

# ECE 240 Formula Sheet

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## 1. Time-domain signals

A continuous-time signal takes the form

$$x(t + nT) = x(t) \quad n \in \mathbb{Z}.$$

A signal  $z(t) = \alpha x(t + aT_1) + \beta x(t + bT_2)$  will be periodic if

$$\frac{T_1}{T_2} = \frac{a}{b}$$

for some  $a, b \in \mathbb{Z}$ .

Let  $x(t)$  be some signal.

- The *total energy* is given by

$$E = \lim_{L \rightarrow \infty} \int_{-L}^L |x(t)|^2 dt.$$

- The *average power* is given by

$$P = \lim_{L \rightarrow \infty} \frac{1}{2L} \int_{-L}^L |x(t)|^2 dt.$$

- If  $x(t)$  is periodic,

$$P = \frac{1}{T} \int_0^T |x(t)|^2 dt.$$

$E$  finite  $\rightarrow$  **Energy signal**  $\rightarrow P = 0$ .

$E$  infinite and  $P$  finite  $\rightarrow$  **Power signal**.

Periodic signal  $\rightarrow$  **Power signal**.

The *unit step signal* is defined as

$$u(t) = \begin{cases} 1 & t > 0, \\ 0 & t < 0. \end{cases}$$

A *rectangular pulse* is represented as

$$\text{rect}\left(\frac{t}{T}\right) = u\left(t + \frac{T}{2}\right) - u\left(t - \frac{T}{2}\right).$$

A *ramp signal* is represented as

$$r(t) = \int u(t) dt = tu(t) = \begin{cases} t & t \geq 0, \\ 0 & t < 0. \end{cases}$$

The *unit impulse*  $\delta(t)$  (Dirac delta function) is defined as

$$\int_{t_1}^{t_2} x(t)\delta(t) dt = x(0) \quad t_1 < 0 < t_2.$$

It has the following properties:

- $\delta(t) = 0$  for  $t \neq 0$ ,
- $\int_{-\infty}^{\infty} \delta(t) dt = 1$ ,
- $\delta(-t) = \delta(t)$ , and
- $\delta(0) = \infty$ .

Some  $p(t)$  can be used as a model of a delta function if

- $p(t)$  is even,

- $\lim_{\epsilon \rightarrow 0^+} p(t) = +\infty$  for  $t = 0$ ,
- $\lim_{\epsilon \rightarrow 0^+} p(t) = 0$  for  $t \neq 0$ , and
- $\int_{-\infty}^{\infty} p(t) dt = 1$  for all  $\epsilon > 0$ .

The *sifting property* is represented as

$$\int_{t_1}^{t_2} x(t)\delta(t - t_0) dt = \begin{cases} x(t_0) & t_1 < t_0 < t_2, \\ 0 & \text{otherwise.} \end{cases}$$

If  $x(t)$  is continuous at  $t = t_0$ , the *sampling property* states that

$$x(t)\delta(t - t_0) = x(t_0)\delta(t - t_0).$$

The *scaling property* states that

$$\delta(at + b) = \frac{1}{|a|} \delta\left(t + \frac{b}{a}\right) \quad a \neq 0.$$

The derivative of  $\delta(t)$  is defined as

$$\int_{t_1}^{t_2} x(t)\delta'(t - t_0) dt = -x'(t_0) \quad t_1 < t_0 < t_2.$$

It has the following properties:

- $x(t) * \delta'(t) = \int_{-\infty}^{\infty} x(\tau)\delta'(t - \tau) d\tau = x'(t)$ ,
- $x(t)\delta'(t - t_0) = x(t_0)\delta'(t - t_0) - x'(t_0)\delta(t - t_0)$ ,
- $\int_{-\infty}^t \delta'(\tau - t_0) d\tau = \delta(t - t_0)$ , and
- $\delta'(-t) = -\delta'(t) \rightarrow \int_{-\infty}^{\infty} \delta'(t) dt = 0$ .

## 2. Continuous-time systems

A system is *linear* if the superposition principle can be applied:

$$\alpha x_1(t) + \beta x_2(t) = \alpha y_1(t) + \beta y_2(t).$$

If we have  $x(t) \rightarrow y(t)$ , the system is *time-invariant* if

$$x(t - t_0) \rightarrow y(t - t_0).$$

A system is *memoryless* if the present output only depends on the present input.

- linear time-variant &  $y(t) = k(t)x(t) \rightarrow$  memoryless.
- linear time-invariant &  $y(t) = kx(t) \rightarrow$  memoryless.

A system is *causal* if the output at any time  $t_0$  only depends on the values of the input for  $t \leq t_0$ . Equivalently, if

$$x_1(t) = x_2(t) \quad t \leq t_0$$

implies

$$y_1(t) = y_2(t) \quad t \leq t_0,$$

the system is causal.

A system is *invertible* if the input can be determined from the output alone.

A system is *stable* if some bounded input  $|x(t)| \leq \infty$  causes a bounded output  $|y(t)| \leq \infty$  for all  $t$ .

Convolution: for a linear time-invariant (LTI) system, the response  $y(t)$  with impulse response  $h(t)$  and input  $x(t)$  is given by

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

Some properties of convolution are

- $x(t) * \delta(t) = x(t)$ ,
- $x(t) * u(t) = \int_{-\infty}^t x(\tau) d\tau$ ,
- $x(t) * \delta'(t) = x'(t)$ , and

A LTI system is *memoryless* if

$$h(t) = k\delta(t).$$

A LTI system is *causal* if

$$h(t) = 0 \text{ for all } t < 0.$$

A LTI system described by  $h(t)$  is *invertible* if there exists an  $h_1(t)$  such that

$$h(t) * h_1(t) = \delta(t).$$

A LTI system is *BIBO stable* if

$$\int_{-\infty}^{\infty} |h(\tau)| d\tau < \infty.$$

## 3. Fourier series

The exponential function

$$e^{j\frac{2\pi nt}{T}} \quad n \in \mathbb{Z}$$

can be used to represent  $x(t)$  via the Fourier series expansion, given by

$$x(t) = \sum_{n=-\infty}^{\infty} c_n e^{j\frac{2\pi nt}{T}},$$

where

$$c_n = \frac{1}{T} \int_{t_0}^{t_0+T} x(t) e^{-j\frac{2\pi nt}{T}} dt.$$

Note that  $c_n$  can also be expressed as

$$c_n = |c_n| e^{j\angle c_n}.$$

The plot of  $|c_n|$  is called the *amplitude spectrum* of  $x(t)$  while the plot of  $\angle c_n$  is called the *phase spectrum* of  $x(t)$ .

For real valued  $x(t)$ , we have

$$c_n^* = c_{-n}.$$

The Fourier series of  $x(t)$  can also be expressed via the *trigonometric Fourier series* expansion, given by

$$x(t) = a_0 + \sum_{n=1}^{\infty} \left[ a_n \cos\left(\frac{2\pi nt}{T}\right) + b_n \sin\left(\frac{2\pi nt}{T}\right) \right],$$

where

$$\begin{aligned} a_0 &= \frac{1}{T} \int_{\langle T \rangle} x(t) dt, \\ a_n &= \frac{2}{T} \int_{\langle T \rangle} x(t) \cos\left(\frac{2\pi nt}{T}\right) dt, \\ b_n &= \frac{2}{T} \int_{\langle T \rangle} x(t) \sin\left(\frac{2\pi nt}{T}\right) dt. \end{aligned}$$

Recall that  $\langle T \rangle$  represents any interval of length  $T$ . Also, note that

$$a_0 = c_0,$$

$$a_n = 2\text{Re}\{c_n\}, \quad b_n = -2\text{Im}\{c_n\}.$$

Another way to represent  $x(t)$  is via the *amplitude-phase trigonometric Fourier series* expansion, given by

$$x(t) = c_0 + \sum_{n=1}^{\infty} A_n \cos\left(\frac{2\pi nt}{T} + \phi_n\right),$$

where

$$A_n = 2|c_n|, \quad \phi_n = \angle c_n.$$

If  $x(t)$  is *even*,

$$\begin{aligned} a_0 &= \frac{2}{T} \int_0^{\frac{T}{2}} x(t) dt, \\ a_n &= \frac{4}{T} \int_0^{\frac{T}{2}} x(t) \cos\left(\frac{2\pi nt}{T}\right) dt, \\ b_n &= 0. \end{aligned}$$

If  $x(t)$  is *odd*,

$$\begin{aligned} a_0 &= a_n = 0, \\ b_n &= \frac{4}{T} \int_0^{\frac{T}{2}} x(t) \sin\left(\frac{2\pi nt}{T}\right) dt. \end{aligned}$$

For half-wave odd symmetry where  $x(t+T/2) = -x(t)$ , we have

$$\begin{aligned} a_n &= \begin{cases} \frac{4}{T} \int_0^{\frac{T}{2}} x(t) \cos\left(\frac{2\pi nt}{T}\right) dt, & n \text{ odd}, \\ 0, & n \text{ even}. \end{cases} \\ b_n &= \begin{cases} \frac{4}{T} \int_0^{\frac{T}{2}} x(t) \sin\left(\frac{2\pi nt}{T}\right) dt, & n \text{ odd}, \\ 0, & n \text{ even}. \end{cases} \end{aligned}$$

Let  $x(t)$  and  $y(t)$  be periodic signals with the same period such that

$$\begin{aligned} x(t) &= \sum_{n=-\infty}^{\infty} \beta_n e^{jn\omega_0 t}, \\ y(t) &= \sum_{n=-\infty}^{\infty} \gamma_n e^{jn\omega_0 t}. \end{aligned}$$

Then, via *linearity*,  $z(t) = k_1 x(t) + k_2 y(t)$  can be represented via

$$z(t) = \sum_{n=-\infty}^{\infty} \alpha_n e^{jn\omega_0 t},$$

where  $\alpha = k_1 \beta_n + k_2 \gamma_n$ .

Furthermore, the *product* of the previous two signals  $z(t) = x(t)y(t)$  can be represented as

$$z(t) = \sum_{l=-\infty}^{\infty} \alpha_l e^{jn\omega_0 t},$$

where

$$\begin{aligned} \alpha_l &= \frac{1}{T} \int_{\langle T \rangle} x(t)y(t)e^{-jn\omega_0 t} dt \\ &= \sum_{m=-\infty}^{\infty} \beta_{l-m} \gamma_m. \end{aligned}$$

Using the previous two signals, the *circular convolution* is defined as

$$z(t) = \frac{1}{T} \int_{\langle T \rangle} x(\tau)y(t-\tau) d\tau.$$

The Fourier series coefficients for the circular convolution  $z(t)$  are

$$\alpha_n = \beta_n \gamma_n.$$

*Shift property*: if  $x(t)$  has Fourier series coefficients  $c_n$ , then the coefficients representing  $x(t-\tau)$  are

$$d_n = c_n e^{-jn\omega_0 \tau}.$$

An LTI system is *distortionless* if

$$y(t) = Kx(t-t_d).$$

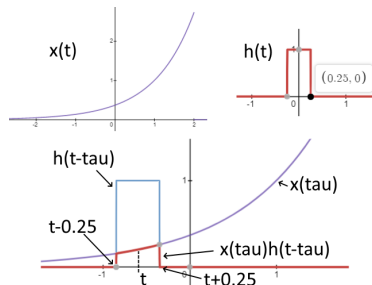
## Examples

• Is  $x(t) = -te^t u(-3t+6)$  an energy signal, power signal, or neither?

$$\begin{aligned} E &= \lim_{L \rightarrow \infty} \int_{-L}^L |-te^t u(-3[t-2])|^2 dt \\ &= \lim_{L \rightarrow \infty} \int_{-L}^2 t^2 e^{2t} dt \\ &= \lim_{L \rightarrow \infty} \left[ \left( \frac{t^2}{2} - \frac{2t}{4} + \frac{1}{4} \right) e^{2t} \right]_{-L}^2 \\ &= \left[ \left( 2 - 1 + \frac{1}{4} \right) e^4 - 0 \right] \\ &= 1.25e^4 \end{aligned}$$

Since  $E$  is finite,  $x(t)$  is an energy signal.

•  $x(t) = e^{t-1} u(-t+2)$  is applied to the input of an LTI system with impulse response  $h(t) = \text{rect}(2t)$ ; sketch  $x(t)$ ,  $h(t)$ , and  $x(\tau)h(\tau-\tau)$ , then determine  $y(t) = x(t) * h(t)$ .



For  $-\infty < t \leq 1.75$ :

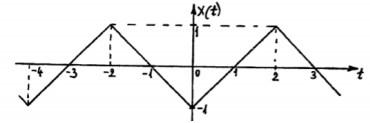
$$\begin{aligned} y(t) &= \int_{t-0.25}^{t+0.25} e^{\tau-1} d\tau \\ &= e^{\tau-1} \Big|_{t-0.25}^{t+0.25} \\ &\approx 0.186e^t. \end{aligned}$$

For  $1.75 < t \leq 2.25$ :

$$\begin{aligned} y(t) &= \int_{t-0.25}^2 e^{\tau-1} d\tau \\ &= e^{\tau-1} \Big|_{t-0.25}^2 \\ &= e - e^{t-1.25}. \end{aligned}$$

For  $t > 2.25$ ,  $y(t) = 0$ .

• Given  $x(t)$  below, find any symmetry exhibited and find the trigonometric Fourier series coefficients of  $x(t)$ .



$x(t)$  exhibits even symmetry and half-wave odd symmetry. This means that  $b_n = 0$  for all  $n$  and  $a_n = 0$  for even  $n$  (and hence,  $a_0 = 0$ ). Due to even symmetry, we have

$$a_n = \frac{4}{T} \int_0^{T/2} x(t) \cos\left(\frac{2\pi nt}{T}\right) dt.$$

Note that  $x(t)$  can be written as

$$x(t) = t - 1 \quad \text{for } 0 \leq t \leq 2.$$

So, since the period of  $x(t)$  is  $T = 4$ ,

$$\begin{aligned} a_n &= \frac{4}{4} \int_0^2 (t-1) \cos\left(\frac{\pi nt}{2}\right) dt \\ &= \int_0^2 t \cos\left(\frac{\pi nt}{2}\right) dt - \int_0^2 \cos\left(\frac{\pi nt}{2}\right) dt \\ &= \frac{2}{n\pi} \int_0^2 \frac{\pi nt}{2} \cos\left(\frac{\pi nt}{2}\right) dt - \frac{\sin\left(\frac{\pi nt}{2}\right)}{\frac{\pi n}{2}} \Big|_0^2 \\ &\rightarrow \text{let } x = \frac{\pi nt}{2} \\ &= \left(\frac{2}{n\pi}\right)^2 \int_0^{n\pi} x \cos x dx - \underbrace{\left(\frac{\sin(n\pi)}{\frac{n\pi}{2}} - 0\right)}_{=0} \\ &= \left(\frac{2}{n\pi}\right)^2 (\cos x + x \sin x) \Big|_0^{n\pi} \\ &= \left(\frac{2}{n\pi}\right)^2 (\cos(n\pi) - 1) \\ &= \begin{cases} -2\left(\frac{2}{n\pi}\right)^2, & n \text{ odd}, \\ 0, & n \text{ even}. \end{cases} \end{aligned}$$

## Miscellaneous Identities

$$\begin{aligned} \sin(t) &= \frac{1}{2j} (e^{jt} - e^{-jt}) \\ \cos(t) &= \frac{1}{2} (e^{jt} + e^{-jt}) \end{aligned}$$