

# Digital Signal Processing

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*Abstract*—This manual provides a simple introduction to digital signal processing.

## 1 SOFTWARE INSTALLATION

Run the following commands

```
sudo apt-get update
sudo apt-get install libffi-dev libsndfile1 python3
  -scipy python3-numpy python3-matplotlib
sudo pip install cffi pysoundfile
```

## 2 DIGITAL FILTER

### 2.1 Download the sound file from

```
wget https://github.com/Pradeep8802/EE3900
  -Digital-Signal-Processing/blob/main/
  Assignment1/codes/Sound_Noise.wav
```

2.2 You will find a spectrogram at <https://academo.org/demos/spectrum-analyzer>. Upload the sound file that you downloaded in Problem 2.1 in the spectrogram and play. Observe the spectrogram. What do you find?

**Solution:** There are a lot of yellow lines between 440 Hz to 5.1 KHz. These represent the synthesizer key tones. Also, the key strokes are audible along with background noise.

2.3 Write the python code for removal of out of band noise and execute the code.

**Solution:**

```
import soundfile as sf
from scipy import signal

#read .wav file
input_signal,fs = sf.read('Sound_Noise.wav'
    )

#sampling frequency of Input signal
sampl_freq=fs

#order of the filter
order=4

#cutoff frequency 4kHz
cutoff_freq=4000.0

#digital frequency
Wn=2*cutoff_freq/sampl_freq

# b and a are numerator and denominator
  polynomials respectively
b, a = signal.butter(order,Wn, 'low')

#filter the input signal with butterworth filter
output_signal = signal.filtfilt(b, a,
    input_signal)
#output_signal = signal.lfilter(b, a,
    input_signal)

#write the output signal into .wav file
sf.write('Sound_With_ReducedNoise.wav',
    output_signal, fs)
```

2.4 The output of the python script in Problem 2.3 is the audio file Sound\_With\_ReducedNoise.wav. Play the file in the spectrogram in Problem 2.2. What do you observe?

**Solution:** The key strokes as well as background noise is subdued in the audio. Also, the signal is blank for frequencies above 5.1 kHz.

### 3 DIFFERENCE EQUATION

3.1 Let

$$x(n) = \left\{ \underset{\uparrow}{1}, 2, 3, 4, 2, 1 \right\} \quad (3.1)$$

Sketch  $x(n)$ .

**Solution:** The following code yields Fig. 3.2.

```
wget https://github.com/Pradeep8802/
EE3900-Digital-Signal-
Processing/blob/main/
Assignment1/codes/3.1.py
```

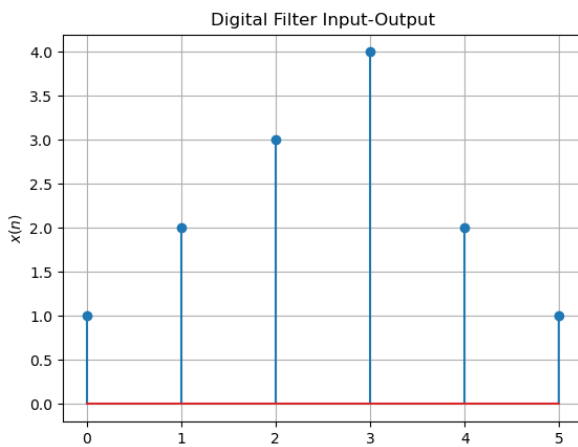


Fig. 3.1

3.2 Let

$$y(n) + \frac{1}{2}y(n-1) = x(n) + x(n-2),$$

$$y(n) = 0, n < 0 \quad (3.2)$$

Sketch  $y(n)$ .

**Solution:** The following code yields Fig. 3.2.

```
wget https://github.com/Pradeep8802/EE3900
-Digital-Signal-Processing/blob/main/
Assignment1/codes/3.2.py
```

3.3 Repeat the above exercise using a C code.

**Solution:** The following c code is used to find  $y(n)$

```
wget https://github.com/Pradeep8802/
EE3900-Digital-Signal-
Processing/blob/main/
Assignment1/codes/3.3.c
```

The following code yields Fig. 3.3.

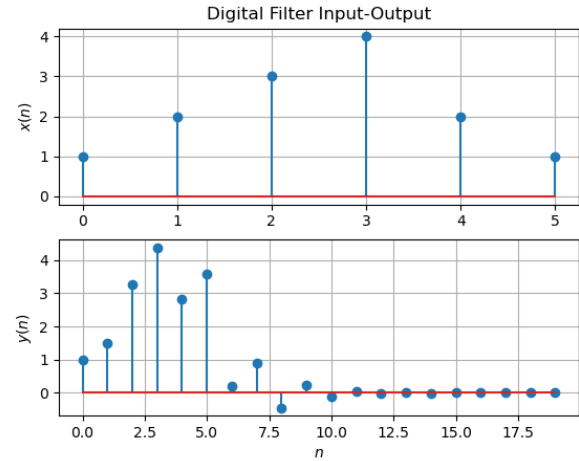


Fig. 3.2

```
wget https://github.com/Pradeep8802/
EE3900-Digital-Signal-
Processing/blob/main/
Assignment1/codes/3.3.py
```

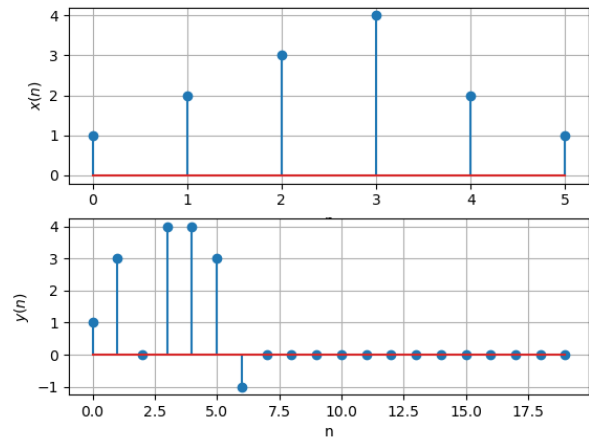


Fig. 3.3

### 4 Z-TRANSFORM

4.1 The Z-transform of  $x(n]$  is defined as

$$X(z) = \mathcal{Z}\{x(n)\} = \sum_{n=-\infty}^{\infty} x(n)z^{-n} \quad (4.1)$$

Show that

$$\mathcal{Z}\{x(n-1)\} = z^{-1}X(z) \quad (4.2)$$

and find

$$\mathcal{Z}\{x(n-k)\} \quad (4.3)$$

**Solution:** From (4.1),

$$\begin{aligned} \mathcal{Z}\{x(n-1)\} &= \sum_{n=-\infty}^{\infty} x(n-1)z^{-n} \quad (4.4) \\ &= \sum_{n=-\infty}^{\infty} x(n)z^{-n-1} = z^{-1} \sum_{n=-\infty}^{\infty} x(n)z^{-n} \quad (4.5) \end{aligned}$$

resulting in (4.2). Similarly, it can be shown that

$$\mathcal{Z}\{x(n-k)\} = z^{-k}X(z) \quad (4.6)$$

4.2 Obtain  $X(z)$  for  $x(n)$  defined in problem 3.1.

**Solution:** Z-transform of  $x(n)$ ,  $X(z)$  is given by

$$\mathcal{Z}\{x(n)\} = \sum_{n=-\infty}^{\infty} x(n)z^{-n} \quad (4.7)$$

$$= \sum_{n=0}^5 x(n)z^{-n} \quad (4.8)$$

$$= 1 + 2z^{-1} + 3z^{-2} + 4z^{-3} + 2z^{-4} + z^{-5} \quad (4.9)$$

4.3 Find

$$H(z) = \frac{Y(z)}{X(z)} \quad (4.10)$$

from (3.2) assuming that the Z-transform is a linear operation.

**Solution:** Applying (4.6) in (3.2),

$$Y(z) + \frac{1}{2}z^{-1}Y(z) = X(z) + z^{-2}X(z) \quad (4.11)$$

$$\Rightarrow \frac{Y(z)}{X(z)} = \frac{1 + z^{-2}}{1 + \frac{1}{2}z^{-1}} \quad (4.12)$$

4.4 Find the Z transform of

$$\delta(n) = \begin{cases} 1 & n = 0 \\ 0 & \text{otherwise} \end{cases} \quad (4.13)$$

and show that the Z-transform of

$$u(n) = \begin{cases} 1 & n \geq 0 \\ 0 & \text{otherwise} \end{cases} \quad (4.14)$$

is

$$U(z) = \frac{1}{1 - z^{-1}}, \quad |z| > 1 \quad (4.15)$$

**Solution:** The Z-transform of  $\delta(n)$  is defined

as

$$\mathcal{Z}\{\delta(n)\} = \sum_{n=-\infty}^{\infty} \delta(n)z^{-n} \quad (4.16)$$

$$= \delta(0)z^{-0} \quad (4.17)$$

$$= 1 \quad (4.18)$$

Hence we can say that

$$\delta(n) \stackrel{\mathcal{Z}}{\rightleftharpoons} 1 \quad (4.19)$$

and from (4.14),

$$U(z) = \sum_{n=0}^{\infty} z^{-n} \quad (4.20)$$

$$= \frac{1}{1 - z^{-1}}, \quad |z| > 1 \quad (4.21)$$

using the formula for the sum of an infinite geometric progression.

4.5 Show that

$$a^n u(n) \stackrel{\mathcal{Z}}{\rightleftharpoons} \frac{1}{1 - az^{-1}} \quad |z| > |a| \quad (4.22)$$

**Solution:**

$$\mathcal{Z}\{a^n u(n)\} = \sum_{n=-\infty}^{\infty} a^n u(n)z^{-n} \quad (4.23)$$

$$= \sum_{n=0}^{\infty} a^n z^{-n} \quad (4.24)$$

$$= \sum_{n=0}^{\infty} (z^{-1}a)^n \quad (4.25)$$

$$= \frac{1}{1 - az^{-1}}, \quad |z^{-1}a| < 1 \quad (4.26)$$

$$= \frac{1}{1 - az^{-1}}, \quad |z| > |a| \quad (4.27)$$

using the formula for the sum of an infinite geometric progression.

4.6 Let

$$H(e^{j\omega}) = H(z = e^{j\omega}). \quad (4.28)$$

Plot  $|H(e^{j\omega})|$ . Is it periodic? If so, find the period.  $H(e^{j\omega})$  is known as the *Discrete Time Fourier Transform* (DTFT) of  $h(n)$ .

**Solution:**

wget <https://github.com/Pradeep8802/EE3900-Digital-Signal-Processing/blob/main/Assignment1/codes/4.5.py>

$H(e^{j\omega})$  is given by

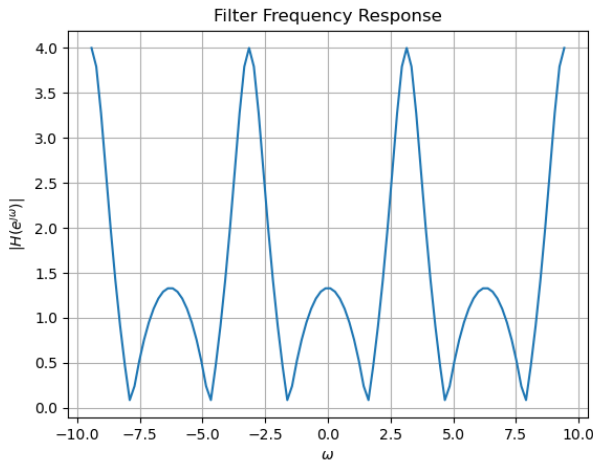


Fig. 4.6:  $|H(e^{j\omega})|$

$$H(e^{j\omega}) = \frac{1 + (e^{j\omega})^{-2}}{1 + \frac{1}{2}(e^{j\omega})^{-1}} \quad (4.29)$$

$$= 2 \frac{1 + \cos(-2\omega) + j \sin(-2\omega)}{2 + \cos(-\omega) + j \sin(-\omega)} \quad (4.30)$$

$$= 2 \frac{1 + \cos(2\omega) - j \sin(2\omega)}{2 + \cos(\omega) - j \sin(\omega)} \quad (4.31)$$

$$= 2 \frac{2 \cos^2(\omega) - 2j \sin(\omega) \cos(\omega)}{2 + \cos(\omega) - j \sin(\omega)} \quad (4.32)$$

$$= 4 \cos(\omega) \frac{\cos(\omega) - j \sin(\omega)}{2 + \cos(\omega) - j \sin(\omega)} \quad (4.33)$$

$$= 4 |\cos(\omega)| \frac{e^{j\omega}}{2 + e^{j\omega}} \quad (4.34)$$

So,

$$|H(e^{j\omega})| = 4 |\cos(\omega)| \frac{|e^{j\omega}|}{|2 + e^{j\omega}|} \quad (4.35)$$

$$= \frac{|4 \cos(\omega)|}{\sqrt{5 + 4 \cos(\omega)}} \quad (4.36)$$

The period of  $|\cos(\omega)|$  is  $\pi$ . The period of  $5 + 4 \cos(\omega)$  is  $2\pi$ . Hence  $|H(e^{j\omega})|$  is periodic with period  $2\pi$ . (The LCM of the period of  $|\cos(\omega)|$  and  $5 + 4 \cos(\omega)$  is  $2\pi$ ) The graph of  $|H(e^{j\omega})|$  is symmetric with respect to y-axis. It is continuous over  $\omega$ . The following code plots Fig. 4.6.

4.7 Express  $h(n)$  in terms of  $H(e^{j\omega})$ .

**Solution:** We know that

$$H(e^{j\omega}) = \sum_{k=-\infty}^{\infty} h(k) e^{-j\omega k} \quad (4.37)$$

$$\frac{1}{2\pi} \int_{-\pi}^{\pi} H(e^{j\omega}) e^{j\omega n} d\omega \quad (4.38)$$

$$= \frac{1}{2\pi} \int_{-\pi}^{\pi} \sum_{k=-\infty}^{\infty} h(k) e^{-j\omega k} e^{j\omega n} d\omega \quad (4.39)$$

$$= \frac{1}{2\pi} \sum_{k=-\infty}^{\infty} h(k) \int_{-\pi}^{\pi} e^{j\omega(n-k)} d\omega \quad (4.40)$$

$$(4.41)$$

case-1: If  $(n \neq k)$

$$= \frac{1}{2\pi} \sum_{k \neq n} h(k) \frac{e^{j\omega(n-k)}}{j(n-k)} \Big|_{-\pi}^{\pi} \quad (4.42)$$

$$= \frac{1}{2\pi} \sum_{k \neq n} h(k) \frac{2 \sin(\pi(n-k))}{(n-k)} \quad (4.43)$$

$$= 0 \quad (4.44)$$

case-2: If  $(n = k)$

$$= \frac{1}{2\pi} h(n) \int_{-\pi}^{\pi} d\omega \quad (4.45)$$

$$= h(n) \quad (4.46)$$

Hence, we can say,

$$h(n) = \frac{1}{2\pi} \int_{-\pi}^{\pi} H(e^{j\omega}) e^{j\omega n} d\omega \quad (4.47)$$

## 5 IMPULSE RESPONSE

5.1 Using long division, find

$$h(n), \quad n < 5 \quad (5.1)$$

for  $H(z)$  in (4.12).

**Solution:**  $H(z)$  is given by

$$H(z) = \frac{1 + z^{-2}}{1 + \frac{1}{2}z^{-1}} = \frac{2 + 2z^{-2}}{2 + z^{-1}} \quad (5.2)$$

$$\frac{2z^{-1} - 4}{z^{-1} + 2} \quad (5.3)$$

$$2z^{-2} + 2 \quad (5.4)$$

$$2z^{-2} + 4z^{-1} \quad (5.5)$$

$$-4z^{-1} + 2 \quad (5.6)$$

$$-4z^{-1} - 8 \quad (5.7)$$

$$10 \quad (5.8)$$

So,

$$H(z) = 2z^{-1} - 4 + \frac{10}{z^{-1} + 2} \quad (5.9)$$

$$= 2z^{-1} - 4 + \frac{5}{\frac{1}{2}z^{-1} + 1} \quad (5.10)$$

$$= 2z^{-1} - 4 + 5 \sum_{n=0}^{\infty} \left(-\frac{z^{-1}}{2}\right)^n \quad (5.11)$$

$$= 1 - \frac{1}{2}z^{-1} + 5 \times \sum_{n=2}^{\infty} \left(-\frac{1}{2}\right)^n z^{-n} \quad (5.12)$$

So,  $h(n)$  will be given by

$$h(n) = \begin{cases} 5 \times \left(-\frac{1}{2}\right)^n & n \geq 2 \\ \left(-\frac{1}{2}\right)^n & 2 > n \geq 0 \\ 0 & n < 0 \end{cases} \quad (5.13)$$

5.2 Find an expression for  $h(n)$  using  $H(z)$ , given that

$$h(n) \stackrel{Z}{\rightleftharpoons} H(z) \quad (5.14)$$

and there is a one to one relationship between  $h(n)$  and  $H(z)$ .  $h(n)$  is known as the *impulse response* of the system defined by (3.2).

**Solution:** From (4.12),

$$H(z) = \frac{1}{1 + \frac{1}{2}z^{-1}} + \frac{z^{-2}}{1 + \frac{1}{2}z^{-1}} \quad (5.15)$$

$$\Rightarrow h(n) = \left(-\frac{1}{2}\right)^n u(n) + \left(-\frac{1}{2}\right)^{n-2} u(n-2) \quad (5.16)$$

using (4.22) and (4.6).

5.3 Sketch  $h(n)$ . Is it bounded? Justify theoretically.

**Solution:** The following code plots Fig. 5.3.

```
wget https://github.com/Pradeep8802/EE3900
-Digital-Signal-Processing/blob/main/
Assignment1/codes/5.3.py
```

on simplifying we get  $h(n)$  as

$$\begin{cases} 5 \times \left(-\frac{1}{2}\right)^n & n \geq 2 \\ \left(-\frac{1}{2}\right)^n & 2 > n \geq 0 \\ 0 & n < 0 \end{cases} \quad (5.17)$$

$$\therefore 5 \times \left(-\frac{1}{2}\right)^n \rightarrow 0 \quad \text{for } n \rightarrow \infty \quad (5.18)$$

So, we can conclude that  $h(n)$  is bounded.

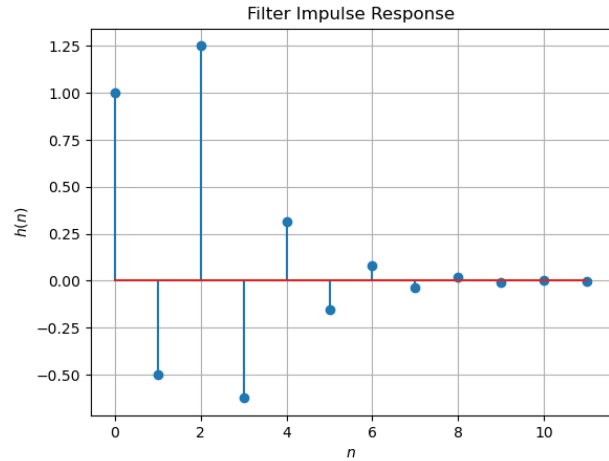


Fig. 5.3:  $h(n)$  wrt  $n$

5.4 Convergent? Justify using the ratio test.

**Solution:** We can say a given real sequence  $\{x_n\}$  is convergent if

$$\lim_{n \rightarrow \infty} \left| \frac{x_{n+1}}{x_n} \right| < 1 \quad (5.19)$$

This is known as Ratio test.

In this case the limit will become,

$$\lim_{n \rightarrow \infty} \left| \frac{h(n+1)}{h(n)} \right| = \lim_{n \rightarrow \infty} \left| \frac{5 \left(\frac{-1}{2}\right)^{n+1}}{5 \left(\frac{-1}{2}\right)^n} \right| \quad (5.20)$$

$$= \lim_{n \rightarrow \infty} \left| \frac{-1}{2} \right| \quad (5.21)$$

$$= \frac{1}{2} \quad (5.22)$$

As  $\frac{1}{2} < 1$ , from root test we can say that  $h(n)$  is convergent.

5.5 The system with  $h(n)$  is defined to be stable if

$$\sum_{n=-\infty}^{\infty} h(n) < \infty \quad (5.23)$$

Is the system defined by (3.2) stable for the impulse response in (5.14)?

**Solution:** For system of 3.2,  $h(n)$  is defined in

(5.13) So,

$$\sum_{n=-\infty}^{\infty} h(n) = \sum_{n=2}^{\infty} 5 \times \left(-\frac{1}{2}\right)^n + \sum_{n=0}^1 \left(-\frac{1}{2}\right)^n + \sum_{n=-\infty}^{-1} 0 \quad (5.24)$$

$$= 5 \times \frac{1}{6} + \frac{1}{2} \quad (5.25)$$

$$= \frac{4}{3} \quad (5.26)$$

Since the sum is finite so the system is stable for impulsive response

5.6 Verify the above result using a python code.

**Solution:** The above result is verified using the below python code

```
wget https://github.com/Pradeep8802/EE3900
-Digital-Signal-Processing/tree/main/
Assignment1/codes/5.6.py
```

5.7 Compute and sketch  $h(n)$  using

$$h(n) + \frac{1}{2}h(n-1) = \delta(n) + \delta(n-2), \quad (5.27)$$

This is the definition of  $h(n)$ .

**Solution:** The following code plots Fig. 5.7. Note that this is the same as Fig. 3.1.

```
wget https://github.com/Pradeep8802/EE3900
-Digital-Signal-Processing/tree/main/
Assignment1/codes/5.7.py
```

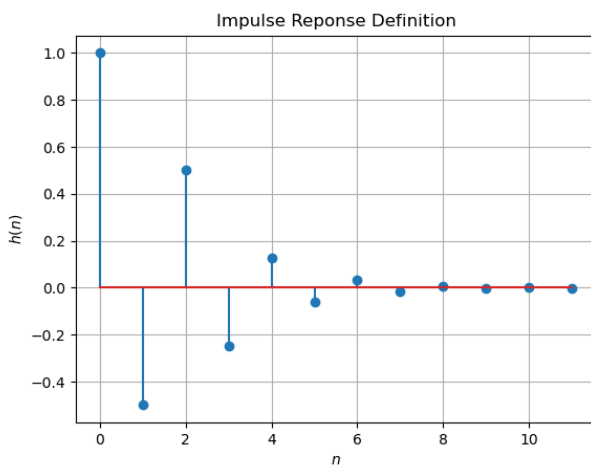


Fig. 5.7:  $h(n)$  from the definition

5.8 Compute

$$y(n) = x(n) * h(n) = \sum_{k=-\infty}^{\infty} x(k)h(n-k) \quad (5.28)$$

Comment. The operation in (5.28) is known as *convolution*.

**Solution:** The following code plots Fig. 5.8. Note that this is the same as  $y(n)$  in Fig. 3.1.

```
wget https://github.com/Pradeep8802/EE3900
-Digital-Signal-Processing/tree/main/
Assignment1/codes/5.4.py
```

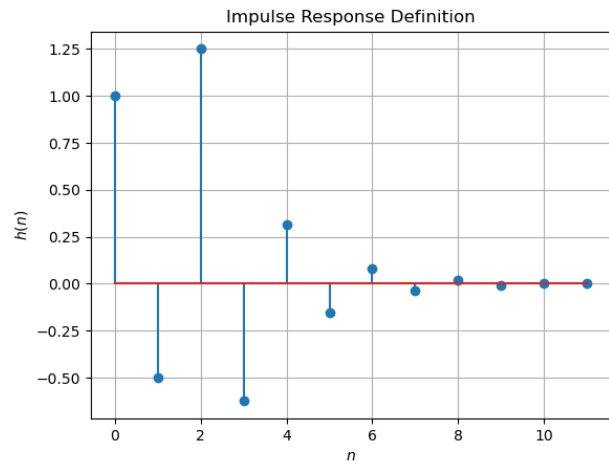


Fig. 5.8:  $y(n)$  from the definition of convolution

5.9 Express the above convolution using a Toeplitz matrix.

**Solution:**

```
wget https://github.com/Pradeep8802/EE3900
-Digital-Signal-Processing/tree/main/
Assignment1/codes/5.9.py
```

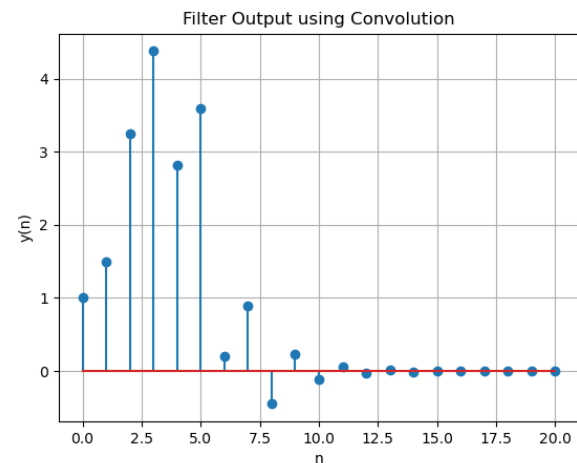


Fig. 5.9: Convolution of  $x(n)$  and  $h(n)$  using toeplitz matrix

From (5.28), we express  $y(n)$  as

$$y(n) = \sum_{k=-\infty}^{\infty} x(k)h(n-k) \quad (5.29)$$

To understand how we can use a Toeplitz matrix, we will see what we are doing in (5.28)

$$y(0) = x(0)h(0) \quad (5.30)$$

$$y(1) = x(0)h(1) + x(1)h(0) \quad (5.31)$$

$$y(2) = x(0)h(2) + x(1)h(1) + x(2)h(0) \quad (5.32)$$

·  
·

The same thing can be written as,

$$y(0) = \begin{pmatrix} h(0) & 0 & 0 & \dots & \dots & .0 \end{pmatrix} \begin{pmatrix} x(0) \\ x(1) \\ x(2) \\ \vdots \\ \vdots \\ x(5) \end{pmatrix} \quad (5.33)$$

$$y(1) = \begin{pmatrix} h(1) & h(0) & 0 & 0 & \dots & \dots & .0 \end{pmatrix} \begin{pmatrix} x(0) \\ x(1) \\ x(2) \\ \vdots \\ \vdots \\ x(5) \end{pmatrix} \quad (5.34)$$

$$y(2) = \begin{pmatrix} h(2) & h(1) & h(0) & 0 & \dots & \dots & .0 \end{pmatrix} \begin{pmatrix} x(0) \\ x(1) \\ x(2) \\ \vdots \\ \vdots \\ x(5) \end{pmatrix} \quad (5.35)$$

·  
·

Using Toeplitz matrix of  $h(n)$  we can simplify it as,

$$y(n) = \begin{pmatrix} h(0) & 0 & 0 & \dots & \dots & .0 \\ h(1) & h(0) & 0 & \dots & \dots & .0 \\ h(2) & h(1) & h(0) & \dots & \dots & .0 \\ \vdots & \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & \dots & h(m-1) \end{pmatrix} \begin{pmatrix} x(0) \\ x(1) \\ x(2) \\ \vdots \\ \vdots \\ x(5) \end{pmatrix} \quad (5.36)$$

Now from (3.1) we will take  $n$

$$x(n) = \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 2 \\ 1 \end{pmatrix} \quad (5.37)$$

And from (5.13) we will take some values of  $n$ ,

$$h(n) = \begin{pmatrix} 1 \\ -0.5 \\ 1.25 \\ \vdots \\ \vdots \end{pmatrix} \quad (5.38)$$

Now using (5.36),

$$y(n) = x(n) * h(n) \quad (5.39)$$

$$= \begin{pmatrix} 1 & 0 & 0 & \dots & \dots & .0 \\ -0.5 & 1 & 0 & \dots & \dots & .0 \\ 1.25 & -0.5 & 1 & \dots & \dots & .0 \\ \vdots & \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & \dots & \vdots \end{pmatrix} \begin{pmatrix} x(0) \\ x(1) \\ x(2) \\ \vdots \\ \vdots \\ x(5) \end{pmatrix} \quad (5.40)$$

$$= \begin{pmatrix} 1 \\ 1.5 \\ 3.25 \\ \vdots \\ \vdots \end{pmatrix} \quad (5.41)$$

The above equation (5.41) is the convolution of  $x(n)$  and  $h(n)$

5.10 Show that

$$y(n) = \sum_{k=-\infty}^{\infty} x(n-k)h(k) \quad (5.42)$$

**Solution:** From (5.28),

$$y(n) = \sum_{k=-\infty}^{\infty} x(k)h(n-k) \quad (5.43)$$

Replacing  $n - k$  with  $a$ , we get

$$y(n) = \sum_{n-a=-\infty}^{\infty} x(n-a)h(a) \quad (5.44)$$

$$= \sum_{-a=-\infty}^{\infty} x(n-a)h(a) \quad (5.45)$$

$$= \sum_{a=-\infty}^{\infty} x(n-a)h(a) \quad (5.46)$$

## 6 DFT AND FFT

### 6.1 Compute

$$X(k) \triangleq \sum_{n=0}^{N-1} x(n)e^{-j2\pi kn/N}, \quad k = 0, 1, \dots, N-1 \quad (6.1)$$

and  $H(k)$  using  $h(n)$ .

**Solution:** Run the following codes to compute  $X(k)$  which is plotted in 6.1.

```
wget https://github.com/Pradeep8802/EE3900
-Digital-Signal-Processing/blob/main/
Assignment1/codes/6.1.py
```

Run the following codes to compute  $H(k)$ .

```
wget https://github.com/Pradeep8802/EE3900
-Digital-Signal-Processing/blob/main/
Assignment1/codes/6.1_2.py
```

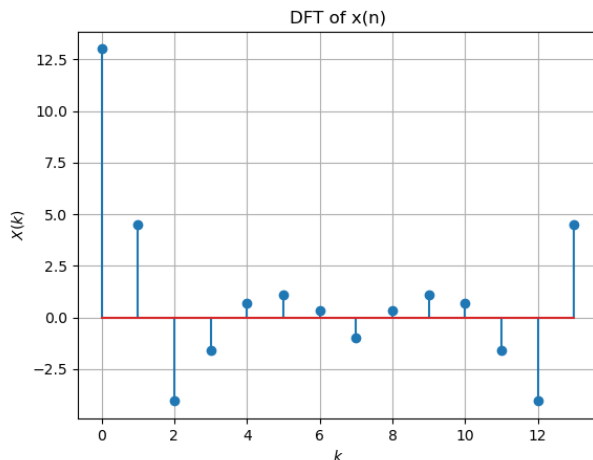


Fig. 6.1: DFT of  $x(k)$

### 6.2 Compute

$$Y(k) = X(k)H(k) \quad (6.2)$$

**Solution:** Run the following codes to compute  $Y(k)$  respectively.

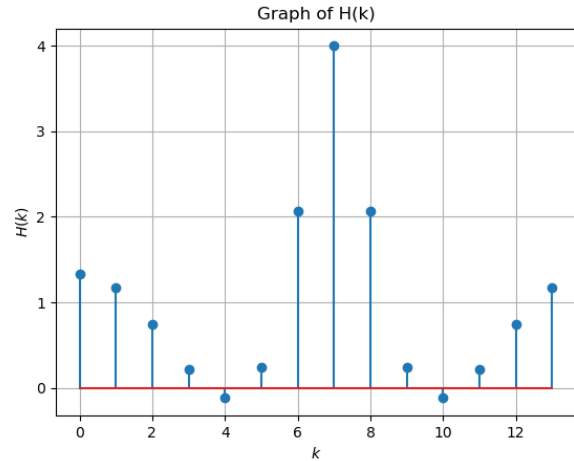


Fig. 6.1:  $H(n)$

```
wget https://github.com/Pradeep8802/EE3900
-Digital-Signal-Processing/blob/main/
Assignment1/codes/6.2.py
```

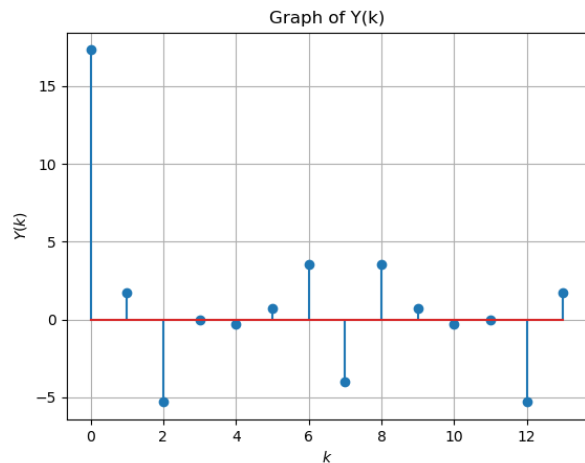


Fig. 6.2: DFT of  $xyn$

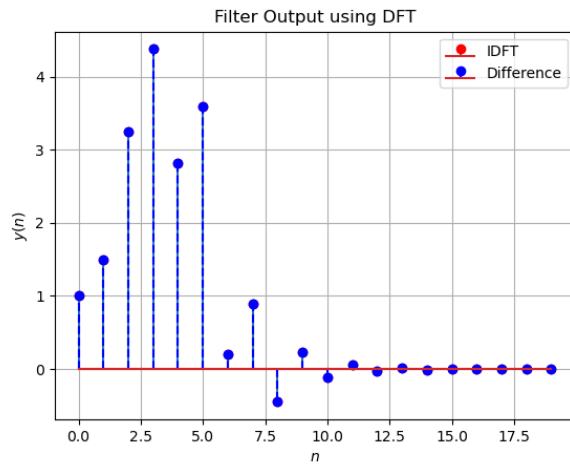
### 6.3 Compute

$$y(n) = \frac{1}{N} \sum_{k=0}^{N-1} Y(k) \cdot e^{j2\pi kn/N}, \quad n = 0, 1, \dots, N-1 \quad (6.3)$$

**Solution:** The following code plots Fig. 6.2. Note that this is the same as  $y(n)$  in Fig. 3.1.

```
wget https://github.com/Pradeep8802/EE3900
-Digital-Signal-Processing/blob/main/
```

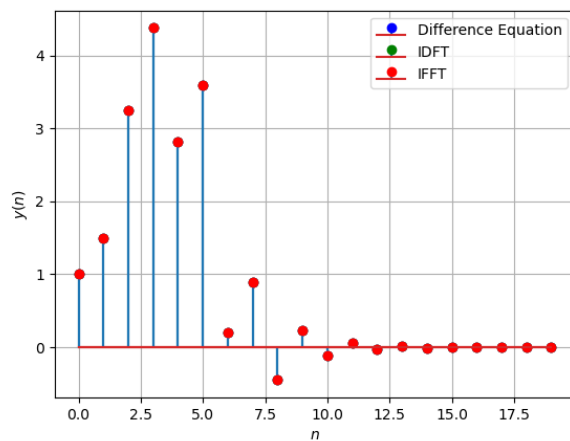


Fig. 6.3:  $y(n)$ 

6.4 Repeat the previous exercise by computing  $X(k)$ ,  $H(k)$  and  $y(n)$  through FFT and IFFT.

**Solution:** Run the following code to plot

```
wget https://github.com/Pradeep8802/EE3900
-Digital-Signal-Processing/blob/main/
Assignment1/codes/6.4.py
```

Fig. 6.4:  $y(n)$