Filter Design - Filter #114

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Download all python codes from

https://github.com/varunireddy/EE3025_IDP/tree/main/filter_design/codes

and latex-tikz codes from

https://github.com/varunireddy/EE3025_IDP/tree/main/filter_design

1 Introduction

We are supposed to design the equivalent FIR and IIR filter realizations for filter number 114. This is a bandpass filter whose specifications are available below.

2 Filter Specifications

The sampling rate for the filter has been specified as $F_s = 48$ kHz. Let the un-normalized discrete-time (natural) frequency is F, the corresponding normalized digital filter (angular) frequency is given by $\omega = 2\pi\left(\frac{F}{F_s}\right)$.

2.1 The Digital Filter

1) **Tolerances:** The passband (δ_1) and stopband (δ_2) tolerances are given to be equal, so let $\delta_1 = \delta_2 = \delta = 0.15$.
2) **Passband:** The passband of filter number j, j going from 109 to 135 is from {3 + 0.6(j-109)}kHz to {3 + 0.6(j-107)}kHz. Since our filter number is 114, Substituting $j = 114$ gives the passband range as 6 kHz - 7.2 kHz. Hence, the un-normalized discrete time filter passband frequencies are

$$F_{p1} = 7.2 \text{ kHz} \tag{2.1.1}$$
$$F_{p2} = 6 \text{ kHz} \tag{2.1.2}$$

and corresponding normalized digital filter passband frequencies are

$$\omega_{p1} = 2\pi\frac{F_{p1}}{F_s} = 0.3\pi \tag{2.1.3}$$
$$\omega_{p2} = 2\pi\frac{F_{p2}}{F_s} = 0.25\pi \tag{2.1.4}$$

Center Frequency is given by,

$$\omega_c = \frac{\omega_{p1} + \omega_{p2}}{2} = 0.275\pi \tag{2.1.5}$$

3) **Stopband:** The *transition band* for bandpass filters is $\Delta F = 0.3$ kHz on either side of the passband.
Hence, the un-normalized *stopband* frequencies are

$$F_{s1} = 7.2 + 0.3 = 7.5 \tag{2.1.6}$$
$$F_{s2} = 6.0 - 0.3 = 5.7 \tag{2.1.7}$$

and their corresponding Normalized frequencies are,

$$\omega_{s1} = 0.3125\pi \tag{2.1.8}$$
$$\omega_{s2} = 0.2375\pi \tag{2.1.9}$$

2.2 The Analog filter

In the bilinear transform, the analog filter is related to the corresponding digital filter as.,

$$s = \frac{2}{T}\left[\frac{z-1}{z+1}\right] \tag{2.2.1}$$

Substitute.,

$$z = e^{j\omega} \tag{2.2.2}$$
$$s = j\Omega \tag{2.2.3}$$

where,
Ω is analog filter frequency
ω is digital filter frequency
The equation.2.2.1 becomes,

$$\Omega = \frac{2}{T}\tan\frac{\omega}{2} \tag{2.2.4}$$

Using the above relation, we obtain the analog passband and stopband frequencies as

$$\Omega_{p1} = 0.5095 \tag{2.2.5}$$
$$\Omega_{p2} = 0.4142 \tag{2.2.6}$$
$$\Omega_{s1} = 0.5345 \tag{2.2.7}$$
$$\Omega_{s2} = 0.3914 \tag{2.2.8}$$

3 IIR Filter Design

Filter Type: We are supposed to design filters whose stopband is monotonic and passband equiripple. Hence, we use the *Chebyschev approximation* to design our bandpass IIR filter.

3.1 The Analog Filter

1) **Low Pass Analog Filter Specifications:** If $H_{a,BP}(j\Omega)$ be the desired analog band pass filter, with the specifications provided in Section 2.2, and $H_{a,LP}(j\Omega_L)$ be the equivalent low pass filter, then we map the frequencies as following.,

$$\Omega_L \leftarrow A(\Omega^2 - \Omega_0^2) \tag{3.1.1}$$

Whenever the Ω on the right (which is the BPF) is equal to either Ω_0 or $-\Omega_0$, the Ω_L on the left is zero. Now, suppose we set A=$Q/\Omega_0\Omega$ which is still non-zero and non-infinite for $\Omega = \Omega_0$).

$$\Omega_L = Q\left[\frac{\Omega}{\Omega_0} - \frac{\Omega_0}{\Omega}\right] \tag{3.1.2}$$

Where,

$$Q = \frac{\Omega_0}{\Omega_{p1} - \Omega_{p2}} \tag{3.1.3}$$

$$\Omega_0 = \sqrt{\Omega_{p1}\Omega_{p2}} \tag{3.1.4}$$

The equation.3.1.2 can be rewritten as the following.,

$$\Omega_L = \frac{\Omega^2 - \Omega_0^2}{B\Omega} \tag{3.1.5}$$

where., B $= \Omega_{p1} - \Omega_{p2}$. The above equation maps bandpass frequencies to low pass frequencies. Substituting the values, we get.,

$$\Omega_0 = \sqrt{\Omega_{p1}\Omega_{p2}} = 0.4594 \tag{3.1.6}$$

$$B = \Omega_{p1} - \Omega_{p2} = 0.0953 \tag{3.1.7}$$

The low pass filter has the passband edge at $\Omega_{Lp} = 1$ and stopband edges at $\Omega_{Ls_1} = 1.4653$ and $\Omega_{Ls_2} = -1.5511$. We choose the stopband edge of the analog low pass filter as $\Omega_{Ls} = \min(|\Omega_{Ls_1}|, |\Omega_{Ls_2}|)$.

$$\Omega_{Lp} = 1 \tag{3.1.8}$$

$$\Omega_{Ls} = 1.4653 \tag{3.1.9}$$

2) **The Low Pass Chebyschev Filter Paramters:** The magnitude squared of the Chebyschev low pass filter is given by

$$|H_{a,LP}(j\Omega_L)|^2 = \frac{1}{1 + \epsilon^2 c_N^2(\Omega_L/\Omega_{Lp})} \tag{3.1.10}$$

where $c_N(x) = \cosh(N\cosh^{-1} x)$ and the integer N, which is the order of the filter, and ϵ are design paramters. Since $\Omega_{Lp} = 1$, (3.1.10) may be rewritten as

$$|H_{a,LP}(j\Omega_L)|^2 = \frac{1}{1 + \epsilon^2 c_N^2(\Omega_L)} \tag{3.1.11}$$

Also, the design paramters have the following constraints

$$\frac{\sqrt{D_2}}{c_N(\Omega_{Ls})} \le \epsilon \le \sqrt{D_1},$$
$$N \ge \left\lceil \frac{\cosh^{-1}\sqrt{D_2/D_1}}{\cosh^{-1}\Omega_{Ls}} \right\rceil, \tag{3.1.12}$$

where,

$$D_1 = \frac{1}{(1-\delta)^2} - 1 \tag{3.1.13}$$

$$D_2 = \frac{1}{\delta^2} - 1 \tag{3.1.14}$$

After appropriate substitutions, we obtain,

$$N \ge 4 \tag{3.1.15}$$

$$0.3184 \le \epsilon \le 0.6197 \tag{3.1.16}$$

iir/paraplot.py

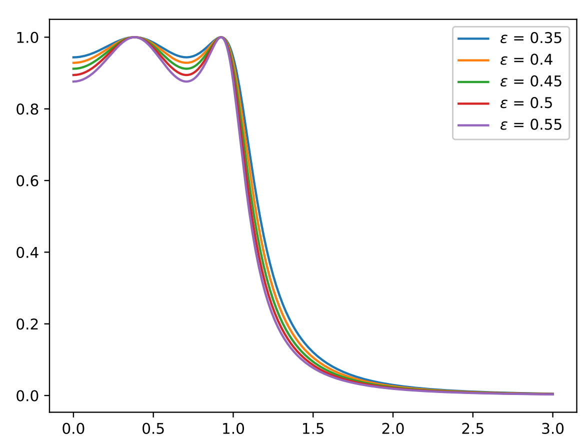

Fig. 2: Analog low pass response for varying epsilon

In Figure.2, we plot $|H(j\Omega)|$ for a range of values of ϵ, for $N = 4$. We find that for larger values of ϵ, $|H(j\Omega)|$ decreases in the transition band. We choose $\epsilon = 0.4$ for our IIR filter design. The following code generates the values of all parameters.

```
iir/para.py
```

3) **The Low Pass Chebyschev Filter:** Thus, we obtain

$$|H_{a,LP}(j\Omega_L)|^2 = \frac{1}{1 + 0.16c_4^2(\Omega_L)} \tag{3.1.17}$$

where

$$c_4(x) = 8x^4 + 8x^2 + 1. \tag{3.1.18}$$

The poles of the frequency response in (3.1.10) lying in the left half plane are in general obtained as $r_1 \cos\phi_k + jr_2 \sin\phi_k$, where

$$\phi_k = \frac{\pi}{2} + \frac{(2k+1)\pi}{2N}, k = 0, 1, \ldots, N-1$$

$$r_1 = \frac{\beta^2 - 1}{2\beta} \tag{3.1.19}$$

$$r_2 = \frac{\beta^2 + 1}{2\beta} \tag{3.1.20}$$

$$\beta = \left[\frac{\sqrt{1+\epsilon^2} + 1}{\epsilon}\right]^{\frac{1}{N}} \tag{3.1.21}$$

Thus, for N even, the low-pass stable Chebyschev filter, with a gain G has the form

$$H_{LP}(s_L) = \frac{G_{LP}}{\prod_k (s_L^2 - 2r_1 C(\phi_k)s_L + r_1^2 C^2(\phi_k) + r_2^2 S^2(\phi_k)} \tag{3.1.22}$$

where, (3.1.23)

$$C(\phi_k) = \cos(\phi_k) \tag{3.1.24}$$

$$S(\phi_k) = \sin(\phi_k) \tag{3.1.25}$$

Substituting $N = 4$, $\epsilon = 0.5$ and $H_{a,LP}(j) = \frac{1}{\sqrt{1+\epsilon^2}}$, we obtain

$$H_{a,LP}(s_L) = \frac{0.3125}{s_L^4 + 1.12s_L^3 + 1.61s_L^2 + 0.91s_L + 0.34} \tag{3.1.26}$$

```
iir/lpanalog.py
```

In Figure 3 we plot $|H(j\Omega)|$ using (3.1.17) and (3.1.26), thereby verifying that our low-pass Chebyschev filter design meets the specifications.

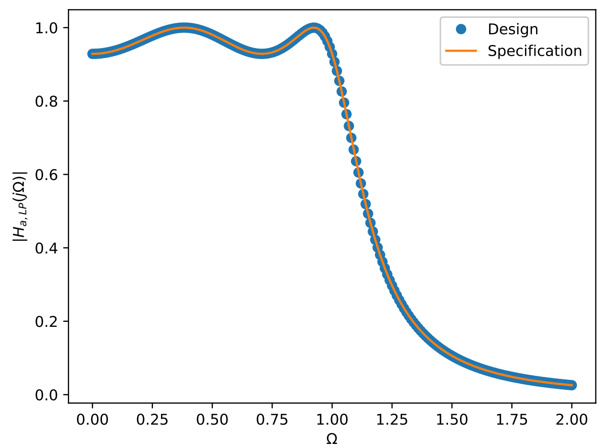

Fig. 3: LP specifications in 3.1.17, 3.1.28

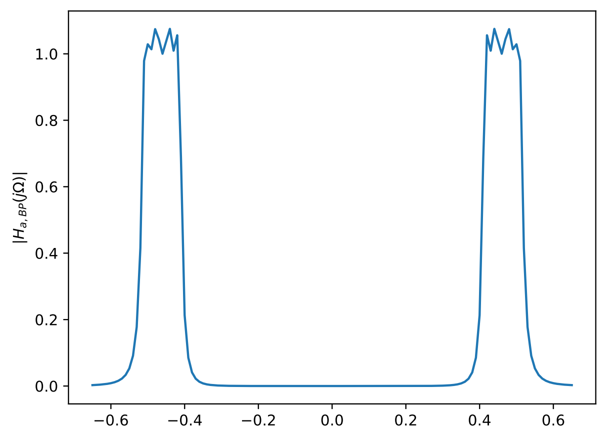

Fig. 4: Analog bandpass from eq.3.1.28

4) **The Band Pass Chebyschev Filter:** The analog bandpass filter is obtained from (3.1.26) by substituting $s_L = \frac{s^2+\Omega_0^2}{Bs}$. Hence

$$H_{a,BP}(s) = G_{BP}H_{a,LP}(s_L)\Big|_{s_L=\frac{s^2+\Omega_0^2}{Bs}}, \tag{3.1.27}$$

where G_{BP} is the gain of the bandpass filter. After appropriate substitutions, and evaluating the gain such that $H_{a,BP}(j\Omega_{p1}) = 1$, we obtain

$$H_{a,BP}(s) = \frac{2.78 \times 10^{-5}s^4}{s^8 + 0.11s^7 + 0.8s^6 + 0.07s^5 + 0.3s^4 + 0.01s^3 + 0.04s^2 + 0.001s + 0.002} \tag{3.1.28}$$

```
iir/iirfinal.py
```

In Figure 4, we plot $|H_{a,BP}(j\Omega)|$ as a function of Ω for both positve as well as negative frequencies. We find that the passband and stopband frequencies in the figure match well with those obtained analytically through BT.

3.2 The Digital Filter

From the bilinear transformation, we obtain the digital bandpass filter from the corresponding analog filter as

$$H_{d,BP}(z) = GH_{a,BP}(s)\big|_{s=\frac{1-z^{-1}}{1+z^{-1}}} \tag{3.2.1}$$

where G is the gain of the digital filter. From (3.1.28) and (3.2.1), we obtain

$$H_{d,BP}(z) = G\frac{N(z)}{D(z)} \tag{3.2.2}$$

where $G = 2.7776 \times 10^{-5}$,

$$N(z) = 1 - 4z^{-2} + 6z^{-4} - 4z^{-6} + z^{-8} \tag{3.2.3}$$

and

$$\begin{aligned} D(z) = 2.36 - 12z^{-1} + 31.88z^{-2} - 53.75z^{-3} + 62.81z^{-4} \\ - 51.47z^{-5} + 29.23z^{-6} - 10.53z^{-7} + 1.98z^{-8} \end{aligned} \tag{3.2.4}$$

The plot of $|H_{d,BP}(z)|$ with respect to the normalized angular frequency (normalizing factor π) is available in Figure.4. Again we find that the passband and stopband frequencies meet the specifications well enough.

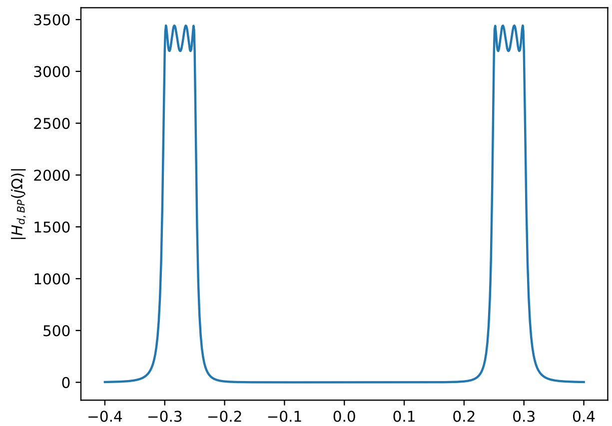

Fig. 4: The magnitude response of the bandpass digital filter designed to meet the given specifications

4 The FIR Filter

We design the FIR filter by first obtaining the (non-causal) lowpass equivalent using the Kaiser window and then converting it to a causal bandpass filter.

4.1 The Equivalent Lowpass Filter

The lowpass filter has a passband frequency ω_l and transition band $\Delta\omega = 2\pi\frac{\Delta F}{F_s} = 0.0125\pi$. The stopband tolerance is δ.

1) The *passband frequency* ω_l is defined as $\omega_l = \frac{\omega_{p1}-\omega_{p2}}{2}$. Substituting the values of ω_{p1} and ω_{p2} from section 2.1, we obtain $\omega_l = 0.025\pi$.
2) *The impulse response* $h_{lp}(n)$ of the desired lowpass filter with cutoff frequency ω_l is given by

$$h_l(n) = \frac{\sin(n\omega_l)}{n\pi}w(n), \tag{4.1.1}$$

where $w(n)$ is the Kaiser window obtained from the design specifications.

4.2 The Kaiser Window

The Kaiser window is defined as

$$\begin{aligned} w(n) &= \frac{I_0\left[\beta N\sqrt{1-\left(\frac{n}{N}\right)^2}\right]}{I_0(\beta N)}, -N \le n \le N, \beta > 0 \\ &= 0 \qquad \text{else,} \end{aligned} \tag{4.2.1}$$

where $I_0(x)$ is the modified Bessel function of the first kind of order zero in x and β and N are the window shaping factors. In the following, we find β and N using the design parameters in section 2.1.

1) N is chosen according to

$$N \ge \frac{A-8}{4.57\Delta\omega}, \tag{4.2.2}$$

where $A = -20\log_{10}\delta$. Substituting the appropriate values from the design specifications, we obtain $A = 16.4782$ and $N \ge 48$.
2) β is chosen according to

$$\beta N = \begin{cases} 0.1(A-8.7) & A > 50 \\ 0.6(A-21)^{0.4} + 0.1(A-21) & 21 \le A \le 50 \\ 0 & A < 21 \end{cases} \tag{4.2.3}$$

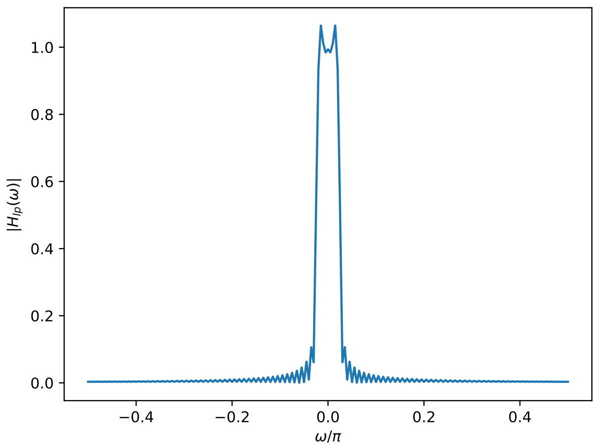

Fig. 3: The magnitude response of the FIR lowpass digital filter designed to meet the given specifications

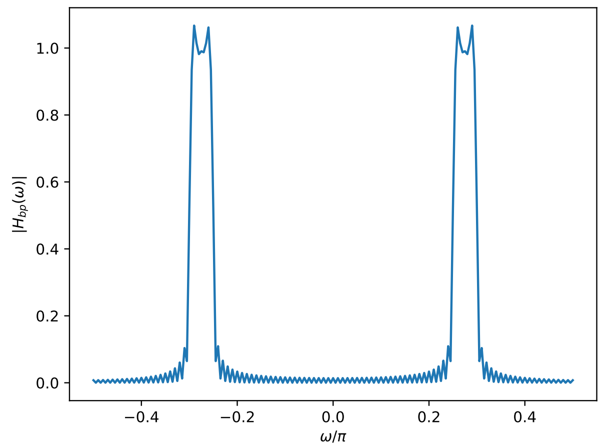

Fig. 3: The magnitude response of the FIR bandpass digital filter designed to meet the given specifications

In our design, we have $A = 16.4782 < 21$. Hence, from (4.2.3) we obtain $\beta = 0$.

3) We choose $N = 100$, to ensure the desired low pass filter response. Substituting in (4.2.1) gives us the rectangular window

$$\begin{aligned} w(n) &= 1, -100 \le n \le 100 \\ &= 0 \quad \text{otherwise} \end{aligned} \tag{4.2.4}$$

From (4.1.1) and (4.2.4), we obtain the desired lowpass filter impulse response

$$\begin{aligned} h_{lp}(n) &= \frac{\sin(\frac{n\pi}{40})}{n\pi} - 100 \le n \le 100 \\ &= 0, \quad \text{otherwise} \end{aligned} \tag{4.2.5}$$

The magnitude response of the filter in (4.2.5) is shown in Figure.3.

4.3 The FIR Bandpass Filter

The centre of the passband of the desired bandpass filter was found to be $\omega_c = 0.275\pi$ in Section 2.1. The impulse response of the desired bandpass filter is obtained from the impulse response of the corresponding lowpass filter as

$$h_{bp}(n) = 2h_{lp}(n)cos(n\omega_c) \tag{4.3.1}$$

Thus, from (4.2.5), we obtain

$$\begin{aligned} h_{bp}(n) &= \frac{2\sin(\frac{n\pi}{40})\cos(\frac{11n\pi}{40})}{n\pi} - 100 \le n \le 100 \\ &= 0, \quad \text{else} \end{aligned} \tag{4.3.2}$$

The magnitude response of the FIR bandpass filter designed to meet the given specifications is plotted in Figure.3. The following code generates the plots.

```
fir/test.py
```