

**Final Exam of ECE301, Section 3 (CRN 17102-004)**

8–10am, Wednesday, December 12, 2018, WTHR200 and WTHR320.

1. Please make sure that it is your name printed on the exam booklet. Enter your student ID number, and signature in the space provided on this page, **NOW!**
2. This is a closed book exam.
3. This exam contains multiple choice questions and work-out questions. For multiple choice questions, there is no need to justify your answers. You have two hours to complete it. The students are suggested not spending too much time on a single question, and working on those that you know how to solve.
4. Use the back of each page for rough work.
5. Neither calculators nor help sheets are allowed.

Name:

Student ID:

As a Boiler Maker pursuing academic excellence, I pledge to be honest and true in all that I do. Accountable together — We are Purdue.

Signature:

Date:



Question 1: [20%, Work-out question]

1. [1%] What does the acronym AM-DSB stand for?
2. [1%] What is AM asynchronous demodulation? You can either describe how to implement an AM asynchronous demodulator or you can describe the difference between an asynchronous versus a synchronous demodulator. You will receive full points either way.

Prof. Wang wanted to transmit an AM-SSB signal. To that end, he wrote the following MATLAB code.

```
% Initialization
duration=8;
f_sample=44100;
t=((0-4)*f_sample+0.5):((duration-4)*f_sample-0.5)/f_sample;

% Read two different .wav files
[x1, f_sample, N]=audioread('x1.wav');
x1=x1';
[x2, f_sample, N]=audioread('x2.wav');
x2=x2';

% Step 0: Initialize several parameters
W_1=????;
W_2=pi*3000;
W_3=pi*6000;
W_4=????;
W_5=????;
W_6=pi*12000;
W_7=pi*6000;

% Step 1: Make the signals band-limited.
h=1/(pi*t).*(sin(W_1*t));
x1_new=ece301conv(x1, h);
x2_new=ece301conv(x2, h);

% Step 2: Multiply x1_new and x2_new with a sinusoidal wave.
x1_h=x1_new.*sin(W_2*t);
x2_h=x2_new.*sin(W_3*t);

% Step 3: Keep one of the two side bands
h_one=1/(pi*t).*(sin(W_4*t)-sin(W_5*t));
```

```
h_two=1/(pi*t).*(sin(W_6*t)-sin(W_7*t));  
x1_sb=ece301conv(x1_h, h_one);  
x2_sb=ece301conv(x2_h, h_two);
```

```
% Step 4: Create the transmitted signal  
y=x1_sb+x2_sb;  
audiowrite('y.wav', y, f_sample);
```

3. [1.5%] What is the carrier frequency (Hz) of the signal `x1_new`?
4. [1.5%] For the second signal `x2_new`, is this AM-SSB transmitting an upper-side-band signal or a lower-side-band signal?
5. [1.5%] What should the values of `W_4` and `W_5` be in the MATLAB code, if we decide to use a lower-side-band transmission for the first signal `x1_new`?
6. [1.5%] What should the values of `W_4` and `W_5` be in the MATLAB code, if we decide to use an upper-side-band transmission for the first signal `x1_new`?
7. [2%] Continue from the previous sub-question. Suppose upper-side-band transmission is used for the first signal `x1_new`. To ensure that the receiver side can have the best possible quality, it is important for the transmitter to choose the largest `W_1` value when possible. What is the largest `W_1` value that can be used without significantly degrading the quality of any of the two transmitted signals?

Knowing that Prof. Wang decided to use an upper-side-band transmission for the first signal  $x_{1\_new}$  and he chose the  $W_1$  value to be  $W_1 = 2000 \times \pi$ . He then used the code in the previous page to generate the “y.wav” file. A student tried to demodulate the output waveform “y.wav” by the following code.

```
% Initialization
duration=8;
f_sample=44100;
t=((0-4)*f_sample+0.5):((duration-4)*f_sample-0.5)/f_sample;

% Read the .wav files
[y, f_sample, N]=audioread('y.wav');
y=y';

% Initialize several parameters
W_8=????;
W_9=????;
W_10=????;

% Create a low-pass filter.
h_M=1/(pi*t).*(sin(W_8*t));

% demodulate signal 1
y1=2*y.*sin(pi*W_9*t);
x1_hat=ece301conv(y1,h_M);

sound(x1_hat,f_sample)

% demodulate signal 2
y2=2*y.*sin(pi*W_10*t);
x2_hat=ece301conv(y2,h_M);

sound(x2_hat,f_sample)
```

"2\*" should be changed to "4\*"

"2\*" should be changed to "4\*"

8. [2%] Continue from the previous questions. What should the value of  $W_8$  be in the MATLAB code? When answering this question, please assume that the first radio  $x_{1\_new}$  was transmitted using the *upper side-band* and  $W_1 = 2000 \times \pi$ .
9. [2%] The student did not know how to choose the  $W_9$  value. Instead, he/she played with different nine choices: i.e.,  $W_9 = 0, 1000, 2000, 3000, 4000, 5000, 6000, 7000,$  or  $8000$ . One of them gave him/her perfect results. Namely, when playing  $x_{1\_hat}$ , the resulting sound is identical to playing the original signal  $x_{1\_new}$ .

Question: Which choice of  $W_9$  is the one that gave the perfect result?

10. [2%] The student did not know how to choose the  $W_{10}$  value. Instead, he/she played with different nine choices: i.e.,  $W_{10} = 0, 1000, 2000, 3000, 4000, 5000, 6000, 7000,$  or 8000. Unfortunately, none of these nine choices gave him/her the perfect result when playing `x2_hat`. That is, when playing `x2_hat`, the quality of the resulting sound is always significantly worse than playing the original signal `x2_new`.

Question: Please use one sentence to describe what kind of sound quality problem that the student is experiencing when playing `x2_hat`?

11. [3%] It turns out that some important commands are missing when the student wrote the demodulation MATLAB code.

Question: What are the missing commands when demodulating `x2_new`? Please clearly state which part of the code you would like to modify or add new commands.

Hint: If you do not know how to write the MATLAB code, you can also describe by words what “function block” is missing in the above MATLAB code. You will receive 2 points if your answer is correct.

12. [1%] In addition to adding new commands, the  $W_{10}$  value also needs to be carefully chosen.

Question: What is the value of  $W_{10}$  needed for perfect demodulation?

Hint: If you do not know the answers of Q1.3 to Q1.12, please simply draw the AMSSB modulation and demodulation diagrams and mark carefully all the parameter values. You will receive 11 points for Q1.3 to Q1.12.







Question 2: [9%, Work-out question]

1. [6%] Consider a discrete time signal  $x[n]$

$$x[n] = \begin{cases} 3 & \text{if } n = 1 \text{ or } n = -1 \\ 0 & \text{if } n = 0 \text{ or } n = 2 \\ \text{periodic with period 4} & \end{cases} \quad (1)$$

Find the DTFS of  $x[n]$  and plot the DTFS coefficients  $a_k$  for the range of  $k = 0$  to 3.

2. [3%] Find the DTFT of  $x[n]$  and plot the DTFT  $X(e^{j\omega})$  for the range of  $-2.75\pi < \omega < 2.75\pi$ .

Hint: If you do not know the answer to the previous subquestion, you can assume  $a_k = 2 \sin(\frac{k\pi}{2})$ . You will receive full credit if your answer is correct.







Question 3: [12%, Work-out question]

1. [2%] Suppose  $w(t) = \sin(3t) + \cos(5t)$ . Question: According to the *sampling theorem*, what is the smallest sampling frequency (Hz) needed in order to perfectly reconstruct  $w(t)$ ?
2. [1.5%] Consider the following continuous time signal

$$x(t) = \frac{2 \sin(\pi t)}{\pi t} \quad (2)$$

Plot  $x(t)$  for the range of  $-4 < t < 4$ .

3. [1.5%] Plot the CTFT  $X(j\omega)$  of  $x(t)$  for the range of  $-5\pi < \omega < 5\pi$ .
4. [3%] If we perform impulse train sampling on  $x(t)$  with the sampling frequency 2Hz and denote the impulse train sampled signal by  $x_p(t)$ . Plot its CTFT  $X_p(j\omega)$  for the range of  $-5\pi \leq \omega \leq 5\pi$ .

Hint: If you do not know the answer to the previous sub-questions, please write down the relationship between  $X(j\omega)$  and  $X_p(j\omega)$ . You will receive 1.5 points if your answer is correct.

5. [3%] We use  $x_{\text{band}}(t)$  to represent the reconstructed signal using “band-limited reconstruction”. Plot  $x_{\text{band}}(t)$  for the range of  $-4 < t < 4$ .

Hint: if you do not know the answer of  $x[n]$ , you can assume that  $x[n] = \delta[n - 6] - \delta[n + 6]$  and the sampling frequency is 2Hz. You will receive full points if your answer is correct.

6. [1%] Write down the exact expression of  $x_{\text{band}}(t)$ .









Question 4: [10%, Work-out question]

Consider a continuous time signal

$$x(t) = \begin{cases} t + 2 & \text{if } -2 < t < 0 \\ 2 - t & \text{if } 0 \leq t < 2 \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

1. [3%] We sample  $x(t)$  with the sampling frequency 2Hz and denote the sampled values by  $x[n]$ . Plot  $x[n]$  for the range of  $-5 \leq n \leq 5$ .
2. [2%] We use  $x_{\text{lin}}(t)$  to represent the reconstructed signal using “linear interpolation”. Plot  $x_{\text{lin}}(t)$  for the range of  $-4 < t < 4$ .
3. [5%] Suppose we pass  $x[n]$  through a discrete-time LTI system with  $h[n] = \delta[n] + \delta[n - 4]$ . Denote the new discrete-time array by  $y[n]$ . We then again apply linear interpolation to  $y[n]$  and construct the corresponding  $y_{\text{lin}}(t)$ . Plot  $y_{\text{lin}}(t)$  for the range of  $-4 < t < 4$ .







Question 5: [10%, Work-out question]

Consider the following continuous time signals

$$x(t) = \begin{cases} 2 & \text{if } -2 < t < 2 \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

$$h(t) = \begin{cases} 3 & \text{if } -3 < t < 3 \\ \delta(t - 8) & \text{if } 3 \leq t < 10 \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

1. [2%] Plot  $h(t)$  for the range of  $-10 < t < 10$ .
2. [8%] Plot the signal  $y(t) = x(t) * h(t)$  for the range of  $-10 < t < 10$ .









Question 6: [14%, Work-out question]

Consider the differential equation.

$$y(t) + 3\frac{d}{dt}y(t) + 2\frac{d^2}{dt^2}y(t) = 2x(t) \quad (6)$$

1. [7%] Find the impulse response  $h(t)$  and the corresponding frequency response  $H(j\omega)$ .
2. [7%] Suppose the input is  $x(t) = \sum_{k=1}^6 e^{j(k-2)\pi t}$ . Find the expression of  $y(t)$ .

Hint 1: If you do not know the answer to the previous question, you can assume that  $h(t) = \left(\frac{\sin(\pi t)}{\pi t}\right)^2$ . You will receive full credit if your answer is correct.

Hint 2: There is no need to have a highly simplified answer. For example, your answer can be something like  $(1 + j)e^{j3t} - (1 - 2j)e^{j5t}$ .







Question 7: [10%, Work-out question]

1. [5%] Consider the following discrete time signal.

$$y[n] = \begin{cases} 1 & \text{if } n \geq 3 \\ 0 & \text{otherwise} \end{cases} . \quad (7)$$

Derive the Z-transform expression of  $y[n]$  and *derive* the corresponding region of convergence. Please carefully write down your reasonings. If you use the table without explanation, then you will receive 3 points instead.

Hint: You may need the following formulas

$$\sum_{k=1}^{\infty} ar^{k-1} = \frac{a}{1-r} \text{ if } |r| < 1 \quad (8)$$

$$\sum_{k=1}^{\infty} akr^{k-1} = \frac{a}{(1-r)^2} \text{ if } |r| < 1 \quad (9)$$

2. [2%] Continue from the previous question. Plot the region of convergence of  $y[n]$  in the complex plane. (I.e., the horizontal axis is  $\text{Re}(z)$  and the vertical axis is  $\text{Im}(z)$ .)
3. [3%] Consider the following discrete time signal.

$$x[n] = \begin{cases} 2 & \text{if } 10 \leq n \leq 59 \\ 1 & \text{if } 60 \leq n \leq 79 \\ 0 & \text{if } 80 \leq n \leq 109 \\ \text{periodic with period 100} & \end{cases} . \quad (10)$$

Let  $a_k$  denote the DTFS of  $x[n]$ . Find the value of  $\sum_{k=0}^{99} a_k(-1)^k$









Question 8: [15%, Multiple-choice question] Consider two signals

$$h_1(t) = \begin{cases} \sin(2t) & \text{if } \sin(t) > 0 \\ 0 & \text{if } \sin(t) \leq 0 \end{cases} \quad (11)$$

and

$$h_2[n] = (1 + j)^{-n} \sin(0.75\pi n) + \left(\frac{1 - j}{2}\right)^n \sin(0.75\pi|n|) \quad (12)$$

1. [1.25%] Is  $h_1(t)$  periodic?
2. [1.25%] Is  $h_2[n]$  periodic?
3. [1.25%] Is  $h_1(t)$  even or odd or neither?
4. [1.25%] Is  $h_2[n]$  even or odd or neither?
5. [1.25%] Is  $h_1(t)$  of finite energy?
6. [1.25%] Is  $h_2[n]$  of finite energy?

Suppose the above two signals are also the impulse responses of two LTI systems: System 1 and System 2, respectively.

1. [1.25%] Is System 1 memoryless?
2. [1.25%] Is System 2 memoryless?
3. [1.25%] Is System 1 causal?
4. [1.25%] Is System 2 causal?
5. [1.25%] Is System 1 stable?
6. [1.25%] Is System 2 stable?



Discrete-time Fourier series

$$x[n] = \sum_{k=\langle N \rangle} a_k e^{jk(2\pi/N)n} \quad (1)$$

$$a_k = \frac{1}{N} \sum_{n=\langle N \rangle} x[n] e^{-jk(2\pi/N)n} \quad (2)$$

Continuous-time Fourier series

$$x(t) = \sum_{k=-\infty}^{\infty} a_k e^{jk(2\pi/T)t} \quad (3)$$

$$a_k = \frac{1}{T} \int_T x(t) e^{-jk(2\pi/T)t} dt \quad (4)$$

Continuous-time Fourier transform

$$x(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} X(j\omega) e^{j\omega t} d\omega \quad (5)$$

$$X(j\omega) = \int_{-\infty}^{\infty} x(t) e^{-j\omega t} dt \quad (6)$$

Discrete-time Fourier transform

$$x[n] = \frac{1}{2\pi} \int_{2\pi} X(e^{j\omega}) e^{j\omega n} d\omega \quad (7)$$

$$X(e^{j\omega}) = \sum_{n=-\infty}^{\infty} x[n] e^{-j\omega n} \quad (8)$$

Laplace transform

$$x(t) = \frac{1}{2\pi} e^{\sigma t} \int_{-\infty}^{\infty} X(\sigma + j\omega) e^{j\omega t} d\omega \quad (9)$$

$$X(s) = \int_{-\infty}^{\infty} x(t) e^{-st} dt \quad (10)$$

Z transform

$$x[n] = r^n \mathcal{F}^{-1}(X(re^{j\omega})) \quad (11)$$

$$X(z) = \sum_{n=-\infty}^{\infty} x[n] z^{-n} \quad (12)$$

TABLE 3.1 PROPERTIES OF CONTINUOUS-TIME FOURIER SERIES

Property	Section	Periodic Signal	Fourier Series Coefficients
		$x(t)$ } Periodic with period $T$ and $y(t)$ } fundamental frequency $\omega_0 = 2\pi/T$	$a_k$ $b_k$
Linearity	3.5.1	$Ax(t) + By(t)$	$Aa_k + Bb_k$
Time Shifting	3.5.2	$x(t - t_0)$	$a_k e^{-jk\omega_0 t_0} = a_k e^{-jk(2\pi/T)t_0}$
Frequency Shifting		$e^{jM\omega_0 t} x(t) = e^{jM(2\pi/T)t} x(t)$	$a_{k-M}$
Conjugation	3.5.6	$x^*(t)$	$a_{-k}^*$
Time Reversal	3.5.3	$x(-t)$	$a_{-k}$
Time Scaling	3.5.4	$x(\alpha t), \alpha > 0$ (periodic with period $T/\alpha$ )	$a_k$
Periodic Convolution		$\int_T x(\tau)y(t - \tau)d\tau$	$T a_k b_k$
Multiplication	3.5.5	$x(t)y(t)$	$\sum_{l=-\infty}^{+\infty} a_l b_{k-l}$
Differentiation		$\frac{dx(t)}{dt}$	$jk\omega_0 a_k = jk \frac{2\pi}{T} a_k$
Integration		$\int_{-\infty}^t x(t) dt$ (finite valued and periodic only if $a_0 = 0$ )	$\left(\frac{1}{jk\omega_0}\right) a_k = \left(\frac{1}{jk(2\pi/T)}\right) a_k$
Conjugate Symmetry for Real Signals	3.5.6	$x(t)$ real	$\begin{cases} a_k = a_{-k}^* \\ \Re\{a_k\} = \Re\{a_{-k}\} \\ \Im\{a_k\} = -\Im\{a_{-k}\} \\  a_k  =  a_{-k}  \\ \angle a_k = -\angle a_{-k} \end{cases}$
Real and Even Signals	3.5.6	$x(t)$ real and even	$a_k$ real and even
Real and Odd Signals	3.5.6	$x(t)$ real and odd	$a_k$ purely imaginary and odd
Even-Odd Decomposition of Real Signals		$\begin{cases} x_e(t) = \mathcal{E}\{x(t)\} & [x(t) \text{ real}] \\ x_o(t) = \mathcal{O}\{x(t)\} & [x(t) \text{ real}] \end{cases}$	$\begin{cases} \Re\{a_k\} \\ \Im\{a_k\} \end{cases}$
Parseval's Relation for Periodic Signals			
$\frac{1}{T} \int_T  x(t) ^2 dt = \sum_{k=-\infty}^{+\infty}  a_k ^2$			

three examples, we illustrate this. The last example in this section then demonstrates how properties of a signal can be used to characterize the signal in great detail.

### Example 3.6

Consider the signal  $g(t)$  with a fundamental period of 4, shown in Figure 3.10. We could determine the Fourier series representation of  $g(t)$  directly from the analysis equation (3.39). Instead, we will use the relationship of  $g(t)$  to the symmetric periodic square wave  $x(t)$  in Example 3.5. Referring to that example, we see that, with  $T = 4$  and  $T_1 = 1$ ,

$$g(t) = x(t - 1) - 1/2. \quad (3.40)$$

Thus, in general, *none* of the finite partial sums in eq. (3.52) yield the exact values of  $x(t)$ , and convergence issues, such as those considered in Section 3.4, arise as we consider the problem of evaluating the limit as the number of terms approaches infinity.

### 3.7 PROPERTIES OF DISCRETE-TIME FOURIER SERIES

There are strong similarities between the properties of discrete-time and continuous-time Fourier series. This can be readily seen by comparing the discrete-time Fourier series properties summarized in Table 3.2 with their continuous-time counterparts in Table 3.1.

**TABLE 3.2** PROPERTIES OF DISCRETE-TIME FOURIER SERIES

Property	Periodic Signal	Fourier Series Coefficients
	$x[n]$ } Periodic with period $N$ and $y[n]$ } fundamental frequency $\omega_0 = 2\pi/N$	$a_k$ } Periodic with $b_k$ } period $N$
Linearity	$Ax[n] + By[n]$	$Aa_k + Bb_k$
Time Shifting	$x[n - n_0]$	$a_k e^{-jk(2\pi/N)n_0}$
Frequency Shifting	$e^{jM(2\pi/N)n} x[n]$	$a_{k-M}$
Conjugation	$x^*[n]$	$a_{-k}^*$
Time Reversal	$x[-n]$	$a_{-k}$
Time Scaling	$x_{(m)}[n] = \begin{cases} x[n/m], & \text{if } n \text{ is a multiple of } m \\ 0, & \text{if } n \text{ is not a multiple of } m \end{cases}$ (periodic with period $mN$ )	$\frac{1}{m} a_k$ (viewed as periodic) (with period $mN$ )
Periodic Convolution	$\sum_{r=(N)} x[r]y[n-r]$	$Na_k b_k$
Multiplication	$x[n]y[n]$	$\sum_{l=(N)} a_l b_{k-l}$
First Difference	$x[n] - x[n-1]$	$(1 - e^{-jk(2\pi/N)})a_k$
Running Sum	$\sum_{k=-\infty}^n x[k]$ (finite valued and periodic only) (if $a_0 = 0$ )	$\left(\frac{1}{1 - e^{-jk(2\pi/N)}}\right)a_k$
Conjugate Symmetry for Real Signals	$x[n]$ real	$\begin{cases} a_k = a_{-k}^* \\ \Re\{a_k\} = \Re\{a_{-k}\} \\ \Im\{a_k\} = -\Im\{a_{-k}\} \\  a_k  =  a_{-k}  \\ \angle a_k = -\angle a_{-k} \end{cases}$
Real and Even Signals	$x[n]$ real and even	$a_k$ real and even
Real and Odd Signals	$x[n]$ real and odd	$a_k$ purely imaginary and odd
Even-Odd Decomposition of Real Signals	$\begin{cases} x_e[n] = \mathcal{E}\{x[n]\} & [x[n] \text{ real}] \\ x_o[n] = \mathcal{O}\{x[n]\} & [x[n] \text{ real}] \end{cases}$	$\begin{cases} \Re\{a_k\} \\ j\Im\{a_k\} \end{cases}$

Parseval's Relation for Periodic Signals

$$\frac{1}{N} \sum_{n=(N)} |x[n]|^2 = \sum_{k=(N)} |a_k|^2$$

## 4.6 TABLES OF FOURIER PROPERTIES AND OF BASIC FOURIER TRANSFORM PAIRS

In the preceding sections and in the problems at the end of the chapter, we have considered some of the important properties of the Fourier transform. These are summarized in Table 4.1, in which we have also indicated the section of this chapter in which each property has been discussed.

In Table 4.2, we have assembled a list of many of the basic and important Fourier transform pairs. We will encounter many of these repeatedly as we apply the tools of

**TABLE 4.1** PROPERTIES OF THE FOURIER TRANSFORM

Section	Property	Aperiodic signal	Fourier transform
		$x(t)$ $y(t)$	$X(j\omega)$ $Y(j\omega)$
-----			
4.3.1	Linearity	$ax(t) + by(t)$	$aX(j\omega) + bY(j\omega)$
4.3.2	Time Shifting	$x(t - t_0)$	$e^{-j\omega t_0} X(j\omega)$
4.3.6	Frequency Shifting	$e^{j\omega_0 t} x(t)$	$X(j(\omega - \omega_0))$
4.3.3	Conjugation	$x^*(t)$	$X^*(-j\omega)$
4.3.5	Time Reversal	$x(-t)$	$X(-j\omega)$
4.3.5	Time and Frequency Scaling	$x(at)$	$\frac{1}{ a } X\left(\frac{j\omega}{a}\right)$
4.4	Convolution	$x(t) * y(t)$	$X(j\omega)Y(j\omega)$
4.5	Multiplication	$x(t)y(t)$	$\frac{1}{2\pi} \int_{-\infty}^{+\infty} X(j\theta)Y(j(\omega - \theta))d\theta$
4.3.4	Differentiation in Time	$\frac{d}{dt}x(t)$	$j\omega X(j\omega)$
4.3.4	Integration	$\int_{-\infty}^t x(t)dt$	$\frac{1}{j\omega} X(j\omega) + \pi X(0)\delta(\omega)$
4.3.6	Differentiation in Frequency	$tx(t)$	$j \frac{d}{d\omega} X(j\omega)$
4.3.3	Conjugate Symmetry for Real Signals	$x(t)$ real	$\begin{cases} X(j\omega) = X^*(-j\omega) \\ \Re\{X(j\omega)\} = \Re\{X(-j\omega)\} \\ \Im\{X(j\omega)\} = -\Im\{X(-j\omega)\} \\  X(j\omega)  =  X(-j\omega)  \\ \angle X(j\omega) = -\angle X(-j\omega) \end{cases}$
4.3.3	Symmetry for Real and Even Signals	$x(t)$ real and even	$X(j\omega)$ real and even
4.3.3	Symmetry for Real and Odd Signals	$x(t)$ real and odd	$X(j\omega)$ purely imaginary and odd
4.3.3	Even-Odd Decomposition for Real Signals	$x_e(t) = \mathcal{E}\{x(t)\}$ [ $x(t)$ real] $x_o(t) = \mathcal{O}\{x(t)\}$ [ $x(t)$ real]	$\Re\{X(j\omega)\}$ $j\Im\{X(j\omega)\}$
-----			
4.3.7	Parseval's Relation for Aperiodic Signals		
	$\int_{-\infty}^{+\infty}  x(t) ^2 dt = \frac{1}{2\pi} \int_{-\infty}^{+\infty}  X(j\omega) ^2 d\omega$		

TABLE 4.2 BASIC FOURIER TRANSFORM PAIRS

Signal	Fourier transform	Fourier series coefficients (if periodic)
$\sum_{k=-\infty}^{+\infty} a_k e^{jk\omega_0 t}$	$2\pi \sum_{k=-\infty}^{+\infty} a_k \delta(\omega - k\omega_0)$	$a_k$
$e^{j\omega_0 t}$	$2\pi \delta(\omega - \omega_0)$	$a_1 = 1$ $a_k = 0$ , otherwise
$\cos \omega_0 t$	$\pi[\delta(\omega - \omega_0) + \delta(\omega + \omega_0)]$	$a_1 = a_{-1} = \frac{1}{2}$ $a_k = 0$ , otherwise
$\sin \omega_0 t$	$\frac{\pi}{j}[\delta(\omega - \omega_0) - \delta(\omega + \omega_0)]$	$a_1 = -a_{-1} = \frac{1}{2j}$ $a_k = 0$ , otherwise
$x(t) = 1$	$2\pi \delta(\omega)$	$a_0 = 1$ , $a_k = 0$ , $k \neq 0$ (this is the Fourier series representation for any choice of $T > 0$ )
Periodic square wave		
$x(t) = \begin{cases} 1, &  t  < T_1 \\ 0, & T_1 <  t  \leq \frac{T}{2} \end{cases}$	$\sum_{k=-\infty}^{+\infty} \frac{2 \sin k\omega_0 T_1}{k} \delta(\omega - k\omega_0)$	$\frac{\omega_0 T_1}{\pi} \operatorname{sinc}\left(\frac{k\omega_0 T_1}{\pi}\right) = \frac{\sin k\omega_0 T_1}{k\pi}$
and $x(t + T) = x(t)$		
$\sum_{n=-\infty}^{+\infty} \delta(t - nT)$	$\frac{2\pi}{T} \sum_{k=-\infty}^{+\infty} \delta\left(\omega - \frac{2\pi k}{T}\right)$	$a_k = \frac{1}{T}$ for all $k$
$x(t) \begin{cases} 1, &  t  < T_1 \\ 0, &  t  > T_1 \end{cases}$	$\frac{2 \sin \omega T_1}{\omega}$	—
$\frac{\sin Wt}{\pi t}$	$X(j\omega) = \begin{cases} 1, &  \omega  < W \\ 0, &  \omega  > W \end{cases}$	—
$\delta(t)$	1	—
$u(t)$	$\frac{1}{j\omega} + \pi \delta(\omega)$	—
$\delta(t - t_0)$	$e^{-j\omega t_0}$	—
$e^{-at} u(t), \operatorname{Re}\{a\} > 0$	$\frac{1}{a + j\omega}$	—
$t e^{-at} u(t), \operatorname{Re}\{a\} > 0$	$\frac{1}{(a + j\omega)^2}$	—
$\frac{t^{n-1}}{(n-1)!} e^{-at} u(t), \operatorname{Re}\{a\} > 0$	$\frac{1}{(a + j\omega)^n}$	—

**TABLE 5.1** PROPERTIES OF THE DISCRETE-TIME FOURIER TRANSFORM

Section	Property	Aperiodic Signal	Fourier Transform
		$x[n]$	$X(e^{j\omega})$ } periodic with
		$y[n]$	$Y(e^{j\omega})$ } period $2\pi$
5.3.2	Linearity	$ax[n] + by[n]$	$aX(e^{j\omega}) + bY(e^{j\omega})$
5.3.3	Time Shifting	$x[n - n_0]$	$e^{-j\omega n_0} X(e^{j\omega})$
5.3.3	Frequency Shifting	$e^{j\omega_0 n} x[n]$	$X(e^{j(\omega - \omega_0)})$
5.3.4	Conjugation	$x^*[n]$	$X^*(e^{-j\omega})$
5.3.6	Time Reversal	$x[-n]$	$X(e^{-j\omega})$
5.3.7	Time Expansion	$x_{(k)}[n] = \begin{cases} x[n/k], & \text{if } n = \text{multiple of } k \\ 0, & \text{if } n \neq \text{multiple of } k \end{cases}$	$X(e^{jk\omega})$
5.4	Convolution	$x[n] * y[n]$	$X(e^{j\omega})Y(e^{j\omega})$
5.5	Multiplication	$x[n]y[n]$	$\frac{1}{2\pi} \int_{2\pi} X(e^{j\theta})Y(e^{j(\omega - \theta)})d\theta$
5.3.5	Differencing in Time	$x[n] - x[n - 1]$	$(1 - e^{-j\omega})X(e^{j\omega})$
5.3.5	Accumulation	$\sum_{k=-\infty}^n x[k]$	$\frac{1}{1 - e^{-j\omega}} X(e^{j\omega})$
5.3.8	Differentiation in Frequency	$nx[n]$	$j \frac{dX(e^{j\omega})}{d\omega}$
5.3.4	Conjugate Symmetry for Real Signals	$x[n]$ real	$\begin{cases} X(e^{j\omega}) = X^*(e^{-j\omega}) \\ \Re\{X(e^{j\omega})\} = \Re\{X(e^{-j\omega})\} \\ \Im\{X(e^{j\omega})\} = -\Im\{X(e^{-j\omega})\} \\  X(e^{j\omega})  =  X(e^{-j\omega})  \\ \angle X(e^{j\omega}) = -\angle X(e^{-j\omega}) \end{cases}$
5.3.4	Symmetry for Real, Even Signals	$x[n]$ real and even	$X(e^{j\omega})$ real and even
5.3.4	Symmetry for Real, Odd Signals	$x[n]$ real and odd	$X(e^{j\omega})$ purely imaginary and odd
5.3.4	Even-odd Decomposition of Real Signals	$x_e[n] = \mathcal{E}\{x[n]\}$ [ $x[n]$ real ] $x_o[n] = \mathcal{O}\{x[n]\}$ [ $x[n]$ real ]	$\Re\{X(e^{j\omega})\}$ $j\Im\{X(e^{j\omega})\}$
5.3.9	Parseval's Relation for Aperiodic Signals	$\sum_{n=-\infty}^{+\infty}  x[n] ^2 = \frac{1}{2\pi} \int_{2\pi}  X(e^{j\omega}) ^2 d\omega$	

a duality relationship between the discrete-time Fourier transform and the continuous-time Fourier series. This relation is discussed in Section 5.7.2.

### 5.7.1 Duality in the Discrete-Time Fourier Series

Since the Fourier series coefficients  $a_k$  of a periodic signal  $x[n]$  are themselves a periodic sequence, we can expand the sequence  $a_k$  in a Fourier series. The duality property for discrete-time Fourier series implies that the Fourier series coefficients for the periodic sequence  $a_k$  are the values of  $(1/N)x[-n]$  (i.e., are proportional to the values of the original



**TABLE 5.2 BASIC DISCRETE-TIME FOURIER TRANSFORM PAIRS**

Signal	Fourier Transform	Fourier Series Coefficients (if periodic)
$\sum_{k=(N)} a_k e^{jk(2n/N)n}$	$2\pi \sum_{k=-\infty}^{+\infty} a_k \delta\left(\omega - \frac{2\pi k}{N}\right)$	$a_k$
$e^{j\omega_0 n}$	$2\pi \sum_{l=-\infty}^{+\infty} \delta(\omega - \omega_0 - 2\pi l)$	(a) $\omega_0 = \frac{2\pi m}{N}$ $a_k = \begin{cases} 1, & k = m, m \pm N, m \pm 2N, \dots \\ 0, & \text{otherwise} \end{cases}$ (b) $\frac{\omega_0}{2\pi}$ irrational $\Rightarrow$ The signal is aperiodic
$\cos \omega_0 n$	$\pi \sum_{l=-\infty}^{+\infty} \{\delta(\omega - \omega_0 - 2\pi l) + \delta(\omega + \omega_0 - 2\pi l)\}$	(a) $\omega_0 = \frac{2\pi m}{N}$ $a_k = \begin{cases} \frac{1}{2}, & k = \pm m, \pm m \pm N, \pm m \pm 2N, \dots \\ 0, & \text{otherwise} \end{cases}$ (b) $\frac{\omega_0}{2\pi}$ irrational $\Rightarrow$ The signal is aperiodic
$\sin \omega_0 n$	$\frac{\pi}{j} \sum_{l=-\infty}^{+\infty} \{\delta(\omega - \omega_0 - 2\pi l) - \delta(\omega + \omega_0 - 2\pi l)\}$	(a) $\omega_0 = \frac{2\pi r}{N}$ $a_k = \begin{cases} \frac{1}{2j}, & k = r, r \pm N, r \pm 2N, \dots \\ -\frac{1}{2j}, & k = -r, -r \pm N, -r \pm 2N, \dots \\ 0, & \text{otherwise} \end{cases}$ (b) $\frac{\omega_0}{2\pi}$ irrational $\Rightarrow$ The signal is aperiodic
$x[n] = 1$	$2\pi \sum_{l=-\infty}^{+\infty} \delta(\omega - 2\pi l)$	$a_k = \begin{cases} 1, & k = 0, \pm N, \pm 2N, \dots \\ 0, & \text{otherwise} \end{cases}$
Periodic square wave $x[n] = \begin{cases} 1, &  n  \leq N_1 \\ 0, & N_1 <  n  \leq N/2 \end{cases}$ and $x[n + N] = x[n]$	$2\pi \sum_{k=-\infty}^{+\infty} a_k \delta\left(\omega - \frac{2\pi k}{N}\right)$	$a_k = \frac{\sin[(2\pi k/N)(N_1 + \frac{1}{2})]}{N \sin[2\pi k/2N]}$ , $k \neq 0, \pm N, \pm 2N, \dots$ $a_k = \frac{2N_1 + 1}{N}$ , $k = 0, \pm N, \pm 2N, \dots$
$\sum_{k=-\infty}^{+\infty} \delta[n - kN]$	$\frac{2\pi}{N} \sum_{k=-\infty}^{+\infty} \delta\left(\omega - \frac{2\pi k}{N}\right)$	$a_k = \frac{1}{N}$ for all $k$
$a^n u[n]$ , $ a  < 1$	$\frac{1}{1 - ae^{-j\omega}}$	—
$x[n] = \begin{cases} 1, &  n  \leq N_1 \\ 0, &  n  > N_1 \end{cases}$	$\frac{\sin[\omega(N_1 + \frac{1}{2})]}{\sin(\omega/2)}$	—
$\frac{\sin Wn}{\pi n} = \frac{W}{\pi} \text{sinc}\left(\frac{Wn}{\pi}\right)$ $0 < W < \pi$	$X(\omega) = \begin{cases} 1, & 0 \leq  \omega  \leq W \\ 0, & W <  \omega  \leq \pi \end{cases}$ $X(\omega)$ periodic with period $2\pi$	—
$\delta[n]$	1	—
$u[n]$	$\frac{1}{1 - e^{-j\omega}} + \sum_{k=-\infty}^{+\infty} \pi \delta(\omega - 2\pi k)$	—
$\delta[n - n_0]$	$e^{-j\omega n_0}$	—
$(n + 1)a^n u[n]$ , $ a  < 1$	$\frac{1}{(1 - ae^{-j\omega})^2}$	—
$\frac{(n + r - 1)!}{n!(r - 1)!} a^n u[n]$ , $ a  < 1$	$\frac{1}{(1 - ae^{-j\omega})^r}$	—

an important  
illustrate some  
poles, zeros,  
response.  
eigenfunction  
the complex  
(2). Also, from  
the frequency  
function of the  
, and impulse  
(10.96)  
representation of  
10.5.7,

ng properties  
ars 9 and 10  
ctions 10.5.4  
0.18. These,  
and 5 follow  
n the proper-  
transform pairs,  
transforms of  
easily evalu-

Example 10.3.  
ss of the z-  
Chap. 10

TABLE 10.1 PROPERTIES OF THE z-TRANSFORM

Section	Property	Signal	z-Transform	ROC
		$x[n]$	$X(z)$	$R$
		$x_1[n]$	$X_1(z)$	$R_1$
		$x_2[n]$	$X_2(z)$	$R_2$
10.5.1	Linearity	$ax_1[n] + bx_2[n]$	$aX_1(z) + bX_2(z)$	At least the intersection of $R_1$ and $R_2$
10.5.2	Time shifting	$x[n - n_0]$	$z^{-n_0}X(z)$	$R$ , except for the possible addition or deletion of the origin
10.5.3	Scaling in the z-domain	$e^{j\omega_0 n}x[n]$	$X(e^{-j\omega_0}z)$	$R$
		$z_0^n x[n]$	$X\left(\frac{z}{z_0}\right)$	$z_0 R$
		$a^n x[n]$	$X(a^{-1}z)$	Scaled version of $R$ (i.e., $ a R =$ the set of points $\{ a z\}$ for $z$ in $R$ )
10.5.4	Time reversal	$x[-n]$	$X(z^{-1})$	Inverted $R$ (i.e., $R^{-1} =$ the set of points $z^{-1}$ , where $z$ is in $R$ )
10.5.5	Time expansion	$x_{(r)}[n] = \begin{cases} x[r], & n = rk \\ 0, & n \neq rk \end{cases}$	$X(z^k)$	$R^{1/k}$ (i.e., the set of points $z^{1/k}$ , where $z$ is in $R$ )
10.5.6	Conjugation	$x^*[n]$	$X^*(z^*)$	$R$
10.5.7	Convolution	$x_1[n] * x_2[n]$	$X_1(z)X_2(z)$	At least the intersection of $R_1$ and $R_2$
10.5.7	First difference	$x[n] - x[n - 1]$	$(1 - z^{-1})X(z)$	At least the intersection of $R$ and $ z  > 0$
10.5.7	Accumulation	$\sum_{k=-\infty}^n x[k]$	$\frac{1}{1 - z^{-1}}X(z)$	At least the intersection of $R$ and $ z  > 1$
10.5.8	Differentiation in the z-domain	$nx[n]$	$-z \frac{dX(z)}{dz}$	$R$
10.5.9	Initial Value Theorem			
	If $x[n] = 0$ for $n < 0$ , then			
	$x[0] = \lim_{z \rightarrow \infty} X(z)$			

TABLE 10.2 SOME COMMON z-TRANSFORM PAIRS

Signal	Transform	ROC
1. $\delta[n]$	1	All $z$
2. $u[n]$	$\frac{1}{1-z^{-1}}$	$ z  > 1$
3. $-u[-n-1]$	$\frac{1}{1-z^{-1}}$	$ z  < 1$
4. $\delta[n-m]$	$z^{-m}$	All $z$ , except 0 (if $m > 0$ ) or $\infty$ (if $m < 0$ )
5. $\alpha^n u[n]$	$\frac{1}{1-\alpha z^{-1}}$	$ z  >  \alpha $
6. $-\alpha^n u[-n-1]$	$\frac{1}{1-\alpha z^{-1}}$	$ z  <  \alpha $
7. $n\alpha^n u[n]$	$\frac{\alpha z^{-1}}{(1-\alpha z^{-1})^2}$	$ z  >  \alpha $
8. $-n\alpha^n u[-n-1]$	$\frac{\alpha z^{-1}}{(1-\alpha z^{-1})^2}$	$ z  <  \alpha $
9. $[\cos \omega_0 n]u[n]$	$\frac{1 - [\cos \omega_0]z^{-1}}{1 - [2 \cos \omega_0]z^{-1} + z^{-2}}$	$ z  > 1$
10. $[\sin \omega_0 n]u[n]$	$\frac{[\sin \omega_0]z^{-1}}{1 - [2 \cos \omega_0]z^{-1} + z^{-2}}$	$ z  > 1$
11. $[r^n \cos \omega_0 n]u[n]$	$\frac{1 - [r \cos \omega_0]z^{-1}}{1 - [2r \cos \omega_0]z^{-1} + r^2 z^{-2}}$	$ z  > r$
12. $[r^n \sin \omega_0 n]u[n]$	$\frac{[r \sin \omega_0]z^{-1}}{1 - [2r \cos \omega_0]z^{-1} + r^2 z^{-2}}$	$ z  > r$

### 10.7.1 Causality

A causal LTI system has an impulse response  $h[n]$  that is zero for  $n < 0$ , and therefore is right-sided. From Property 4 in Section 10.2 we then know that the ROC of  $H(z)$  is the exterior of a circle in the  $z$ -plane. For some systems, e.g., if  $h[n] = \delta[n]$ , so that  $H(z) = 1$ , the ROC can extend all the way in to and possibly include the origin. Also, in general, for a right-sided impulse response, the ROC may or may not include infinity. For example, if  $h[n] = \delta[n+1]$ , then  $H(z) = z$ , which has a pole at infinity. However, as we saw in Property 8 in Section 10.2, for a causal system the power series

$$H(z) = \sum_{n=0}^{\infty} h[n]z^{-n}$$

does not include any positive powers of  $z$ . Consequently, the ROC includes infinity. Summarizing, we have the follow principle:

A discrete-time LTI system is causal if and only if the ROC of its system function is the exterior of a circle, including infinity.