, group, and impulse responses.

```
%% Step by Step Impulse Invariance Design
% Step-1: Choose Td
Td = 2;
% Step-2: Compute Analog Edge Frequencies
Omegap = 2/Td*tan(omegap/2); Omegas = 2/Td*tan(omegas/2);
% Step-3: Design Analog Butterworth Approximation
[N,Omegac] = buttord(Omegap,Omegas,Ap,As,'s');
[C,D] = butter(N,Omegac,'s');
% Step-4: Obtain Digital Butterworth Filter
[B,A] = bilinear(C,D,1/Td);
% Plotting Parameters and Filter Responses
om = linspace(0,1,501)*pi; H = freqz(B,A,om);
Hmag = abs(H); Hpha = angle(H); Hdb = 20*log10(Hmag);
Hgdl = -diff(unwrap(Hpha))./diff(om); Hgdl = [Hgdl,Hgdl(end)];
Hgdl = medfilt1(Hgdl,3);
NN = 50; n = 0:NN; x = (n==0); h = filter(B,A,x);
t = linspace(0,NN*Td,501); hc = impulse(C,D,t);
% Exact Frequency:
ind = find(Hdb < -Ap,1,'first'); om1 = om(ind)/pi; % Exact Passband Edge
ind = find(Hdb < -As,1,'first'); om2 = om(ind)/pi; % Exact Stopband Edge
%% Design Plots
```

```
hfa = figconfg('P1112a','small'); % Log-Magnitude Response in dB
plot(om/pi,Hdb,'b','linewidth',1); axis([0,1,-80,10]);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Decibels','fontsize',LFS);
title('Log-Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,omegap,omegas,pi]/pi);
set(gca,'ytick',[-80,-As,-Ap]); grid; box off;

hfb = figconfg('P1112b','small'); % Phase Plot
plot(om/pi,Hpha,'b','linewidth',1);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('rad','fontsize',LFS);
title('Phase Response','fontsize',TFS);
set(gca,'xtick',[0,omegap,omegas,pi]/pi);

hfc = figconfg('P1112c','small'); % Group-Delay Plot in Samples
plot(om/pi,Hgdl,'b','linewidth',1);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Samples','fontsize',LFS);
title('Group Delay Response','fontsize',TFS);
set(gca,'xtick',[0,omegap,omegas,pi]/pi);

hfd = figconfg('P1112d','small'); % Impulse Response Plots
stem(n*Td,h/Td,'filled','markersize',3,'color','r'); hold on;
plot(t,hc,'b','linewidth',1);
xlabel('Time in seconds','fontsize',LFS);
ylabel('Amplitude','fontsize',LFS);
title('Impulse Responses','fontsize',TFS);
```

13. See plot below.

    MATLAB script:

```
% P1113: Lowpass filter design by Chebyshev I and tranformation
%        using bilinear method
clc; close all;
% Given Design Parameters
omegap = 0.2*pi; omegas = 0.3*pi; Ap = 1; As = 60;
% Analog Design Parameters (Eq. 10.9)
epsilon = sqrt(10^(0.1*Ap)-1); A = 10^(0.05*As);
Rp = 1/sqrt(1+epsilon^2);
```

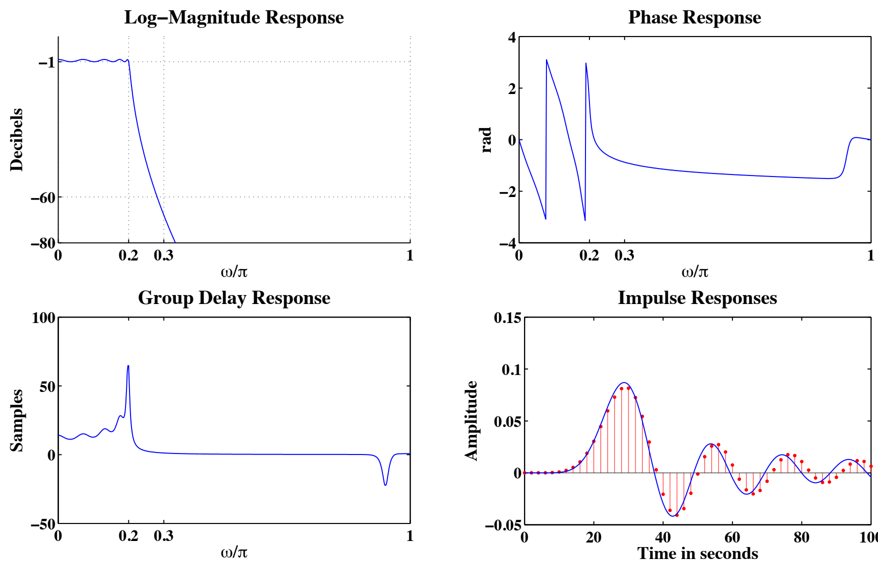

FIGURE 11.20: Plots of log-magnitude, phase, group, and impulse responses.

```
%% Step by Step Impulse Invariance Design
% Step-1: Choose Td
Td = 2;
% Step-2: Compute Analog Edge Frequencies
Omegap = 2/Td*tan(omegap/2); Omegas = 2/Td*tan(omegas/2);
% Step-3: Design Analog Chebyshev I Approximation
[N,Omegac] = cheb1ord(Omegap,Omegas,Ap,As,'s');
[C,D] = cheby1(N,Ap,Omegac,'s');
% Step-4: Obtain Digital Chebyshev I Filter
[B,A] = bilinear(C,D,1/Td);
[sos G] = tf2sos(B,A);
% Plotting Parameters and Filter Responses
om = linspace(0,1,501)*pi; H = freqz(B,A,om);
Hmag = abs(H); Hpha = angle(H); Hdb = 20*log10(Hmag);
Hgdl = -diff(unwrap(Hpha))./diff(om); Hgdl = [Hgdl,Hgdl(end)];
Hgdl = medfilt1(Hgdl,3);
NN = 50; n = 0:NN; x = (n==0); h = filter(B,A,x);
t = linspace(0,NN*Td,501); hc = impulse(C,D,t);
% Exact Frequency:
ind = find(Hdb < -Ap,1,'first'); om1 = om(ind)/pi; % Exact Passband Edge
ind = find(Hdb < -As,1,'first'); om2 = om(ind)/pi; % Exact Stopband Edge
```

```
%% Design Plots
hfa = figconfg('P1113a','small'); % Log-Magnitude Response in dB
plot(om/pi,Hdb,'b','linewidth',1); axis([0,1,-80,10]);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Decibels','fontsize',LFS);
title('Log-Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,omegap,omegas,pi]/pi);
set(gca,'ytick',[-80,-As,-Ap]); grid; box off;

hfb = figconfg('P1113b','small'); % Phase Plot
plot(om/pi,Hpha,'b','linewidth',1);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('rad','fontsize',LFS);
title('Phase Response','fontsize',TFS);
set(gca,'xtick',[0,omegap,omegas,pi]/pi);

hfc = figconfg('P1113c','small'); % Group-Delay Plot in Samples
plot(om/pi,Hgdl,'b','linewidth',1);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Samples','fontsize',LFS);
title('Group Delay Response','fontsize',TFS);
set(gca,'xtick',[0,omegap,omegas,pi]/pi);

hfd = figconfg('P1113d','small'); % Impulse Response Plots
stem(n*Td,h/Td,'filled','markersize',3,'color','r'); hold on;
plot(t,hc,'b','linewidth',1);
xlabel('Time in seconds','fontsize',LFS);
ylabel('Amplitude','fontsize',LFS);
title('Impulse Responses','fontsize',TFS);
```

14. See plot below.

    MATLAB script:

```
% P1114: Lowpass filter design by Chebyshev II and tranformation
%        using bilinear method
clc; close all;
% Given Design Parameters
omegap = 0.5*pi; omegas = 0.6*pi; Ap = 2; As = 50;
% Analog Design Parameters (Eq. 10.9)
epsilon = sqrt(10^(0.1*Ap)-1); A = 10^(0.05*As);
```

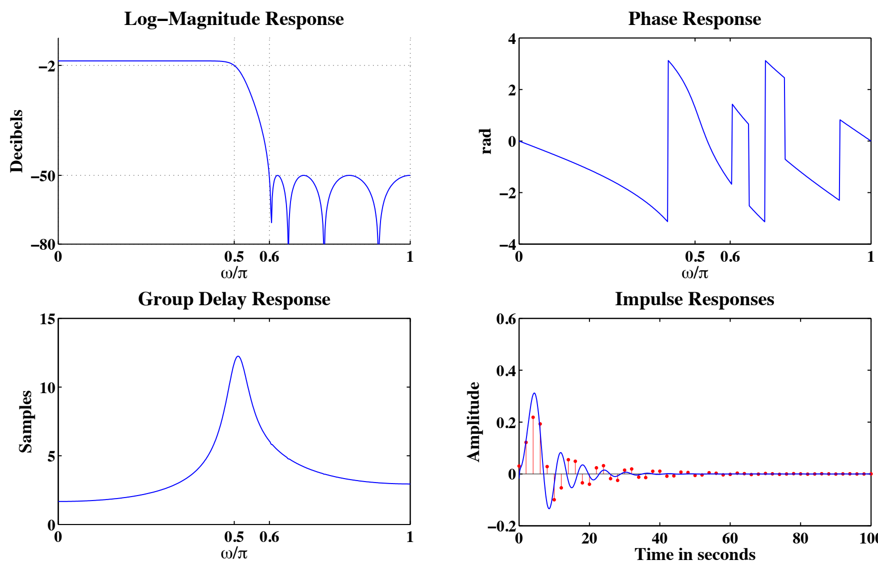

FIGURE 11.21: Plots of log-magnitude, phase, group, and impulse responses.

```
Rp = 1/sqrt(1+epsilon^2);
%% Step by Step Impulse Invariance Design
% Step-1: Choose Td
Td = 2;
% Step-2: Compute Analog Edge Frequencies
Omegap = 2/Td*tan(omegap/2); Omegas = 2/Td*tan(omegas/2);
% Step-3: Design Analog Chebyshev II Approximation
[N,Omegac] = cheb2ord(Omegap,Omegas,Ap,As,'s');
[C,D] = cheby2(N,As,Omegac,'s');
% Step-4: Obtain Digital Chebyshev II Filter
[B,A] = bilinear(C,D,1/Td);
[sos G] = tf2pf(B,A);
% Plotting Parameters and Filter Responses
om = linspace(0,1,501)*pi; H = freqz(B,A,om);
Hmag = abs(H); Hpha = angle(H); Hdb = 20*log10(Hmag);
Hgdl = -diff(unwrap(Hpha))./diff(om); Hgdl = [Hgdl,Hgdl(end)];
Hgdl = medfilt1(Hgdl,3);
NN = 50; n = 0:NN; x = (n==0); h = filter(B,A,x);
t = linspace(0,NN*Td,501); hc = impulse(C,D,t);
% Exact Frequency:
ind = find(Hdb < -Ap,1,'first'); om1 = om(ind)/pi; % Exact Passband Edge
```

```
ind = find(Hdb < -As,1,'first'); om2 = om(ind)/pi; % Exact Stopband Edge
%% Design Plots
hfa = figconfg('P1114a','small'); % Log-Magnitude Response in dB
plot(om/pi,Hdb,'b','linewidth',1); axis([0,1,-80,10]);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Decibels','fontsize',LFS);
title('Log-Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,omegap,omegas,pi]/pi);
set(gca,'ytick',[-80,-As,-Ap]); grid; box off;

hfb = figconfg('P1114b','small'); % Phase Plot
plot(om/pi,Hpha,'b','linewidth',1);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('rad','fontsize',LFS);
title('Phase Response','fontsize',TFS);
set(gca,'xtick',[0,omegap,omegas,pi]/pi);

hfc = figconfg('P1114c','small'); % Group-Delay Plot in Samples
plot(om/pi,Hgdl,'b','linewidth',1);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Samples','fontsize',LFS);
title('Group Delay Response','fontsize',TFS);
set(gca,'xtick',[0,omegap,omegas,pi]/pi);

hfd = figconfg('P1114d','small'); % Impulse Response Plots
stem(n*Td,h/Td,'filled','markersize',3,'color','r'); hold on;
plot(t,hc,'b','linewidth',1);
xlabel('Time in seconds','fontsize',LFS);
ylabel('Amplitude','fontsize',LFS);
title('Impulse Responses','fontsize',TFS);
```

15. See plot below.

    MATLAB script:

```
% P1115: Lowpass filter design by elliptic and tranformation
%        using bilinear method
clc; close all;
% Given Design Parameters
omegap = 0.1*pi; omegas = 0.2*pi; Ap = 0.5; As = 45;
% Analog Design Parameters (Eq. 10.9)
```

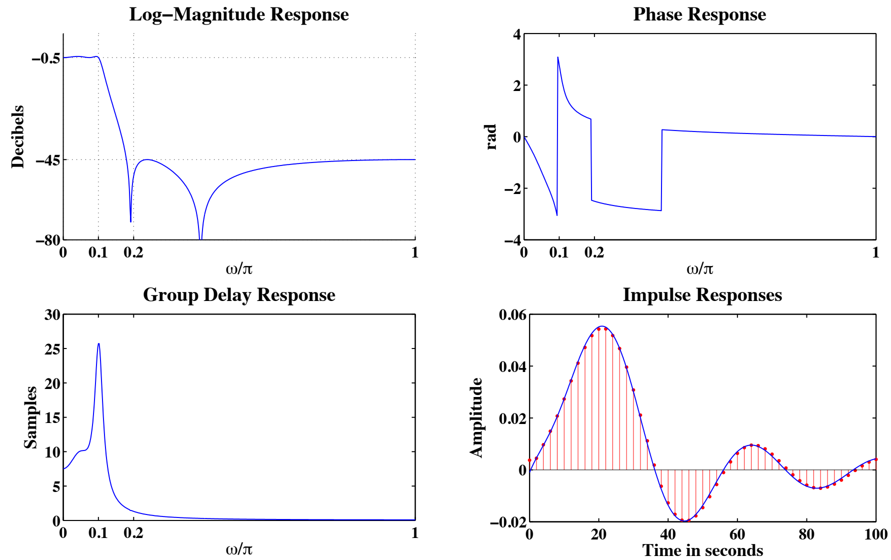

FIGURE 11.22: Plots of log-magnitude, phase, group, and impulse responses.

```
epsilon = sqrt(10^(0.1*Ap)-1); A = 10^(0.05*As);
Rp = 1/sqrt(1+epsilon^2);
%% Step by Step Impulse Invariance Design
% Step-1: Choose Td
Td = 2;
% Step-2: Compute Analog Edge Frequencies
Omegap = 2/Td*tan(omegap/2); Omegas = 2/Td*tan(omegas/2);
% Step-3: Design Analog Elliptic Approximation
[N,Omegac] = ellipord(Omegap,Omegas,Ap,As,'s');
[C,D] = ellip(N,Ap,As,Omegac,'s');
% Step-4: Obtain Digital Elliptic Filter
[B,A] = bilinear(C,D,1/Td);
% Plotting Parameters and Filter Responses
om = linspace(0,1,501)*pi; H = freqz(B,A,om);
Hmag = abs(H); Hpha = angle(H); Hdb = 20*log10(Hmag);
Hgdl = -diff(unwrap(Hpha))./diff(om); Hgdl = [Hgdl,Hgdl(end)];
Hgdl = medfilt1(Hgdl,3);
NN = 50; n = 0:NN; x = (n==0); h = filter(B,A,x);
t = linspace(0,NN*Td,501); hc = impulse(C,D,t);
% Exact Frequency:
ind = find(Hdb < -Ap,2,'first'); om1 = om(ind(2))/pi; % Exact Passband Edge
```

```
ind = find(Hdb < -As,1,'first'); om2 = om(ind)/pi; % Exact Stopband Edge
%% Design Plots
hfa = figconfg('P1115a','small'); % Log-Magnitude Response in dB
plot(om/pi,Hdb,'b','linewidth',1); axis([0,1,-80,10]);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Decibels','fontsize',LFS);
title('Log-Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,omegap,omegas,pi]/pi);
set(gca,'ytick',[-80,-As,-Ap]); grid; box off;

hfb = figconfg('P1115b','small'); % Phase Plot
plot(om/pi,Hpha,'b','linewidth',1);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('rad','fontsize',LFS);
title('Phase Response','fontsize',TFS);
set(gca,'xtick',[0,omegap,omegas,pi]/pi);

hfc = figconfg('P1115c','small'); % Group-Delay Plot in Samples
plot(om/pi,Hgdl,'b','linewidth',1);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Samples','fontsize',LFS);
title('Group Delay Response','fontsize',TFS);
set(gca,'xtick',[0,omegap,omegas,pi]/pi);

hfd = figconfg('P1115d','small'); % Impulse Response Plots
stem(n*Td,h/Td,'filled','markersize',3,'color','r'); hold on;
plot(t,hc,'b','linewidth',1);
xlabel('Time in seconds','fontsize',LFS);
ylabel('Amplitude','fontsize',LFS);
title('Impulse Responses','fontsize',TFS);
```

16. See plot below.

    MATLAB script:

```
% P1116: Continuous-Time Frequency Transformation: Lowpass to Lowpass
close all; clc
C = 10; D = [1 1]; Omegac = 10; Td = 2;
[Bc,Ac] = lp2lp(C,D,Omegac); % continuous lowpass filter
[rc,pc,kc] = residue(Bc,Ac);
[B,A] = bilinear(Bc,Ac,1/Td); % digital lowpass filter
```

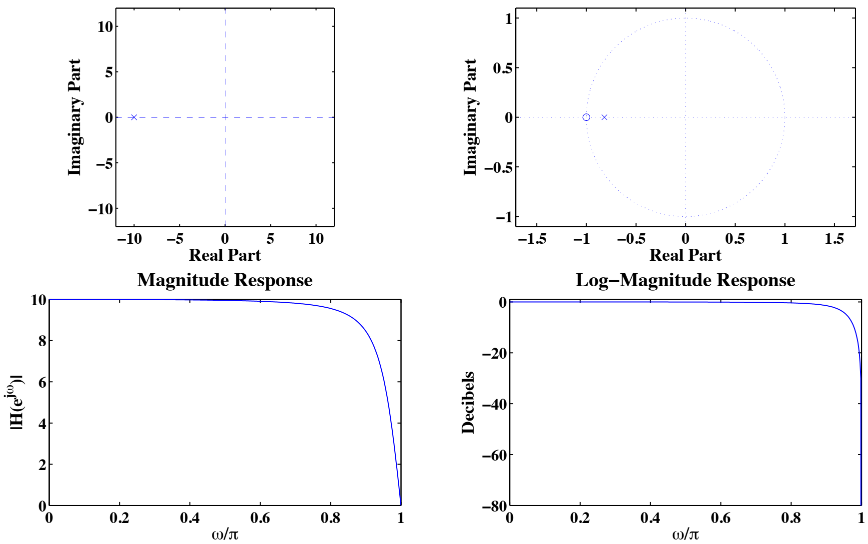

FIGURE 11.23: Plots of pole and zero locations for the analog lowpass filter and for the digital filter with $T_\mathrm{d} = 2$, magnitude response of the digital filter.

```
[r,p,k] = residuez(B,A);
om = linspace(0,1,501)*pi;
H = freqz(B,A,om); Hmag = abs(H); Hdb = 20*log10(Hmag/max(Hmag));

%% Plot
hfa = figconfg('P1116a','small'); % CT Pole-Zero plot
pv = abs(pc); pv = 1.2*pv;
plot(real(pc),imag(pc),'marker','x','color','b','markersize',8);hold on
plot([-pv pv],[0 0],'--b'); plot([0 0],[-pv pv],'--b'); axis square
axis([-pv pv -pv pv])
xlabel('Real Part','fontsize',LFS);
ylabel('Imaginary Part','fontsize',LFS);

hfb = figconfg('P1116b','small'); % DT Pole-Zero plot
zplane(B,A)
xlabel('Real Part','fontsize',LFS);
ylabel('Imaginary Part','fontsize',LFS);

hfc = figconfg('P1116c','small'); % Magnitude Response
plot(om/pi,Hmag,'b','linewidth',1);
```

```
xlabel('\omega/\pi','fontsize',LFS);
ylabel('|H(e^{j\omega})|','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);

hfd = figconfg('P1116d','small'); % Log-Magnitude Response in dB
plot(om/pi,Hdb,'b','linewidth',1);
axis([0,1,-80,1]);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Decibels','fontsize',LFS);
title('Log-Magnitude Response','fontsize',TFS);
```

17. See plot below.

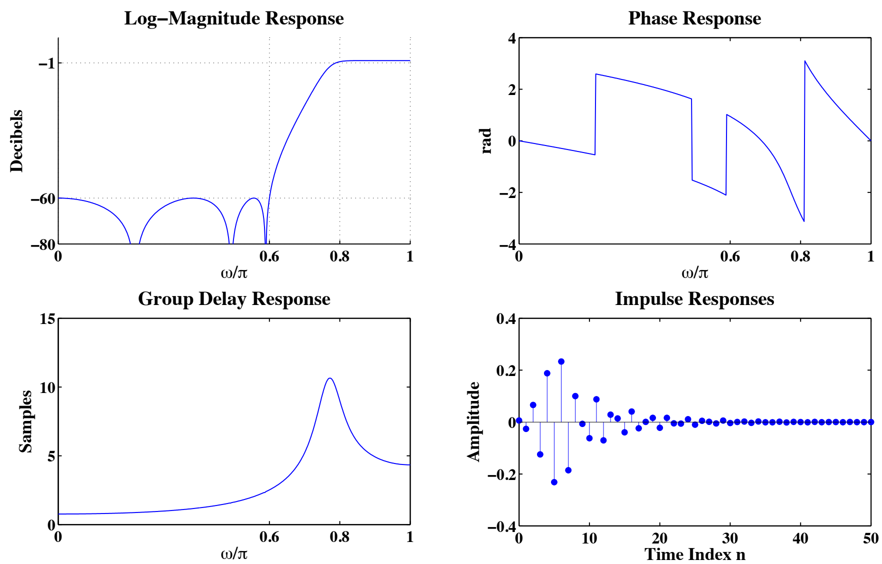

FIGURE 11.24: Plots of log-magnitude, phase, group, and impulse responses.

MATLAB script:

```
% P1117: Digital highpass filter design by Chebyshev II
close all; clc;
%% Filter Design
omegas = 0.6*pi; omegap = 0.8*pi; As = 60; Ap = 1; % Specification
[N,omegac] = cheb2ord(omegap/pi,omegas/pi,Ap,As); % Order define
[B,A] = cheby2(N,As,omegac,'high'); % coefficients
[sos G] = tf2sos(B,A); % cascade form
```

```
%% Plotting Parameters and Filter Responses
om = linspace(0,1,501)*pi; H = freqz(B,A,om);
Hmag = abs(H); Hpha = angle(H); Hdb = 20*log10(Hmag);
Hgdl = -diff(unwrap(Hpha))./diff(om); Hgdl = [Hgdl,Hgdl(end)];
Hgdl = medfilt1(Hgdl,3);
NN = 50; n = 0:NN; x = (n==0); h = filter(B,A,x);
%% Exact band-edge frequencies
ind = find(Hdb < -As,1,'last'); om1 = om(ind)/pi; % Exact stopband Edge
ind = find(Hdb > -Ap,1,'first'); om2 = om(ind)/pi; % Exact Passband Edge
%% Design Plots
hfa = figconfg('P1117a','small'); % Log-Magnitude Response in dB
plot(om/pi,Hdb,'b','linewidth',1); axis([0,1,-80,10]);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Decibels','fontsize',LFS);
title('Log-Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,omegas,omegap,pi]/pi);
set(gca,'ytick',[-80,-As,-Ap]); grid; box off;

hfb = figconfg('P1117b','small'); % Phase Plot
plot(om/pi,Hpha,'b','linewidth',1);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('rad','fontsize',LFS);
title('Phase Response','fontsize',TFS);
set(gca,'xtick',[0,omegas,omegap,pi]/pi);

hfc = figconfg('P1117c','small'); % Group-Delay Plot in Samples
plot(om/pi,Hgdl,'b','linewidth',1);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Samples','fontsize',LFS);
title('Group Delay Response','fontsize',TFS);
set(gca,'xtick',[0,omegas,omegap,pi]/pi);

hfd = figconfg('P1117d','small'); % Impulse Response Plots
stem(n,h,'filled');
xlabel('Time Index n','fontsize',LFS);
ylabel('Amplitude','fontsize',LFS);
title('Impulse Responses','fontsize',TFS);
```

18. See plot below.

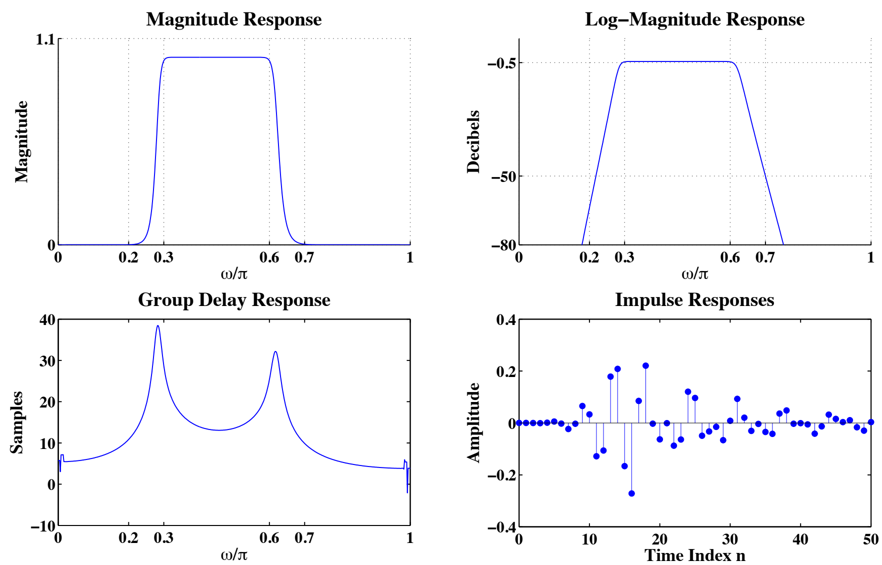

FIGURE 11.25: Plots of magnitude, log-magnitude, group, and impulse responses.

MATLAB script:

```
% P1118: Digital bandpass filter design by Butterworth
close all; clc;
%% Filter Design
omegas1 = 0.2*pi; omegap1 = 0.3*pi; omegap2 = 0.6*pi; omegas2 = 0.7*pi;
As1 = 40; Ap = 0.5; As2 = 50; % Specification
omegap = [omegap1 omegap2]; omegas = [omegas1 omegas2]; As = max(As1,As2);
[N,omegac] = buttord(omegap/pi,omegas/pi,Ap,As); % Order define
[B,A] = butter(N,omegac); % coefficients
%% Plotting Parameters and Filter Responses
om = linspace(0,1,501)*pi; H = freqz(B,A,om);
Hmag = abs(H); Hpha = angle(H); Hdb = 20*log10(Hmag);
Hgdl = -diff(unwrap(Hpha))./diff(om); Hgdl = [Hgdl,Hgdl(end)];
Hgdl = medfilt1(Hgdl,3);
NN = 50; n = 0:NN; x = (n==0); h = filter(B,A,x);
%% Exact band-edge frequencies
ind = find(Hdb > -Ap);
omp1 = om(ind(1))/pi; omp2 = om(ind(end))/pi;% Exact Passband Edge
ind = find(Hdb < -As); ind2 = find(om(ind)<omegap1,1,'last');
```

```
oms1 = om(ind(ind2))/pi; oms2 = om(ind(ind2+1))/pi;% Exact Stopband Edge
%% Design Plots
hfa = figconfg('P1118a','small'); % Magnitude Response
plot(om/pi,Hmag,'b','linewidth',1); axis([0,1,0,1.1]);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,omegas1,omegap1,omegap2,omegas2,pi]/pi);
set(gca,'ytick',[0,1.1]); grid; box off;

hfb = figconfg('P1118b','small'); % Log-Magnitude Response in dB
plot(om/pi,Hdb,'b','linewidth',1); axis([0,1,-80,10]);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Decibels','fontsize',LFS);
title('Log-Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,omegas1,omegap1,omegap2,omegas2,pi]/pi);
set(gca,'ytick',[-80,-As,-Ap]); grid; box off;

hfc = figconfg('P1118c','small'); % Group-Delay Plot in Samples
plot(om/pi,Hgdl,'b','linewidth',1);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Samples','fontsize',LFS);
title('Group Delay Response','fontsize',TFS);
set(gca,'xtick',[0,omegas1,omegap1,omegap2,omegas2,pi]/pi);

hfd = figconfg('P1118d','small'); % Impulse Response Plots
stem(n,h,'filled');
xlabel('Time Index n','fontsize',LFS);
ylabel('Amplitude','fontsize',LFS);
title('Impulse Responses','fontsize',TFS);
```

19. See plot below.

    MATLAB script:

```
% P1119: Digital bandstop filter design by Chebyshev I
close all; clc;
%% Filter Design
omegap1 = 0.4*pi; omegas1 = 0.55*pi; omegas2 = 0.65*pi; omegap2 = 0.75*pi;
Ap1 = 1; As = 50; Ap2 = 1; % Specification
omegap = [omegap1 omegap2]; omegas = [omegas1 omegas2]; Ap = min(Ap1,Ap2);
```

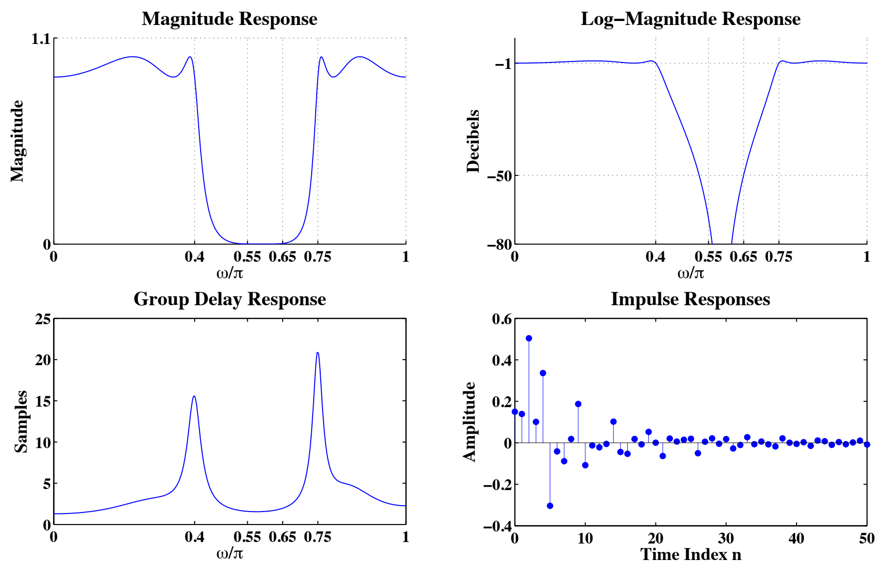

FIGURE 11.26: Plots of magnitude, log-magnitude, group, and impulse responses.

```
[N,omegac] = cheb1ord(omegap/pi,omegas/pi,Ap,As); % Order define
[B,A] = cheby1(N,Ap,omegac,'stop'); % coefficients
[sos G] = tf2pf(B,A); % parallel form
%% Plotting Parameters and Filter Responses
om = linspace(0,1,501)*pi; H = freqz(B,A,om);
Hmag = abs(H); Hpha = angle(H); Hdb = 20*log10(Hmag);
Hgdl = -diff(unwrap(Hpha))./diff(om); Hgdl = [Hgdl,Hgdl(end)];
Hgdl = medfilt1(Hgdl,3);
NN = 50; n = 0:NN; x = (n==0); h = filter(B,A,x);
%% Exact band-edge frequencies
ind = find(Hdb >= -Ap); ind2 = find(om(ind)<omegas1,1,'last');
omp1 = om(ind(ind2))/pi; omp2 = om(ind(ind2+1))/pi;% Exact Passband Edge
ind = find(Hdb <= -As);
oms1 = om(ind(1))/pi; oms2 = om(ind(end))/pi;% Exact Stopband Edge
%% Design Plots
hfa = figconfg('P1119a','small'); % Magnitude Response
plot(om/pi,Hmag,'b','linewidth',1); axis([0,1,0,1.1]);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Magnitude','fontsize',LFS);
title('Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,omegap1,omegas1,omegas2,omegap2,pi]/pi);
```

```
set(gca,'ytick',[0,1.1]); grid; box off;

hfb = figconfg('P1119b','small'); % Log-Magnitude Response in dB
plot(om/pi,Hdb,'b','linewidth',1); axis([0,1,-80,10]);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Decibels','fontsize',LFS);
title('Log-Magnitude Response','fontsize',TFS);
set(gca,'xtick',[0,omegap1,omegas1,omegas2,omegap2,pi]/pi);
set(gca,'ytick',[-80,-As,-Ap]); grid; box off;

hfc = figconfg('P1119c','small'); % Group-Delay Plot in Samples
plot(om/pi,Hgdl,'b','linewidth',1);
xlabel('\omega/\pi','fontsize',LFS);
ylabel('Samples','fontsize',LFS);
title('Group Delay Response','fontsize',TFS);
set(gca,'xtick',[0,omegap1,omegas1,omegas2,omegap2,pi]/pi);

hfd = figconfg('P1119d','small'); % Impulse Response Plots
stem(n,h,'filled');
xlabel('Time Index n','fontsize',LFS);
ylabel('Amplitude','fontsize',LFS);
title('Impulse Responses','fontsize',TFS);
```