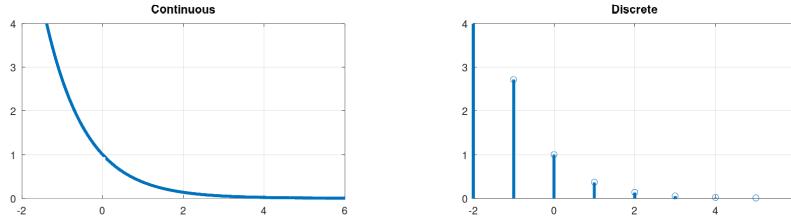


# ELG 3125 Summary Sheet

## 1 Basics of Signals and Systems

We can have a signal that is either continuous or discrete. These signals are represented as math functions. Computers always will display and work with a discrete signal. However



often it is to model a continuous signal.

We call a signal a power signal if its average power is finite. Similarly, we call a signal an energy signal if its total energy is finite.

**Ex.** A 120VAC wall outlet is a power signal.

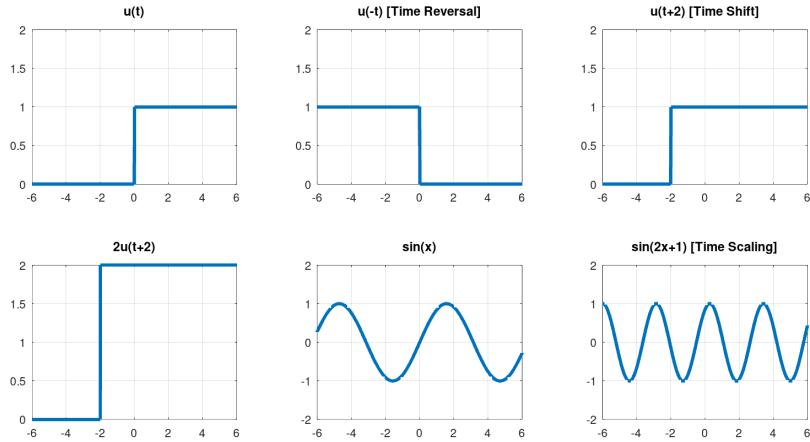
This is because the average power is finite. If we have for example a 1500w heater connected, it will always draw 1500W.

However if we keep it running for a long time, it will use a very large amount of energy. So it is infinite energy.

### 1.1 Transformations

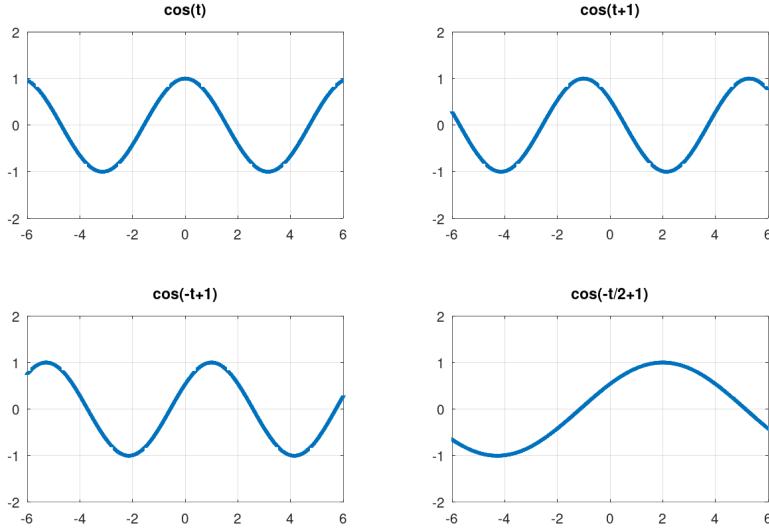
There are many transformations.

When transforming a signal, we usually start with any time shifts. Then we apply other transformations such as a time reversal, or time scaling.



**Ex.** Plot  $\cos(-t/2 + 1)$

We take it in 4 steps:



## 1.2 Periodicity

A signal is called periodic if:

$$x(t) = x(t + T) \quad \forall t \quad (1)$$

We call the fundamental period  $T_0$  the smallest *positive* value of  $T$  for which Equation 1 holds.

We have the same idea in discrete time except we change  $t$  for  $n$ , and  $T$  for  $N$ .

$$x[n] = x[n + N] \quad \forall n \quad (2)$$

Note that any complex exponential in the form of  $e^{j\omega_0 t}$  is periodic with period  $T = \frac{2\pi}{\omega_0}$ .

**Ex.** Find the period of  $x[n]$ .

$$x[n] = e^{j(\frac{2\pi}{3})n} + e^{j(\frac{3\pi}{4})n}$$

I need to find both periods, and find the greatest common multiple.

Note that since I am in discrete time, the period must be an integer.

$$\begin{aligned} T_1 &= \frac{\frac{2\pi}{2\pi}}{\frac{3}{3}} = 3 \\ T_2 &= \frac{\frac{2\pi}{3\pi}}{\frac{8}{4}} = \frac{8}{3} = 8 \text{ since } \frac{8}{3} \notin \mathbb{Z} \end{aligned}$$

$$T = LCM(3, 8) = 24$$

### 1.3 Even and Odd Functions

We call a signal Even if it satisfies Equation 3 or Odd if it satisfies Equation 4.

$$x(t) = x(-t) \quad (3)$$

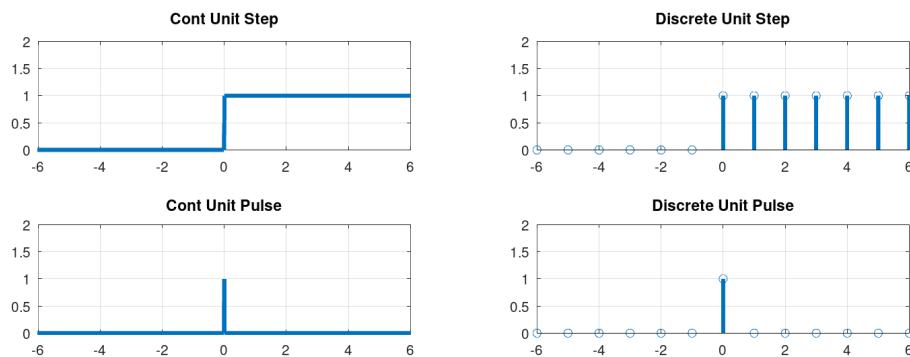
$$x(t) = -x(-t) \quad (4)$$

We can construct any signal by using its even and odd portions.

$$x(t) = Ev\{x(t)\} + Od\{x(t)\} = \frac{1}{2}(x(t) + x(-t)) + \frac{1}{2}(x(t) - x(-t)) \quad (5)$$

### 1.4 Unit Impulse and Unit Step

These are two very useful functions as defined below. The unit step is 0 when  $x$  is negative,



and 1 when positive or 0. The impulse is 1 only when  $x$  is 0.

The unit step function is called  $u(t)$  or  $u[n]$ . The unit pulse is called  $\delta(t)$  or  $\delta[n]$ .

### 1.5 System Properties

#### 1.5.1 Memory

A system is memoryless if the output is only dependant on the input at the same time.

So basically we do not see any time shifts such as  $t - 1$  or  $t + 1$ .

#### 1.5.2 Invertibility

A system is invertible if distinct inputs lead to distinct outputs.

**Ex.** Example found in

### 1.5.3 Causality

A system is causal if the output at any time depends only on input values of present and in the past. It does not depend on any future values.

This is also referred to as being nonanticipative.

Note that all memoryless systems are causal.

Basically if we see something like  $x(t+1)$ , it is non causal. If we see something like  $(t+1)x(t)$ , it is likely causal.

### 1.5.4 Stability

A system is stable if when inputs are bounded, the outputs are always bounded. So:

$$|x(t)| < \infty \implies |y(t)| < \infty \quad (6)$$

Assuming  $x(t)$  is input, and  $y(t)$  is output.

### 1.5.5 Time Invariance

A system is time invariant if a time shift in the input results in an identical time shift in the output.

**Ex.** Is  $y(t) = x(6t)$  time invariant?

We can do:

$$\begin{aligned} y(t - t_0) &= x(6t - 6t_0) && \text{Now we delay by } -t_0 \\ y(t) &= x(6t - 5t_0) && \text{Now we delay by } +t_0 \\ &\neq x(6t) && \text{So it is NOT time invariant.} \end{aligned}$$

### 1.5.6 Linearity

A system is linear if Equation 7 is satisfied.

$$ax_1(t) + bx_2(t) \rightarrow ay_1(t) + by_2(t) \quad (7)$$

**Ex.** Is  $y(t) = x(t)^2$  linear?

We know intuitively that the answer is no here. But we can prove this using the relation:

$$\begin{aligned} y_1(t) &= x_1(t)^2 \\ y_2(t) &= x_2(t)^2 \\ x_3(t) &= ax_1(t) + bx_2(t) \\ y_3(t) &= ay_1(t) + by_2(t) \\ y_3(t) &= ax_1(t)^2 + bx_2(t)^2 \neq [ax_1(t) + bx_2(t)]^2 = x_3(t)^2 \end{aligned}$$

Basically what we did here is find the left side of the equation by finding the output twice, vs finding the left side by doing the input twice.

**Ex.** Find all the properties of  $y(t) = \cos(t)x(t+1)$ .

We see that it is with memory since it relies on  $t+1$ .

It is not causal since it depends on a future value  $t+1$ .

If we have an input that is finite, so  $x(t) < \infty$ , then we also have  $\cos(t) < \infty$  since  $-1 \geq \cos(x) \geq 1$ .

To determine if it is time variant, we need to do  $t = t - t_0$  and then remove the  $t_0$  from each side. We see if we are still the same.

$$\begin{aligned} y(t - t_0) &= \cos(t - t_0)x(t + 1 - t_0) \\ \implies y(t) &= \cos(t - t_0)x(t + 1) \end{aligned} \quad X$$

So it is not time invariant. To see if it is linear we check the equation.

$$\begin{aligned} y_1(t) &= \cos(t)x_1(t+1) \\ y_2(t) &= \cos(t)x_2(t+1) \\ y_3(t) &= y_1(t) + y_2(t) = \cos(t)x_1(t+1) + \cos(t)x_2(t+1) \\ &= \cos(t)[x_1(t+1) + x_2(t+1)] = ay_1(t) + by_2(t) \end{aligned}$$

## 2 LTI Systems

Many systems in the real world are linear and time invariant. An example is a signal amplifier.

### 2.1 Convolution in Discrete Time

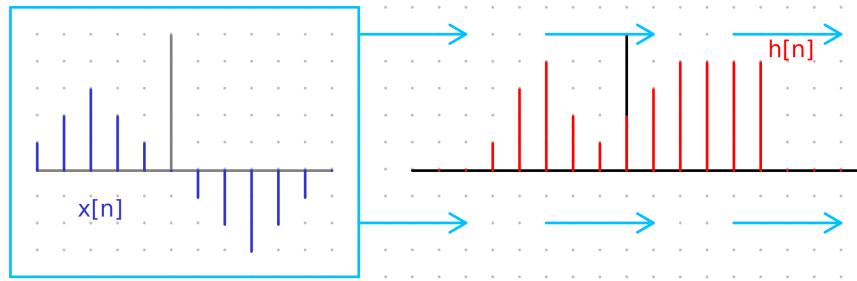
The convolution sum contains 3 parts.

- $h[n]$  is the response of the LTI system
- $x[n]$  is the input to the LTI system
- $y[n]$  is the output of the LTI system

**Ex.** Consider a signal amplifier such as a microphone amplifier, or a speaker amplifier.

If we have a microphone or speaker, the input  $y[n]$  is the input such as the voice or the demodulated radio signal.

The response  $h[n]$  is the algorithms that do all the amplification, and maybe some noise reduction.



The output  $y[n]$  is the final audio signal such as what we hear from a speaker.

The convolution sum is how we calculate the output given an input and response. We can think of this as we have the response  $h[n]$ , and then we send through the input  $x[n]$  throughout the entire response.

The convolution is represented in Equation 8.

$$y[n] = \sum_{k=-\infty}^{\infty} x[k]h[n-k] = x[n] * h[n] \quad (8)$$

Note that when finding the convolution, we now consider  $k$  as the x axis variable, and  $n$  as a constant.

To calculate the convolution sum, we draw  $h[n - k]$  and  $x[k]$ . Then we analyze all overlap regions and find  $x[k] \cdot h[n - k]$  for that region.

## 2.2 Convolution in Continuous Time

This is very similar to the convolution in discrete time except now we have  $h(t), y(t), x(t)$ . We also use an integral to calculate the convolution instead of a sum as shown in Equation 9.

$$y(t) = \int_{-\infty}^{\infty} x(\tau)h(t - \tau)d\tau = x(t) * h(t) \quad (9)$$

Again to solve, we break it up into all the overlap regions and find the product  $(x(t) \cdot h(t))$  for each region.

**Ex.** We have a system response  $h(t)$ . The input  $x(t) = \delta(t)$ . What is the output  $y(t)$ ?

This is very simple. We could go about calculating the convolution sum using equation 9, but we can also think this through logically.

Recall that the response  $h(t)$  is just the stuff that is applied to the input signal  $x(t)$ . Since the input signal is just a single pulse, it will travel through the system visiting each point only **once**.

This means that the output will just be the response.

$$y(t) = x(t) * h(t) = \delta(t) * h(t) = h(t)$$

This is actually a general equation where:

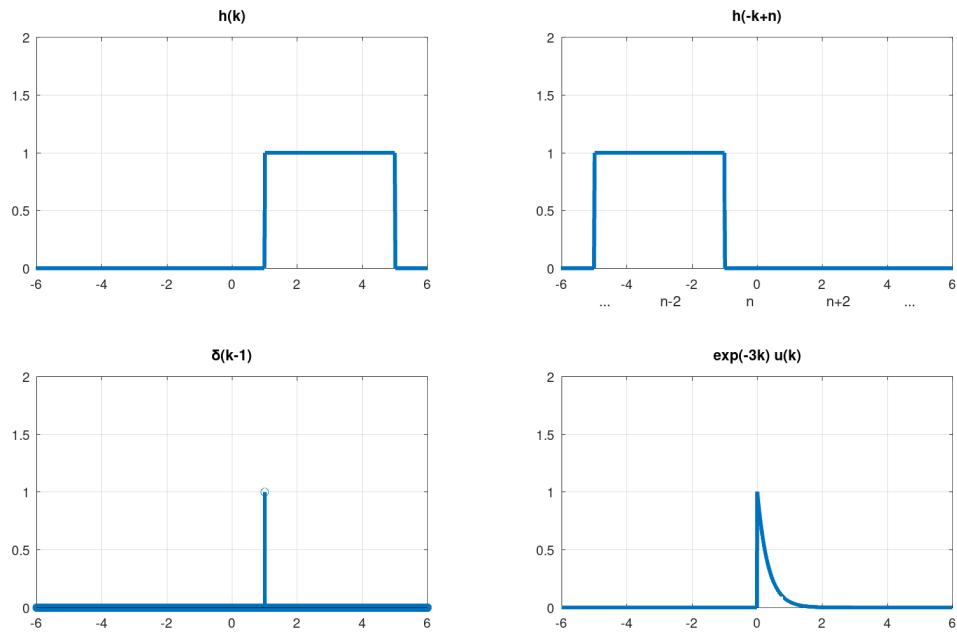
$$x(t) * \delta(t - t_0) = x(t - t_0) \quad (10)$$

**Ex.** We have an input signal and a convolution. Find the output.

$$x(t) = \delta(t - 1) + e^{-3t}u(t) \quad h(t) = u(t - 1) - u(t - 5)$$

To find the output, I need to take the convolution of these two signals. I will need to plot  $h(-k + n)$ , and it will be helpful to have a plot of the input as well.

I see that  $x(t)$  looks complicated to plot. So I will do it in two plots.



Now we need to run the response  $h(n - k)$  through both other functions.

Note that  $k$  is the variable that we change. So we change

Using the first delta function, I have 3 areas:

$$\begin{aligned} n - 1 < 1 &\implies n < 2 &= 0 \\ 1 < n - 1 < 5 &\implies 2 < n < 6 &= 1 \\ n - 1 > 5 &\implies n > 6 &= 0 \end{aligned}$$

Then for the second function, I also have 3 regions.

$$k - 1 < 0 \implies k < 1 \quad = 0$$

$$0 < k - 1 < 4 \implies 1 < k < n$$

$$\int_1^n e^{-3(t-k)} dk = e^{-3t} \int_1^n e^{3k} dk$$

$$k - 1 > 4 \implies k > 5$$

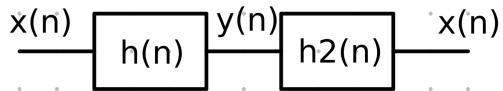
$$= 0$$

Now we can add up the 2 functions to get 5 regions.

## 2.3 Properties

An LTI system is memoryless if  $h[n] = K\delta[n]$  where  $k \in \mathbb{R}$ . This means  $y[n] = Kx[n]$ .

An LTI system is invertable if we can get back the input after applying a convolution to the output.



An LTI system is causal if  $h[n] = 0$  for  $n < 0$ .

An LTI system is stable if for all finite inputs to the response, the output os finite:  $\int_{-\infty}^{\infty} |h(t)| dt < \infty$ .

## 2.4 Differential and Difference Equations

These are equations in the form of:

$$y[n] = y[n - 1] + x[n] \quad \text{Difference Equation}$$

$$\frac{dy(t)}{dt} + y(t) = x(t) \quad \text{Differential Equation}$$

We can solve difference equations by using the initial rest condition which is a time when the output is 0. Then we can solve for consecutive values of  $n$  starting at initial rest.

For differential equations we need to find the homogeneous solution (input is 0) and the particular solution. Then we sum them together.

**Ex.** We have a causal LTI system described by  $y[n] - \frac{1}{3}y[n - 1] = x[n]$

The impulse response  $h[n]$  can be found by remembering that if we let  $x[n] = \delta[n]$  then  $y[n] = h[n]$ .

$$h[n] = \delta[n] + \frac{1}{3}h[n - 1]$$

Then since it is causal, we know that when  $n < 0$ ,  $h[n] = 0$ . So I can try a few values to get a pattern.

$$h[0] = \delta[0] + \frac{1}{3}h[-1] = 1 + \frac{1}{3}(0) = 1$$

$$\begin{aligned}
 h[1] &= \delta[1] + \frac{1}{3}h[0] = \frac{1}{3}(1) = \frac{1}{3} \\
 h[2] &= 0 + \frac{1}{3}\frac{1}{3} = \left[\frac{1}{3}\right]^2 \\
 h[3] &= \left[\frac{1}{3}\right]^3 \\
 h[n] &= \left[\frac{1}{3}\right]^n
 \end{aligned}$$

Now we know  $h[n]$ . We can do many things.

We know the system is stable since if we increase  $n \rightarrow \infty$  then  $h[n]$  is finite.

We also can find the inverse impulse response  $h'[n]$  by just swapping  $x$  for  $y$  in the original equation and then solving using the same method.

If we want to find the output given a certain input we can. We just use the convolution sum to do so. We would end up with three regions, the first of which  $y[n] = 0$ .

**Ex.**

### 3 Fourier Series

Any periodic signal can be represented by sinusoids (or complex exponentials).

We have the signal of  $e^{j\omega_0 t}$  which is periodic. It contains both sin and cos components.

If we change it to  $e^{jk\omega_0 t}$ , for  $k = 0, \pm 1, \pm 2, \dots$  then we say that these are harmonically related. The first harmonic has  $k = \pm 1$ , the second  $k = \pm 2$ , and so on. We have:

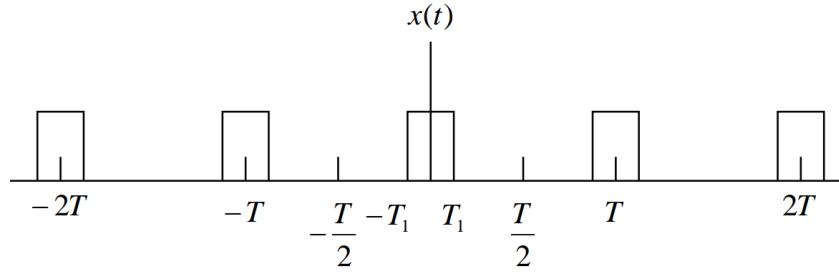
$$x(t) = a_0 + \sum_{k=1}^{\infty} [a_k e^{jk\omega_0 t} + a_{-k} e^{-jk\omega_0 t}] \quad (11)$$

We see that the  $e$  terms are constant, only the coefficients change a meaningful amount. We can calculate the coefficients using Equation 12.

$$a_k = \frac{1}{T} \int_0^T x(t) e^{-jk\omega_0 t} dt \quad (12)$$

$$a_0 = \frac{\text{AREA}}{T} \quad \text{Specific Case for DC offset } (a_0) \quad (13)$$

**Ex.** Find  $a_k$  and  $a_0$



We need to use Equation 12.

$$a_k = \frac{1}{T} \int_0^T x(t) e^{-jk\omega_0 t} dt = \frac{1}{T} \int_{T_1}^{-T_1} 1 \cdot e^{-jk\omega_0 t} dt = \frac{1}{T j k \omega_0} e^{-jk\omega_0 t} \Big|_{-T_1}^{T_1} = \frac{2}{k \omega_0 T} \left[ \frac{e^{jk\omega_0 T_1} - e^{-jk\omega_0 T_1}}{2j} \right]$$

$$= \frac{2}{k \omega_0 T} \cdot \sin(k \omega_0 T_1) \quad \text{Using an identity}$$

$$a_k = \frac{\sin(k \omega_0 T_1)}{k \pi} \quad \text{Using } T = \frac{2\pi}{\omega_0}$$

$$a_0 = \frac{\text{AREA}}{T} = \frac{2T_1}{T} \quad \text{We could also use } a_k \text{ to get } 0/0, \text{ and use l'Hopital}$$

### 3.1 Properties of Continuous Fourier Series

If we have coefficients  $a_k$  already for a signal  $x(t)$ , or maybe more than one signal  $x(t)$  and  $y(t)$ , then after applying some changes to the signals we come up with new coefficients by these properties.

Property	Periodic Signal	Coefficients
Linearity	$Ax(t) + By(t)$	$Aa_k + Bb_k$
Time Shifting	$x(t - t_0)$	$e^{-jk\omega_0 t_0} a_k$
Frequency Shifting	$e^{jM\omega_0 t} x(t)$	$a_{k-M}$
Conjugation	$x^*(t)$	$a_{-k}^*$
Time Reversal	$x(-t)$	$a_{-k}$
Time Scaling	$x(\alpha t), \alpha > 0$	$a_k$
Periodic Convolution	$\int_T x(\tau) y(t - \tau) d\tau$	$T a_k b_k$
Multiplication	$x(t)y(t)$	$\sum_{l=-\infty}^{\infty} a_l b_{k-l}$
Differentiation	$\frac{dx(t)}{dt}$	$jk\omega_0 a_k = jk \frac{w\pi}{T} a_k$
Parseval's Relation	$\frac{1}{T} \int_T  x(t) ^2 dt = \sum_{k=-\infty}^{\infty}  a_k ^2$	

### 3.2 Properties of Discrete Fourier Series

It is the same idea with discrete signals. We have the equations for the coefficients, and the properties.

$$x[n] = \sum_{k=N} a_k e^{jk\omega_0 n} \quad (14)$$

$$a_k = \frac{1}{N} \sum_{n=N} x[n] e^{-jk\omega_0 n} \quad (15)$$

Property	Periodic Signal	Coefficients
Linearity	$Ax[n] + By[n]$	$Aa_k + Bb_k$
Time Shifting	$x[n - n_0]$	$e^{-jk\omega_0 n_0} a_k$
Frequency Shifting	$e^{jM\omega_0 n} x[n]$	$a_{k-M}$
Conjugation	$x^*[n]$	$a_{-k}^*$
Time Reversal	$x[-n]$	$a_{-k}$
Time Scaling	$x_m[n]$	$a_k$
Periodic Convolution	$\sum_{r=N} x[r]y[n-r]$	$Na_k b_k$
Multiplication	$x[n]y[n]$	$\sum_{l=N} a_l b_{k-l}$
Differentiation	$x[n] - x[n-1]$	$(1 - e^{-jk\omega_0})a_k$
Parseval's Relation	$\frac{1}{T} \sum_{n=N}  x[n] ^2 = \sum_{n=N}  a_k ^2$	

## 4 Fourier Transformations

We can also represent non periodic (aperiodic) signals by sinusoids using Fourier Transformations.

We do this by taking a periodic signal, and increasing the period to be very large. This makes it so each pulse of the periodic signal is infinitesimally far apart, which means it is basically a non periodic signal.

We can represent a signal in either the time domain (what we usually do) or the frequency domain. The frequency domain is similar to the fourier series representation of a periodic function.

$$x(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} X(j\omega) e^{j\omega t} d\omega \quad \text{Time Domain (Inverse Fourier Transform)} \quad (16)$$

$$x(j\omega) = \int_{-\infty}^{\infty} x(t) e^{-j\omega t} dt \quad \text{Frequency Domain (Fourier Transform)} \quad (17)$$

We can also fourier transform periodic signals into the frequency domain using:

$$X(j\omega) = \sum_{-\infty}^{\infty} 2\pi a_k \delta(\omega - k\omega_0) \quad (18)$$

These are some common fourier transform pairs:

$e^{-at}u(t) \iff \frac{1}{a+j\omega}, a > 0$	$e^{-a t } \iff \frac{2a}{a^2+\omega^2}, a > 0$
$x(t) = \begin{cases} 1, &  t  < T_1 \iff \frac{2\sin\omega T_1}{\omega} \\ 0, &  t  > T_1 \iff \frac{2\sin\omega T_1}{\omega} \end{cases}$	$\frac{\sin\omega t}{\pi t} \iff X(j\omega) = \begin{cases} 1, &  \omega  < W \\ 0, &  \omega  > W \end{cases}$
$\delta(t) \iff 1$	$\delta(t - t_0) \iff e^{-j\omega t_0}$
$1 \iff 2\pi\delta(\omega)$	$e^{j\omega_0 t} \iff 2\pi\delta(\omega - \omega_0)$
$\sin\omega_0 t \iff \frac{\pi}{j}\delta(\omega - \omega_0) - \frac{\pi}{j}\delta(\omega + \omega_0)$	$\cos\omega_0 t \iff \pi\delta(\omega - \omega_0) + \pi\delta(\omega + \omega_0)$
$\sum_{k=-\infty}^{\infty} a_k e^{jk\omega_0 t} \iff \sum_{k=-\infty}^{\infty} 2\pi a_k \delta(\omega - k\omega_0)$	$\sum_{k=-\infty}^{\infty} \delta(t - kT) \iff \frac{2\pi}{T} \sum_{k=-\infty}^{\infty} \delta\left(\omega - \frac{2\pi k}{T_0}\right)$

## 4.1 Properties

We also have a lot of properties of these transforms such as the derivative which is very useful.

Below is a table with some of the ones:

$$e^{j\omega} Y(e^{j\omega}) -$$

Time Shifting	$x(t - t_0) \iff e^{-j\omega t_0} X(j\omega)$
Conjugate	$x^*(t) \iff X^*(-j\omega)$
Differentiation	$\frac{dx(t)}{dt} \iff j\omega X(j\omega)$
Parseval's Relation	$\int_{-\infty}^{\infty}  x(t) ^2 dt \iff \frac{1}{2\pi} \int_{-\infty}^{\infty}  X(j\omega) ^2 d\omega$
Convolution	$y(t) = h(t) * x(t) \iff Y(j\omega) = H(j\omega)X(j\omega)$
Multiplication	$r(t) = s(t)p(t) \iff R(j\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S(j\theta)P(j(\omega - \theta)) d\theta$

## 5 Discrete Time Fourier Transformation

This is very similar to the fourier transforms in continuous time, but there are slight differences.

The idea is exactly the same, it is just a few equations that we use are a bit different.

We get the two equations of:

$$x[n] = \frac{1}{2\pi} \int_{2\pi} X(e^{j\omega}) e^{j\omega n} d\omega \quad \text{Time Domain (Inverse Fourier Transform)} \quad (19)$$

$$x[e^{j\omega}] = \sum_{n=-\infty}^{\infty} x[n] e^{-j\omega n} \quad \text{Frequency Domain (Fourier Transform)} \quad (20)$$

## 6 Filters

## 7 Bode Plot

## 8 Sampling

## 9 Laplace Transformations

## 10 Appendix

## A few formulas

### Euler

$$e^{j\theta} = \cos(\theta) + j \sin(\theta)$$

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

### Summations, geometric series

$$\sum_{k=n_1}^{\infty} a^k = \frac{a^{n_1}}{1-a} \quad |a| < 1 \quad \sum_{k=n_1}^{n_2} a^k = \frac{a^{n_1} - a^{n_2+1}}{1-a} \quad a \neq 1$$

$$\sum_{k=0}^{\infty} a^k = \frac{1}{1-a} \quad |a| < 1 \quad \sum_{k=0}^{n_1} a^k = \frac{1 - a^{n_1+1}}{1-a} \quad n_1 \geq 0$$

### Even and odd parts

$$x_e(t) = \frac{1}{2}x(t) + \frac{1}{2}x(-t) \quad x_o(t) = \frac{1}{2}x(t) - \frac{1}{2}x(-t)$$

$$x_e[n] = \frac{1}{2}x[n] + \frac{1}{2}x[-n] \quad x_o[n] = \frac{1}{2}x[n] - \frac{1}{2}x[-n]$$

### Convolutions

$$y(t) = x(t) * h(t) = \int_{-\infty}^{\infty} x(\tau)h(t-\tau)d\tau$$

$$y[n] = x[n] * h[n] = \sum_{k=-\infty}^{\infty} x[k]h[n-k]$$

### $h(t)$ response for differential equations describing LTI systems (single order roots)

$$\sum_{k=0}^N a_k \frac{d^k y(t)}{dt^k} = \sum_{k=0}^M b_k \frac{d^k x(t)}{dt^k}$$

$$h(t) = \sum_{k=0}^{N-1} A_k e^{s_k t} u(t) + \sum_{k=0}^{M-N} B_k \frac{d^k \delta(t)}{dt^k}$$

$$\sum_{k=0}^N a_k \frac{d^k y(t)}{dt^k} = x(t) \quad h'(t) = \sum_{k=0}^{N-1} A_k e^{s_k t} u(t) \quad (\text{simpl. sys.})$$

### $h[n]$ response for difference equations describing LTI systems (single order roots)

$$\sum_{k=0}^N a_k y[n-k] = \sum_{k=0}^M b_k x[n-k]$$

$$h[n] = \sum_{k=0}^{N-1} A_k \alpha_k^n u[n] + \sum_{k=0}^{M-N} B_k \delta[n-k]$$

$$\sum_{k=0}^N a_k y[n-k] = x[n] \quad h'[n] = \sum_{k=0}^{N-1} A_k \alpha_k^n u[n] \quad (\text{simpl. sys.})$$

### LTI systems and eigenfunctions

$$e^{st} \xrightarrow{\text{LTI(cont.)}} H(s)e^{st}$$

$$z^n \xrightarrow{\text{LTI(discr.)}} H(z)z^n$$

$$e^{j\omega t} \xrightarrow{\text{LTI(cont.)}} H(j\omega)e^{j\omega t}$$

$$e^{j\omega n} \xrightarrow{\text{LTI(discr.)}} H(e^{j\omega})e^{j\omega n}$$

$$\cos(\omega t) \xrightarrow{\text{LTI(cont.)}} |H(j\omega)| \cos(\omega t + \angle H(j\omega))$$

$$\cos(\omega n) \xrightarrow{\text{LTI(discr.)}} |H(e^{j\omega})| \cos(\omega n + \angle H(e^{j\omega}))$$

Standard first and second order low-pass systems, continuous time

$$H(j\omega) = \frac{1}{1+j\omega\tau} \quad H(j\omega) = \frac{\omega_n^2}{(j\omega)^2 + 2\zeta\omega_n(j\omega) + \omega_n^2}$$

Standard first and second order recursive systems, discrete time

$$H(e^{j\omega}) = \frac{1}{1-ae^{-j\omega}} \quad |a| < 1$$

$$H(e^{j\omega}) = \frac{1}{1-2r \cos \theta e^{-j\omega} + r^2 e^{-j2\omega}} \quad 0 \leq r < 1, 0 \leq \theta \leq \pi$$

### Continuous time sampling

$$x_p(t) = x(t) \times p(t) \quad x_d[n] = x(nT)$$

$$X_p(j\omega) = f_s \sum_{k=-\infty}^{\infty} X(j(\omega - k\omega_s)) \quad \omega_s = \frac{2\pi}{T} = 2\pi f_s$$

$$X_d(e^{j\omega}) = X_p(j\omega f_s)$$

$$H_0(j\omega) = e^{-j\pi\omega/\omega_s} 2 \sin(\pi\omega/\omega_s)/\omega \quad (\text{sample \& hold})$$

### Other formulas

$$A \cos(\phi + \theta) = A \sin(\phi + \theta + \pi/2) = B \cos \phi - C \sin \phi$$

$$(B = A \cos \theta \quad C = A \sin \theta \quad A^2 = \sqrt{B^2 + C^2} \quad \theta = \tan^{-1}\left(\frac{C}{B}\right))$$

$$ae^{j\phi} + a^* e^{-j\phi} = 2 \operatorname{Re}\{ae^{j\phi}\} = 2|a| \cos(\phi + \angle a)$$

$$\cos x \cos y = \frac{1}{2} [\cos(x-y) + \cos(x+y)]$$

$$\sin x \cos y = \frac{1}{2} [\sin(x-y) + \sin(x+y)]$$

$$\sin x \sin y = \frac{1}{2} [\cos(x-y) - \cos(x+y)]$$

$$\int xe^{ax} dx = \frac{e^{ax}}{a^2} (ax - 1) + c$$

$$\frac{d \operatorname{atan}(x)}{dx} = \frac{d \tan^{-1}(x)}{dx} = \frac{1}{1+x^2}$$

## Properties – Continuous time Fourier series (C.T.F.S.)

### Definitions:

$$a_k = \frac{1}{T} \int_T x(t) e^{-jk\omega_0 t} dt$$

$$x(t) = \sum_{k=-\infty}^{\infty} a_k e^{jk\omega_0 t}$$

$$a_0 = \frac{1}{T} \int_T x(t) dt$$

$x(t)$  periodic with period  $T$  sec.,

Fundam. angular frequency  $\omega_0 = 2\pi f_0 = 2\pi/T$  rad./sec.

$$x(t) \xrightarrow{\text{C.T.F.S.}} a_k \quad y(t) \xrightarrow{\text{C.T.F.S.}} b_k$$

$$\text{If } x(t) \xrightarrow{\text{LTI}} y(t) \text{ then } b_k = a_k H(j\omega)|_{\omega=k\omega_0}$$

$$\text{Linearity: } Ax(t) + By(t) \xrightarrow{\text{C.T.F.S.}} A a_k + B b_k$$

$$\text{Shifting: } x(t - t_0) \xrightarrow{\text{C.T.F.S.}} e^{-jk\omega_0 t_0} a_k$$

$$\text{Scaling: } x(\alpha t) \xrightarrow{\text{C.T.F.S.}} a_k \quad (\alpha > 0, \text{ period } T/\alpha)$$

$$\text{Flipping: } x(-t) \xrightarrow{\text{C.T.F.S.}} a_{-k}$$

$$\text{Conjugate: } x^*(t) \xrightarrow{\text{C.T.F.S.}} a_{-k}^* \quad x^*(-t) \xrightarrow{\text{C.T.F.S.}} a_k^*$$

### Symmetries:

if  $x(t)$  is real:  $a_k = a_{-k}^*$ ,  $|a_k| = |a_{-k}|$ ,  $\angle a_k = -\angle a_{-k}$

$x(t)$  real and even :  $a_k$  real and even  $a_k = a_{-k}$

$x(t)$  real and odd:  $a_k$  imaginary and odd  $a_k = -a_{-k}$

### Periodic convolution:

$$\int_T x(\tau) y(t - \tau) d\tau \xrightarrow{\text{C.T.F.S.}} T a_k b_k$$

$$\text{Modulation: } x(t)y(t) \xrightarrow{\text{C.T.F.S.}} a_k * b_k = \sum_{l=-\infty}^{\infty} a_l b_{k-l}$$

$$e^{j m \omega_0 t} x(t) \xrightarrow{\text{C.T.F.S.}} a_{k-m}$$

$$\text{Differentiation: } \frac{dx(t)}{dt} \xrightarrow{\text{C.T.F.S.}} jk\omega_0 a_k$$

$$\text{Integration: } \int_{\tau=-\infty}^t x(\tau) d\tau \xrightarrow{\text{C.T.F.S.}} \frac{a_k}{jk\omega_0} \quad (\text{if } a_0 = 0)$$

$$\text{Parseval: } \frac{1}{T} \int_T |x(t)|^2 dt = \sum_{k=-\infty}^{\infty} |a_k|^2$$

## Table of continuous time Fourier series (C.T.F.S.)

$x(t)$ periodic, period $T = \frac{2\pi}{\omega_0} = \frac{1}{f_0}$ sec.	Fourier series coefficients $a_k$
$e^{j\omega_0 t}$	$a_1 = 1$ $a_k = 0$ elsewhere
$\cos(\omega_0 t)$	$a_1, a_{-1} = 1/2$ $a_k = 0$ elsewhere
$\sin(\omega_0 t)$	$a_1, a_{-1} = 1/(2j)$ $a_k = 0$ elsewhere
$\begin{cases} 1 &  t  < T_1 \\ 0 & T_1 <  t  < T/2 \end{cases}$ (periodic $T$ )	$a_k = \frac{\sin(k\omega_0 T_1)}{k\pi}$ $a_k = \frac{2T_1}{T} = \frac{T_1\omega_0}{\pi}$ $k = 0$
1	$a_0 = 1$ $a_k = 0$ elsewhere
$\sum_{n=-\infty}^{\infty} \delta(t - nT)$	$a_k = \frac{1}{T}$

## Properties – Discrete time Fourier series (D.T.F.S.)

### Definitions:

$$a_k = \frac{1}{N} \sum_{n=-N}^{N-1} x[n] e^{-j(k\frac{2\pi}{N})n}$$

$$x[n] = \sum_{k=-N}^{N-1} a_k e^{j(k\frac{2\pi}{N})n}$$

$$a_0 = \frac{1}{N} \sum_{n=-N}^{N-1} x[n]$$

$x[n]$  periodic with period  $N$  samples (fundamental angular frequency  $\omega_0 = \frac{2\pi}{N}$  rad./sample)

$$x[n] \xrightarrow{\text{D.T.F.S.}} a_k \quad y[n] \xrightarrow{\text{D.T.F.S.}} b_k$$

$$\text{If } x[n] \xrightarrow{\text{LTI}} y[n] \text{ then } b_k = a_k H(e^{j\omega}) \Big|_{\omega=k\frac{2\pi}{N}}$$

**Periodicity:**  $x[n] \xrightarrow{\text{D.T.F.S.}} a_k = a_{k+N}$

**Linearity:**  $Ax[n] + By[n] \xrightarrow{\text{D.T.F.S.}} Aa_k + Bb_k$

**Shifting:**  $x[n - n_0] \xrightarrow{\text{D.T.F.S.}} e^{-jk\frac{2\pi}{N}n_0} a_k$

**Flipping:**  $x[-n] \xrightarrow{\text{D.T.F.S.}} a_{-k}$

**Conjugate:**  $x^*[n] \xrightarrow{\text{D.T.F.S.}} a_{-k}^*$   
 $x^*[-n] \xrightarrow{\text{D.T.F.S.}} a_k^*$

### Symmetries:

if  $x[n]$  is real :  $a_k = a_{-k}^*$ ,  $|a_k| = |a_{-k}|$ ,  $\angle a_k = -\angle a_{-k}$

$x[n]$  real and even :  $a_k$  real and even  $a_k = a_{-k}$

$x[n]$  real and odd:  $a_k$  imaginary and odd  $a_k = -a_{-k}$

### Periodic convolution:

$$\sum_{m=-N}^{N-1} x[m]y[n-m] \xrightarrow{\text{D.T.F.S.}} N a_k b_k$$

**Modulation:**  $x[n]y[n] \xrightarrow{\text{D.T.F.S.}} \sum_{l=-N}^{N-1} a_l b_{k-l}$

$$e^{jm\frac{2\pi}{N}n} x[n] \xrightarrow{\text{D.T.F.S.}} a_{k-m}$$

**Accumulation :**  $\sum_{m=-\infty}^n x[m] \xrightarrow{\text{D.T.F.S.}} \frac{1}{\left(1 - e^{-jk\frac{2\pi}{N}}\right)} a_k$   
 (if  $a_0 = 0$ )

**Parseval:**  $\frac{1}{N} \sum_{n=-N}^{N-1} |x[n]|^2 = \sum_{k=-N}^{N-1} |a_k|^2$

**Duality :** if  $x[n] \xrightarrow{\text{DTFS}} a_k$  then  $a[n] \xrightarrow{\text{DTFS}} \frac{1}{N} x_{-k}$

## Table of discrete time Fourier series (D.T.F.S.)

$x[n]$ periodic, period $N$ samples	Fourier series coefficients $a_k$ (periodic with period $N$ )
$e^{j\omega_0 n}$	If $x[n]$ periodic with $\omega_0 = \frac{2\pi m}{N}$ : $a_k = 1 \quad k = m, m \pm N, m \pm 2N, \dots$ $a_k = 0$ elsewhere
$\cos(\omega_0 n)$	If $x[n]$ periodic with $\omega_0 = \frac{2\pi m}{N}$ : $a_k = 1/2 \quad k = \pm m, \pm m \pm N, \pm m \pm 2N, \dots$ $a_k = 0$ elsewhere
$\sin(\omega_0 n)$	If $x[n]$ periodic with $\omega_0 = \frac{2\pi m}{N}$ : $a_k = 1/(2j) \quad k = \pm m, \pm m \pm N, \pm m \pm 2N, \dots$ $a_k = 0$ elsewhere
$\begin{cases} 1 &  n  \leq N_1 \\ 0 & N_1 <  n  \leq N/2 \end{cases}$ <small>(periodic <math>N</math>, <math>N</math> even)</small>	$a_k = \frac{\sin\left(\frac{2\pi}{N}k(N_1 + 1/2)\right)}{N \sin\left(\frac{\pi}{N}k\right)}$ $a_k = (2N_1 + 1)/N \quad k = 0, \pm N, \pm 2N, \dots$
1	$a_k = 1 \quad k = 0, \pm N, \pm 2N, \dots$ $a_k = 0$ elsewhere
$\sum_{m=-\infty}^{\infty} \delta[n - mN]$	$a_k = \frac{1}{N}$

## Properties – Continuous time Fourier transform (C.T.F.T.)

### Definitions:

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

$\omega$  in rad./sec.

$$X(j\omega) = \sum_{k=-\infty}^{+\infty} 2\pi a_k \delta(\omega - k\omega_0) \text{ if } x(t) \text{ periodic}$$

$$x(t) \xrightarrow{\text{CTFT}} X(j\omega) \quad y(t) \xrightarrow{\text{CTFT}} Y(j\omega)$$

$$\text{Linearity: } ax(t) + by(t) \xrightarrow{\text{CTFT}} aX(j\omega) + bY(j\omega)$$

$$\text{Shifting: } x(t - t_0) \xrightarrow{\text{CTFT}} e^{-j\omega t_0} X(j\omega)$$

$$\text{Scaling: } x(at) \xrightarrow{\text{CTFT}} \frac{1}{|a|} X\left(\frac{j\omega}{a}\right)$$

$$\text{Flipping: } x(-t) \xrightarrow{\text{CTFT}} X(-j\omega)$$

$$\text{Conjugate: } x^*(t) \xrightarrow{\text{CTFT}} X^*(-j\omega)$$

$$x^*(-t) \xrightarrow{\text{CTFT}} X^*(j\omega)$$

### Symmetries:

$$\text{if } x(t) \text{ is real : } X(j\omega) = X^*(-j\omega),$$

$$|X(j\omega)| = |X(-j\omega)|, \angle X(j\omega) = -\angle X(-j\omega)$$

$$x(t) \text{ real and even : } X(j\omega) \text{ real and even } X(j\omega) = X(-j\omega)$$

$$x(t) \text{ real and odd: } X(j\omega) \text{ imag., odd } X(j\omega) = -X(-j\omega)$$

### Convolution:

$$x(t) * y(t) = \int_{-\infty}^{\infty} x(\tau) y(t - \tau) d\tau \xrightarrow{\text{CTFT}} X(j\omega)Y(j\omega)$$

### Modulation:

$$x(t)y(t) \xrightarrow{\text{CTFT}} \frac{1}{2\pi} X(j\omega) * Y(j\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} X(j\theta)Y(j(\omega - \theta))d\theta$$

$$e^{j\omega_0 t} x(t) \xrightarrow{\text{CTFT}} X(j(\omega - \omega_0))$$

$$\cos(\omega_0 t)x(t) \xrightarrow{\text{CTFT}} \frac{1}{2} X(j(\omega - \omega_0)) + \frac{1}{2} X(j(\omega + \omega_0))$$

$$\text{Differentiation: } \frac{dx(t)}{dt} \xrightarrow{\text{CTFT}} j\omega X(j\omega)$$

$$\text{Integration: } \int_{-\infty}^t x(\tau) d\tau \xrightarrow{\text{CTFT}} \frac{1}{j\omega} X(j\omega) + \pi X(j0)\delta(\omega)$$

$$\text{Differentiation in freq.: } tx(t) \xrightarrow{\text{CTFT}} j \frac{dX(j\omega)}{d\omega}$$

### Integration in freq.:

$$-\frac{1}{jt} x(t) + \pi x(0)\delta(t) \xrightarrow{\text{CTFT}} \int_{-\infty}^{\omega} X(j\eta) d\eta$$

$$\text{Parseval: } \int_{-\infty}^{+\infty} |x(t)|^2 dt = \frac{1}{2\pi} \int_{-\infty}^{+\infty} |X(j\omega)|^2 d\omega$$

**Duality :** if  $x(t) \xrightarrow{\text{CTFT}} X(j\omega)$  then

$$X(t) \xrightarrow{\text{CTFT}} 2\pi x(-j\omega)$$

## Table of continuous time Fourier transforms (C.T.F.T.)

signal $x(t)$	typ. aperiodic	$X(j\omega)$ ( $\omega$ in rad./sec.)
if $x(t)$ is periodic, with period $T = \frac{2\pi}{\omega_0} = \frac{1}{f_0}$ sec.		$2\pi \sum_{k=-\infty}^{+\infty} a_k \delta(\omega - k\omega_0)$
$e^{j\omega_0 t}$		$2\pi\delta(\omega - \omega_0)$
$\cos(\omega_0 t)$		$\pi\delta(\omega - \omega_0) + \pi\delta(\omega + \omega_0)$
$\sin(\omega_0 t)$		$\frac{\pi}{j}\delta(\omega - \omega_0) - \frac{\pi}{j}\delta(\omega + \omega_0)$
$\begin{cases} 1 &  t  < T_1 \\ 0 & T_1 <  t  < T/2 \end{cases}$ (periodic $T$ )		$2 \sum_{k=-\infty}^{+\infty} \frac{\sin(k\omega_0 T_1)}{k} \delta(\omega - k\omega_0)$ $\frac{4\pi T_1}{T} \delta(\omega) = 2T_1\omega_0\delta(\omega)$ $k = 0$
1		$2\pi\delta(\omega)$
$\sum_{n=-\infty}^{\infty} \delta(t - nT)$		$\omega_s \sum_{k=-\infty}^{+\infty} \delta(\omega - k\omega_s)$ $\omega_s = \frac{2\pi}{T}$
$\begin{cases} 1 &  t  < T_1 \\ 0 &  t  > T_1 \end{cases}$		$\frac{2\sin(\omega T_1)}{\omega}$
$\frac{\sin(Wt)}{\pi t}$ $W > 0$		$\begin{cases} 1 &  \omega  \leq W \\ 0 &  \omega  > W \end{cases}$
$\delta(t)$		1
$u(t)$		$\frac{1}{j\omega} + \pi\delta(\omega)$
$e^{-at} u(t)$ $\text{Re}\{a\} > 0$		$\frac{1}{a + j\omega}$
$-e^{-at} u(-t)$ $\text{Re}\{a\} < 0$		$\frac{1}{a + j\omega}$
$\frac{t^{n-1}}{(n-1)!} e^{-at} u(t)$ $\text{Re}\{a\} > 0$		$\frac{1}{(a + j\omega)^n}$
$-\frac{t^{n-1}}{(n-1)!} e^{-at} u(-t)$ $\text{Re}\{a\} < 0$		$\frac{1}{(a + j\omega)^n}$
$e^{-at} \sin(\omega_0 t) u(t)$ $a > 0 \quad \omega_0 \geq 0 \quad a, \omega_0 \text{ real}$		$\frac{\omega_0}{(j\omega + a)^2 + \omega_0^2}$
$e^{-at} \cos(\omega_0 t) u(t)$ $a > 0 \quad \omega_0 \geq 0 \quad a, \omega_0 \text{ real}$		$\frac{j\omega + a}{(j\omega + a)^2 + \omega_0^2}$
$-e^{-at} \sin(\omega_0 t) u(-t)$ $a < 0 \quad \omega_0 \geq 0 \quad a, \omega_0 \text{ real}$		$\frac{\omega_0}{(j\omega + a)^2 + \omega_0^2}$
$-e^{-at} \cos(\omega_0 t) u(-t)$ $a < 0 \quad \omega_0 \geq 0 \quad a, \omega_0 \text{ real}$		$\frac{j\omega + a}{(j\omega + a)^2 + \omega_0^2}$

## Properties – Discrete time Fourier transform (D.T.F.T.)

### Definitions:

$x[n] = x(nT) = x(t)|_{t=nT}$ , where  $T = 1/f_s = 2\pi/\omega_s$  is the sampling period in sec., and  $n$  is an integer, results in:

$$X_p(j\omega) = f_s \sum_{k=-\infty}^{\infty} X(j(\omega - k\omega_s)), \quad X(e^{j\omega}) = X_p(j\omega f_s)$$

where  $X(j\omega)$  is the original CTFT of  $x(t)$ , and  $X(e^{j\omega})$  is the DTFT of  $x[n]$  defined as:

$$X(e^{j\omega}) = \sum_{n=-\infty}^{\infty} x[n]e^{-jn\omega} \quad x[n] = \frac{1}{2\pi} \int_{-\pi}^{+\pi} X(e^{j\omega})e^{jn\omega} d\omega$$

**Periodicity:**  $x[n] \xrightarrow{DTFT} X(e^{j\omega}) = X(e^{j(\omega+2\pi)})$

**Linearity:**  $ax[n] + by[n] \xrightarrow{DTFT} aX(e^{j\omega}) + bY(e^{j\omega})$

**Shifting:**  $x[n - n_0] \xrightarrow{DTFT} e^{-jn_0\omega} X(e^{j\omega}) \quad n_0 \text{ integer}$

### Expansion, insertion of zeros:

$$x_{(k)}[n] \xrightarrow{DTFT} X(e^{jk\omega}) \quad \text{where } k \text{ is a positive integer}$$

$$x_{(k)}[n] = x[n/k] \quad \text{if } n \text{ is a multiple of } k$$

$$x_{(k)}[n] = 0 \quad \text{elsewhere}$$

**Flipping:**  $x[-n] \xrightarrow{DTFT} X(e^{-j\omega})$

**Conjugate:**  $x^*[n] \xrightarrow{DTFT} X^*(e^{-j\omega})$

$$x^*[-n] \xrightarrow{DTFT} X^*(e^{j\omega})$$

### Symmetries:

if  $x[n]$  is real :  $X(e^{j\omega}) = X^*(e^{-j\omega})$ ,

$$|X(e^{j\omega})| = |X(e^{-j\omega})|, \angle X(e^{j\omega}) = -\angle X(e^{-j\omega})$$

$x[n]$  real and even :  $X(e^{j\omega})$  real, even  $X(e^{j\omega}) = X(e^{-j\omega})$

$x[n]$  real, odd  $X(e^{j\omega})$  imag., odd  $X(e^{j\omega}) = -X(e^{-j\omega})$

### Convolution:

$$x[n] * y[n] = \sum_{k=-\infty}^{\infty} x[k]y[n-k] \xrightarrow{DTFT} X(e^{j\omega})Y(e^{j\omega})$$

**Modulation:**  $x[n]y[n] \xrightarrow{DTFT} \frac{1}{2\pi} \int_{2\pi} X(e^{j\theta})Y(e^{j(\omega-\theta)})d\theta$

$$e^{j\omega_0 n}x[n] \xrightarrow{DTFT} X(e^{j(\omega-\omega_0)})$$

### Accumulation:

$$\sum_{m=-\infty}^n x[m] \xrightarrow{DTFT} \frac{1}{1-e^{-j\omega}} X(e^{j\omega}) + \pi X(e^{j0}) \sum_{m=-\infty}^{+\infty} \delta(\omega - m2\pi)$$

**Differentiation in freq.:**  $nx[n] \xrightarrow{DTFT} j \frac{dX(e^{j\omega})}{d\omega}$

**Parseval:**  $\sum_{n=-\infty}^{+\infty} |x[n]|^2 = \frac{1}{2\pi} \int_{2\pi} |X(e^{j\omega})|^2 d\omega$

**Duality :** If  $x[n] \xrightarrow{DTFT} X(e^{j\omega})$  then  $X(t) \xrightarrow{CTFS} x_{-k}$

Table of discrete time Fourier transforms (D.T.F.T.)

signal $x[n]$ typ. aperiodic	$X(e^{j\omega})$ (periodic $2\pi$ , $\omega$ in rad./sample)
if $x[n]$ is periodic, with period $N$ samples	$2\pi \sum_{k=-\infty}^{+\infty} a_k \delta(\omega - k \frac{2\pi}{N})$
$e^{j\omega_0 n}$	$2\pi \sum_{l=-\infty}^{\infty} \delta(\omega - \omega_0 - l2\pi)$
$\cos(\omega_0 n)$	$\pi \sum_{l=-\infty}^{\infty} \delta(\omega - \omega_0 - l2\pi)$ $+ \pi \sum_{l=-\infty}^{\infty} \delta(\omega + \omega_0 - l2\pi)$
$\sin(\omega_0 n)$	$\frac{\pi}{j} \sum_{l=-\infty}^{\infty} \delta(\omega - \omega_0 - l2\pi)$ $- \frac{\pi}{j} \sum_{l=-\infty}^{\infty} \delta(\omega + \omega_0 - l2\pi)$
1	$2\pi \sum_{l=-\infty}^{\infty} \delta(\omega - l2\pi)$
$\sum_{m=-\infty}^{\infty} \delta[n-mN]$	$\frac{2\pi}{N} \sum_{m=-\infty}^{+\infty} \delta(\omega - m \frac{2\pi}{N})$
$\begin{cases} 1 &  n  \leq N_1 \\ 0 &  n  > N_1 \end{cases}$	$\sin(\omega(N_1 + \frac{1}{2})) / \sin(\omega/2)$
$\frac{\sin(Wn)}{\pi n} \quad 0 < W < \pi$	$\begin{cases} 1 & 0 \leq  \omega  \leq W \\ 0 & W <  \omega  \leq \pi \end{cases}$ period. $2\pi$
$\delta[n]$	1
$u[n]$	$\frac{1}{1-e^{-j\omega}} + \pi \sum_{k=-\infty}^{\infty} \delta(\omega - k2\pi)$
$a^n u[n] \quad  a  < 1$	$1/(1-ae^{-j\omega})$
$-a^n u[-n-1] \quad  a  > 1$	$1/(1-ae^{-j\omega})$
$\frac{(n+r-1)!}{n!(r-1)!} a^n u[n] \quad  a  < 1$	$\frac{1}{(1-ae^{-j\omega})^r}$
$\frac{-(n+r-1)!}{n!(r-1)!} a^n u[-n-1] \quad  a  > 1$	$\frac{1}{(1-ae^{-j\omega})^r}$
$r^n \sin(\omega_0 n) u[n] \quad 0 \leq r < 1 \quad 0 \leq \omega_0 \leq \pi$	$\frac{r \sin(\omega_0) e^{-j\omega}}{1-2r \cos(\omega_0) e^{-j\omega} + r^2 e^{-j2\omega}}$
$r^n \cos(\omega_0 n) u[n] \quad 0 \leq r < 1 \quad 0 \leq \omega_0 \leq \pi$	$\frac{1-r \cos(\omega_0) e^{-j\omega}}{1-2r \cos(\omega_0) e^{-j\omega} + r^2 e^{-j2\omega}}$
$-r^n \sin(\omega_0 n) u[-n-1] \quad r > 1 \quad 0 \leq \omega_0 \leq \pi$	$\frac{r \sin(\omega_0) e^{-j\omega}}{1-2r \cos(\omega_0) e^{-j\omega} + r^2 e^{-j2\omega}}$
$-r^n \cos(\omega_0 n) u[-n-1] \quad r > 1 \quad 0 \leq \omega_0 \leq \pi$	$\frac{1-r \cos(\omega_0) e^{-j\omega}}{1-2r \cos(\omega_0) e^{-j\omega} + r^2 e^{-j2\omega}}$

## Properties – bilateral (two-sided) Laplace transform

### Definitions:

$$X(s) = \int_{-\infty}^{+\infty} x(t)e^{-st} dt \quad x(t) = \frac{1}{2\pi j} \int_{\sigma-j\infty}^{\sigma+j\infty} X(s)e^{st} ds$$

$$x(t) \xleftarrow{LT} X(s) \quad ROC_x \quad y(t) \xleftarrow{LT} Y(s) \quad ROC_y$$

**Linearity:**  $ax(t) + by(t) \xleftarrow{LT} aX(s) + bY(s)$   
 $ROC_x \cap ROC_y$

**Shifting:**  $x(t-t_0) \xleftarrow{LT} e^{-st_0} X(s) \quad ROC_x$  unchanged

**Scaling:**  $x(at) \xleftarrow{LT} \frac{1}{|a|} X(\frac{s}{a})$

$ROC_x$  dilated factor  $|a|$  or compressed factor  $\frac{1}{|a|}$ ,

and  $ROC_x$  inversed if  $a < 0$

**Flipping:**  $x(-t) \xleftarrow{LT} X(-s) \quad ROC_x$  inversed

**Conjugate:**  $x^*(t) \xleftarrow{LT} X^*(s^*) \quad ROC_x$  unchanged

**Symmetry:** if  $x(t)$  real :  $X(s) = X^*(s^*)$ ,  
 $|X(s)| = |X(s^*)|$

### Convolution:

$$x(t) * y(t) = \int_{-\infty}^{\infty} x(\tau) y(t-\tau) d\tau \xleftrightarrow{LT} X(s)Y(s)$$

$$ROC_x \cap ROC_y$$

**Modulation:**  $e^{s_0 t} x(t) \xleftarrow{LT} X(s-s_0)$   
 $ROC_x$  shifted to right by  $\text{Re}\{s_0\}$

**Differentiation:**  $\frac{dx(t)}{dt} \xleftarrow{LT} s X(s) \quad ROC_x$  unchanged

**Integration:**  $\int_{-\infty}^t x(\tau) d\tau \xleftarrow{LT} \frac{1}{s} X(s)$   
 $ROC_x \cap (\text{Re}\{s\} > 0)$

**Differentiation in freq.:**  $-tx(t) \xleftarrow{LT} \frac{dX(s)}{ds}$   
 $ROC_x$  unchanged

## Table of bilateral (two-sided) Laplace transforms

Signal $x(t)$	Laplace transform $X(s)$	ROC
$\delta(t)$	1	$\forall s$
$u(t)$	$\frac{1}{s}$	$\text{Re}\{s\} > 0$
$-u(-t)$	$\frac{1}{s}$	$\text{Re}\{s\} < 0$
$e^{-at} u(t)$	$\frac{1}{s+a}$	$\text{Re}\{s\} > -a$
$-e^{-at} u(-t)$	$\frac{1}{s+a}$	$\text{Re}\{s\} < -a$
$\frac{t^{n-1}}{(n-1)!} e^{-at} u(t)$	$\frac{1}{(s+a)^n}$	$\text{Re}\{s\} > -a$
$\frac{t^{n-1}}{(n-1)!} e^{-at} u(-t)$	$\frac{1}{(s+a)^n}$	$\text{Re}\{s\} < -a$
$e^{-at} \sin(\omega_0 t) u(t)$ $\omega_0 \geq 0 \quad a, \omega_0$ real	$\frac{\omega_0}{(s+a)^2 + \omega_0^2}$	$\text{Re}\{s\} > -a$
$e^{-at} \cos(\omega_0 t) u(t)$ $\omega_0 \geq 0 \quad a, \omega_0$ real	$\frac{s+a}{(s+a)^2 + \omega_0^2}$	$\text{Re}\{s\} > -a$
$-e^{-at} \sin(\omega_0 t) u(-t)$ $\omega_0 \geq 0 \quad a, \omega_0$ real	$\frac{\omega_0}{(s+a)^2 + \omega_0^2}$	$\text{Re}\{s\} < -a$
$-e^{-at} \cos(\omega_0 t) u(-t)$ $\omega_0 \geq 0 \quad a, \omega_0$ real	$\frac{s+a}{(s+a)^2 + \omega_0^2}$	$\text{Re}\{s\} < -a$