7.26) b) Impulse invariance = aliasing

Bilinear Transformation = warping frequency axis

$\boxed{\text{Bilinear Transform}}$

d) Bilinear Transform

e) Impulse Invariance:

$$H_1(z) = \sum_{k=-\infty}^{\infty} H_{c1}\left(s - j\frac{2\pi}{T_d}k\right)$$

$$H_2(z) = \sum_{k=-\infty}^{\infty} H_{c2}\left(s - j\frac{2\pi}{T_d}k\right)$$

$$H_1(z)H_2(z) = \sum_{k=-\infty}^{\infty}\sum_{l=-\infty}^{\infty} H_{c1}\left(s - j\frac{2\pi}{T_d}k\right) H_{c2}\left(s - j\frac{2\pi}{T_d}l\right) \neq H(z)$$

Bilinear Transformation:

$$H_1(z) = H_{c1}\left[\frac{2}{T_d}\ \frac{1-z^{-1}}{1+z^{-1}}\right]$$

$$H_2(z) = H_{c2}\left[\frac{2}{T_d}\ \frac{1-z^{-1}}{1+z^{-1}}\right]$$

$$H_1(z)H_2(z) = H_{c1}\left[\frac{2}{T_d}\ \frac{1-z^{-1}}{1+z^{-1}}\right] H_{c2}\left[\frac{2}{T_d}\ \frac{1-z^{-1}}{1+z^{-1}}\right] = H_c\left[\frac{2}{T_d}\ \frac{1-z^{-1}}{1+z^{-1}}\right] = H(z)$$

$\boxed{\text{Bilinear Transformation}}$

7.27) (a) $H(e^{j\omega}) = \begin{cases} 1, & |\omega| < \frac{\pi}{4} \\ 0, & \pi/4 < |\omega| \leq \pi \end{cases}$

$H(e^{j\omega}) \xrightarrow{\mathcal{F}^{-1}} h[n]$

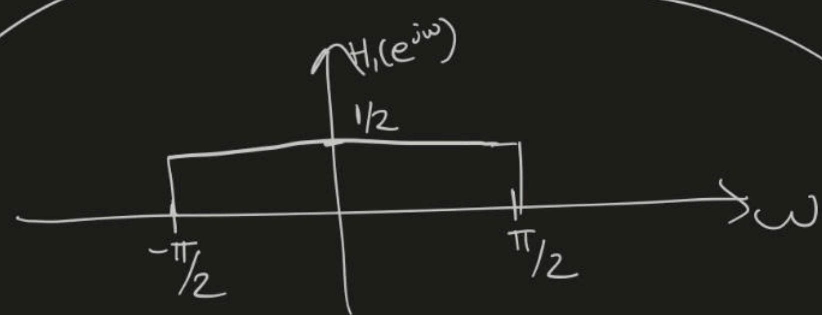
$h[2n] \xrightarrow{\mathcal{F}} H_1(e^{j\omega})$

$$H_1(e^{j\omega}) = \sum_{n=-\infty}^{\infty} h[2n] e^{-j\omega n}$$

$$= \sum_{\substack{n=2k, \\ k=-\infty}}^{\pi/4} h[n] e^{-\frac{j\omega n}{2}}$$

$$= \sum_{n=-\infty}^{\infty} \frac{1}{2}\left(h[n] + (-1)^n h[n]\right) e^{-\frac{j\omega n}{2}}$$

$$= \frac{1}{2} H(e^{\frac{j\omega}{2}}) + \frac{1}{2} H(e^{j\frac{\omega+2\pi}{2}})$$



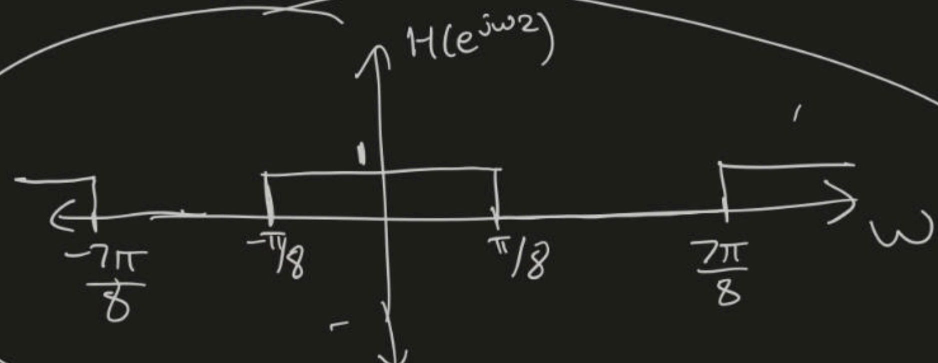
b) $h_2[n] = \begin{cases} h[n/2], & n = 0, \pm 2, \pm 4, \dots \\ 0, & \text{otherwise} \end{cases}$

$$H_2(e^{j\omega}) = \sum_{n=-\infty}^{\infty} h_2[n] e^{-j\omega n}$$

$$= \sum_{\substack{n=2k \\ k=-\infty}}^{\infty} h[n/2] e^{-j\omega n}$$

$$= \sum_{n=-\infty}^{\infty} h[n] e^{-j\omega 2n}$$

$$= H(e^{j\omega 2})$$

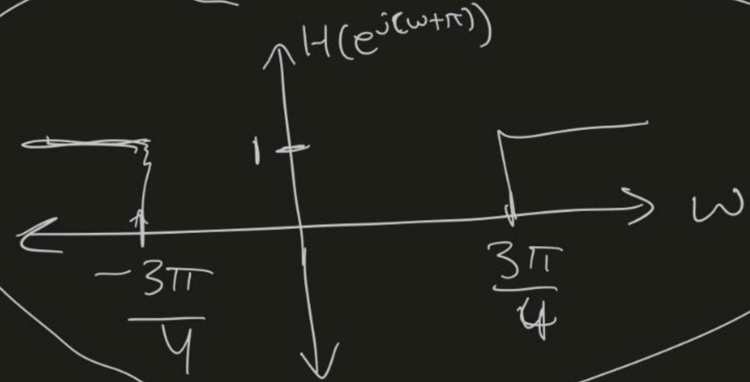


c) $h_3[n] = (-1)^n h[n]$

$$H_3(e^{j\omega}) = \sum_{n=-\infty}^{\infty} (-1)^n h[n] e^{-j\omega n}$$

$$= \sum_{n \text{ even}} h[n] e^{-j\omega n} - \sum_{n \text{ odd}} h[n] e^{-j\omega n}$$

$$= H\left(e^{j(\omega+\pi)}\right)$$



3) Specs:

$0.98 < H(e^{j\omega}) < 1.02 \quad , \quad 0 \le |\omega| \le 0.63\pi$

$-0.15 < H(e^{j\omega}) < 0.15 \quad , \quad 0.65\pi \le |\omega| \le \pi$

Analog Filter Specs:

$0.98 < H(j\Omega) < 1.02 \quad , \quad 0 \le \Omega \le 2\tan\left(\frac{0.63\pi}{2}\right)$

$-0.15 < H(j\Omega) < 0.15 \quad , \quad 2\tan\left(\frac{0.65\pi}{2}\right) \le \Omega \le \infty$

Design Constraints:

$T_d = 1$

$|H_c(j2\tan(0.315\pi))| > 0.98$

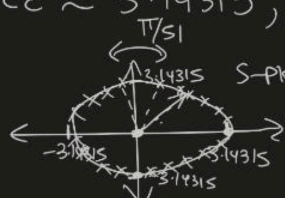
$|H_c(j2\tan(0.325\pi))| < 0.15$

For Butterworth filter, $|H(j\Omega)|^2 = \dfrac{1}{1+\left(\frac{\Omega}{\Omega_c}\right)^{2N}}$ and due to its monotonic response:

$$1+\left(\frac{2\tan(0.315\pi)}{\Omega_c}\right)^{2N} = \left(\frac{1}{0.98}\right)^2$$

$$1+\left(\frac{2\tan(0.325\pi)}{\Omega_c}\right)^{2N} = \left(\frac{1}{0.15}\right)^2$$

$$\Omega_c \simeq 3.14315 \, , \; N = 51$$



→ There will be 102 poles around the circle, the s-plane

$$H_c(s) = \frac{(\Omega_c)^N}{\prod_{k=1}^{N}(s-s_k)}$$ → Rest of steps are done using MATLAB code below

4) $\omega_{pd} = \frac{2}{T_d} \tan\left(\frac{\omega_p}{2}\right)$

$\omega_{sd} = \frac{2}{T_d} \tan\left(\frac{\omega_s}{2}\right)$

$H_1(s)$ will have $T_d = T_1$ designed to pre-warp ω_p & ω_s

$H_2(s)$ will have $T_d = T_2$ with same pre-warped frequencies

$$H_2(s) = H_1\left(s\frac{T_1}{T_2}\right)$$

Starting from $H_1(s) \longrightarrow H_1(z) = H_1\left(\frac{2}{T_1}\frac{1-z^{-1}}{1+z^{-1}}\right)$

$$H_2(z) = H_2\left(\frac{2}{T_2}\frac{1-z^{-1}}{1+z^{-1}}\right) = H_1\left(\frac{2}{T_2}\frac{1-z^{-1}}{1+z^{-1}}\frac{T_1}{T_2}\right)$$

$$= H_1\left(\frac{2T_1}{T_2^2}\frac{1-z^{-1}}{1+z^{-1}}\right)$$

In the appropriate bilinear transformation:

$$\frac{2}{T_1}\cancel{\frac{1-z^{-1}}{1+z^{-1}}} = \frac{2T_1}{T_2^2}\cancel{\frac{1-z^{-1}}{1+z^{-1}}}$$

$$\frac{\cancel{2}}{T_1} = \frac{\cancel{2}T_1}{T_2^2} \longrightarrow \frac{1}{T_1} = \frac{T_1}{T_2^2} \longrightarrow T_1^2 = T_2^2$$

Since $T_1, T_2 \geq 0$:

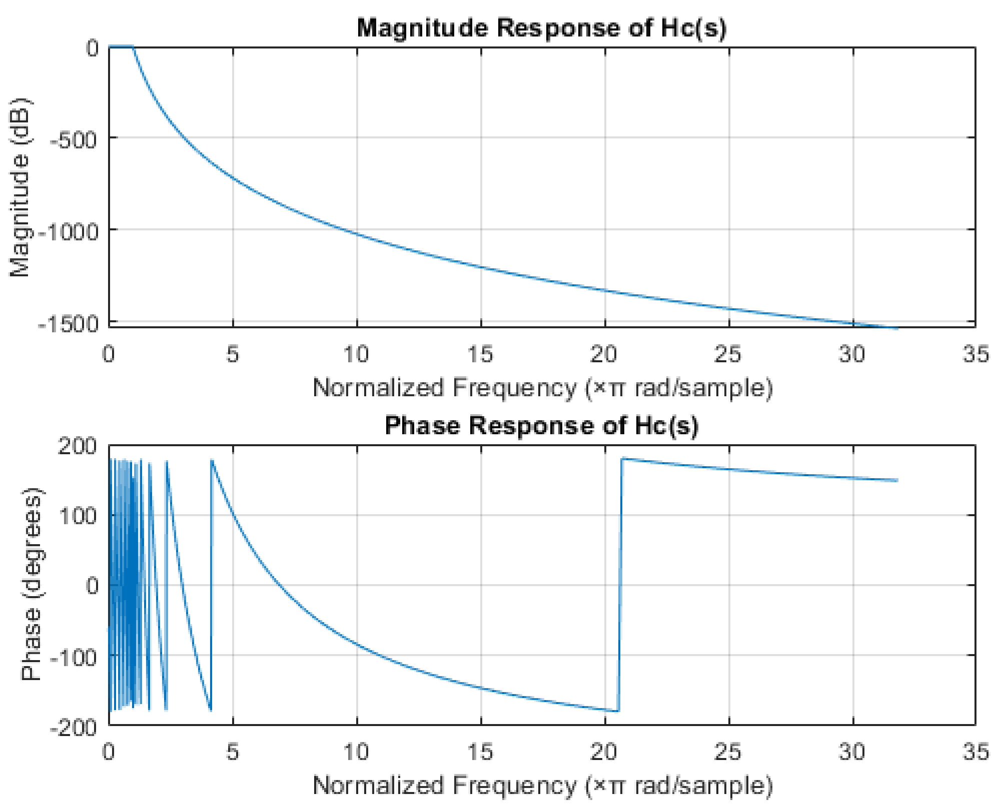
$T_1 = T_2$

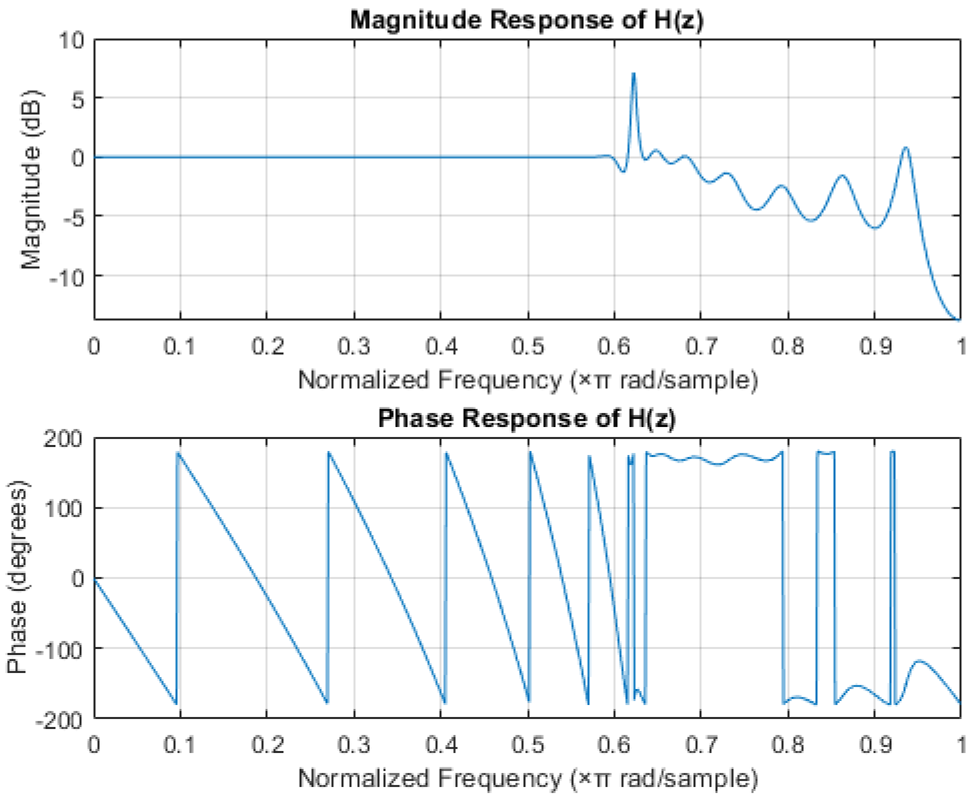
Given a bilinear transformation where $T_d = T_1 = T_2$, both $H_1(s)$ and $H_2(s)$ will result in the same digital filter $H(z)$.

```
% Given specifications
n = 51;
Omega_c = 3.14315;
[z, p, k] = buttap(n);  %returns poles and zeros and gain of Butterworth
filter with parameter n
p = p * Omega_c;
k = k * Omega_c^n;

[num, den] = zp2tf(z, p, k); %convert to transfer function form

Hc = tf(num, den); %transfer function of analog butterworth filter
[Hc_freq, W_c] = freqs(num, den, 1024);
magnitude = 20*log10(abs(Hc_freq));
phase = angle(Hc_freq) * (180/pi);

figure;
subplot(2,1,1); % Magnitude plot
plot(W_c/pi, magnitude);
title('Magnitude Response of Hc(s)');
xlabel('Normalized Frequency (×π rad/sample)');
ylabel('Magnitude (dB)');
grid on;

subplot(2,1,2); % Phase plot
plot(W_c/pi, phase);
title('Phase Response of Hc(s)');
xlabel('Normalized Frequency (×π rad/sample)');
ylabel('Phase (degrees)');
grid on;

fs = 1;
T = 1/fs;
[num_z, den_z] = bilinear(num, den, fs); % Convert Hc(s) to H(z) using
bilinear transform
Hz = tf(num_z, den_z, T);
disp(Hz);
[H_freq, W] = freqz(num_z, den_z, 1024); % Compute frequency response
magnitude = 20*log10(abs(H_freq)); % Convert to dB
phase = angle(H_freq) * (180/pi); % Convert to degrees

figure;
subplot(2,1,1); % Magnitude plot
plot(W/pi, magnitude);
title('Magnitude Response of H(z)');
xlabel('Normalized Frequency (×π rad/sample)');
ylabel('Magnitude (dB)');
grid on;

subplot(2,1,2); % Phase plot
plot(W/pi, phase);
title('Phase Response of H(z)');
xlabel('Normalized Frequency (×π rad/sample)');
```

```
ylabel('Phase (degrees)');
grid on;
```

```
  tf with properties:

       Numerator: {[2.4065e-09 1.2273e-07 3.0683e-06 … ] (1×52 double)}
     Denominator: {[1 14.2001 104.7289 529.1458 2.0457e+03 … ] (1×52 double)}
        Variable: 'z'
         IODelay: 0
      InputDelay: 0
     OutputDelay: 0
       InputName: {''}
       InputUnit: {''}
      InputGroup: [1×1 struct]
      OutputName: {''}
      OutputUnit: {''}
     OutputGroup: [1×1 struct]
           Notes: [0×1 string]
        UserData: []
            Name: ''
              Ts: 1
        TimeUnit: 'seconds'
    SamplingGrid: [1×1 struct]
```





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