

# ELEC 221 Formula Sheet

## Continuous Time Signals

Even and Odd Components:

$$x_e(t) = \frac{1}{2}[x(t) + x(-t)]$$

$$x_o(t) = \frac{1}{2}[x(t) - x(-t)]$$

A signal is periodic with fundamental period  $T_0$  if

$$x(t + kT_0) = x(t) \quad \forall t \in (-\infty, \infty)$$

Energy:

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

Power:

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

Causality:

- Causal:  $x(t) = 0$  for  $t < 0$ .
- Anti-Causal:  $x(t) = 0$  for  $t \geq 0$ .
- A-Causal or Non-Causal: Both of the above.

## Continuous Time Systems

Dynamic systems have memory. Active systems can deliver energy to the outside world.

Linearity:

$$\mathcal{S}[\alpha x(t) + \beta y(t)] = \alpha \mathcal{S}[x(t)] + \beta \mathcal{S}[y(t)]$$

Time Invariance:

$$\text{If } \mathcal{S}[x(t)] = y(t) \text{ then } \mathcal{S}[x(t \pm \tau)] = y(t \pm \tau).$$

Zero-State Response:

Due to the input as the initial conditions are zero.

Zero-Input Response:

Due to the initial conditions as the input is zero.

Convolution:

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

Causality:

A continuous time system  $\mathcal{S}$  is causal if whenever  $x(t) = 0$  and there are no initial conditions,  $y(t) = 0$  and the output  $y(t)$  does not depend on future inputs.

Bounded-Input Bounded-Output Stability:

If an input  $x(t)$  bounded then the output of an BIBO system is also bounded.

$$\int_{-\infty}^{\infty} |h(t)| dt < \infty$$

## Laplace Transform

$$s = \sigma + j\omega$$

Eigenfunction Property:

$$\mathcal{S}[e^{s_0 t}] = H(s_0)e^{s_0 t}$$

One Sided Laplace Transform:

$$F(s) = \mathcal{L}[f(t)u(t)] = \int_{0^-}^{\infty} f(t)e^{-st} dt$$

Signal Support	ROC
Finite support	Entire s-plane.
Causal function	$\sigma > \max(\sigma_i), -\infty < \omega < \infty$
Anti-causal	$\sigma < \min(\sigma_i), -\infty < \omega < \infty$
Non-causal	$\mathcal{R} = \mathcal{R}_{\text{causal}} \cap \mathcal{R}_{\text{anti-causal}}$

Initial Value Theorem:

$$f(0+) \Leftrightarrow \lim_{s \rightarrow \infty} sF(s)$$

Final Value Theorem:

$$\lim_{t \rightarrow \infty} f(t) \Leftrightarrow \lim_{s \rightarrow 0} sF(s)$$

Bounded-Input Bounded-Output Stability:

If the region of convergence contains the  $j\omega$ -axis, then the system is BIBO stable.

## Fourier Series

Fourier analysis in the steady state.

Eigenfunction Property:

$$\mathcal{S}[e^{j\omega_0 t}] = H(j\omega_0)e^{j\omega_0 t}$$

$$x(t) = \sum_k X_k e^{j\omega_k t} \implies y(t) = \sum_k X_k H(j\omega_k) e^{j\omega_k t} \\ = \sum_k X_k |H(j\omega_k)| e^{j(\omega_k t + \angle H(\omega_k))}$$

Fourier Series Coefficients (for any  $t_0$ ):

$$X_k = \frac{1}{T_0} \int_{t_0}^{t_0+T_0} x(t) e^{-jk\omega_0 t} dt$$

Parseval's Power Relation (for any  $t_0$ ):

$$P = \frac{1}{T_0} \int_{t_0}^{t_0+T_0} |x(t)|^2 dt = \sum_{k=-\infty}^{\infty} |X_k|^2$$

Symmetry of Line Spectra:

$$|X_k| = |X_{-k}|$$

$$\angle X_k = -\angle X_{-k}$$

Trigonometric Fourier Series:

$$x(t) = X_0 + 2 \sum_{k=1}^{\infty} |X_k| \cos(k\omega t + \Theta_k)$$

$$x(t) = c_0 + 2 \sum_{k=1}^{\infty} [c_k \cos(k\omega_0 t) + d_k \sin(k\omega_0 t)]$$

$$c_k = \frac{1}{T_0} \int_{t_0}^{t_0+T_0} x(t) \cos(k\omega_0 t) dt \quad k = 0, 1, 2, \dots$$

$$d_k = \frac{1}{T_0} \int_{t_0}^{t_0+T_0} x(t) \sin(k\omega_0 t) dt \quad k = 1, 2, 3, \dots$$

$$\Theta_k = -\arctan(d_k/c_k)$$

Fourier Coefficients from Laplace Transform:

If  $x_1(t)$  is a single period of  $x(t)$ , then

$$X_k = \frac{1}{T_0} \mathcal{L}[x_1(t)]|_{s=jk\omega_0}$$

Response of LTI Systems to Periodic Signals:

If the input to an LTI system has Fourier Series  $x(t) = X_0 + 2 \sum_{k=1}^{\infty} |X_k| \cos(k\omega t + \angle X_k)$ , then the steady state response is  $y(t) = X_0 |H(j\omega)| +$

$$2 \sum_{k=1}^{\infty} |X_k| |H(jk\omega_0)| \cos(k\omega_0 t + \angle X_k + \angle H(jk\omega_0))$$

## Fourier Transform

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

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

Fourier Transform from Laplace Transform (if  $X(s)$  contains the  $j\omega$ -axis):

$$\mathcal{F}[x(t)] = \mathcal{L}[x(t)]|_{s=j\omega} = X(s)|_{s=j\omega}$$

Fourier Transform of Periodic Signals:

$$\sum_k X_k e^{jk\omega_0 t} \xLeftrightarrow{\mathcal{F}} \sum_k 2\pi \delta(\omega - k\omega_0)$$

Parseval's Energy Relation:

$$E = \int_{-\infty}^{\infty} |x(t)|^2 dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} |X(\omega)|^2 d\omega$$

Symmetry of Spectral Representations:

$$|X(\omega)| = |X(-\omega)|$$

$$\text{Re}[X(\omega)] = \text{Re}[X(-\omega)]$$

$$\angle X(\omega) = -\angle X(-\omega)$$

$$\text{Im}[X(\omega)] = -\text{Im}[X(-\omega)]$$

## Sampling Theory

$$x_s(t) = x(nT_s) = x(t)|_{t=nT_s} = x(t) \sum_n \delta(t - nT_s)$$

$$X_s(\omega) = \frac{1}{T_s} \sum_{k=-\infty}^{\infty} X(\omega - k\omega_s)$$

Nyquist-Shannon Sampling Rate:

$$\omega_s = \frac{2\pi}{T_s} \geq 2\omega_{\max}$$

Aliasing occurs if  $\omega_s < 2\omega_{\max}$ .

Reconstruction  $X(\omega) = X_s(\omega)H_{\text{lp}}(\omega)$ :

$$H_{\text{lp}}(\omega) = \begin{cases} T_s & -\frac{\omega_s}{2} \leq \omega \leq \frac{\omega_s}{2} \\ 0 & \text{otherwise} \end{cases}$$

(Inclusive bounds. If represented by a unit step function the bounds are inclusive for filters (Refer to lecture notes))

Signal Reconstruction from Sinc Interpolation:

$$x_r(t) = \sum_{n=-\infty}^{\infty} x(nT_s) \frac{\sin(\pi(t - nT_s)/T_s)}{\pi(t - nT_s)/T_s}$$

## Discrete Time Signals

Define  $x[n] = x(nT_0)$ .

$$x[n] = \sum_{k=-\infty}^{\infty} x[k]\delta[n-k]$$

Periodicity:

$$x[n+kN] = x[n] \quad \forall k \in \mathbb{Z}$$

When sampling an analog sinusoid of fundamental period  $T_0$ , we obtain a periodic discrete sinusoid provided that  $m, N$  not divisible by each-other:

$$T_s/T_0 = m/N$$

Aliasing occurs if:

$$T_s > T_0/2$$

Energy:

$$E = \sum_{n=-\infty}^{\infty} |x[n]|^2$$

Power:

$$P_x = \lim_{N \rightarrow \infty} \frac{1}{2N+1} \sum_{n=-N}^N |x[n]|^2$$

Convolutional Sum:

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

Bounded-Input Bounded-Output Stability:

$$\sum_k |h[n]|^2 < \infty$$

Solution to Autoregressive Discrete System:

$$y[n] = ay[n-1] + bx[n], n \geq 0$$

$$y[n] = \sum_{k=0}^n ba^k x[n-k], n \geq 0$$

## Z-Transform

$$\mathcal{Z}[x(nT_s)] = \mathcal{L}[x_s(t)]|_{z=e^{sT_s}} = \sum_n x(nT_s)z^{-n}$$

Convergence:

$$|X(z)| = \sum_n |x[n]|r^{-n} < \infty$$

Initial Value Theorem:

$$x[0] = \lim_{z \rightarrow \infty} X(z)$$

Final Value Theorem:

$$\lim_{n \rightarrow \infty} x[n] = \lim_{z \rightarrow 1} (z-1)X(z)$$

BIBO Stability:

If the ROC contains radius  $z = 1$ , then the system is BIBO stable.

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<https://github.com/DonneyF/formula-sheets>

## Two-Sided Z-Transforms

$f[n]$	$F(z)$	ROC
$-u[-n-1]$	$\frac{1}{1-z^{-1}}$	$ z  < 1$
$-\alpha^n u[-n-1]$	$\frac{1}{1-\alpha z^{-1}}$	$ z  <  \alpha $
$-n\alpha^n u[-n-1]$	$\frac{\alpha z^{-1}}{(1-\alpha z^{-1})^2}$	$ z  <  \alpha $
$\alpha^{ n },  \alpha  < 1$	$\frac{1}{1-\alpha z^{-1}} - \frac{1}{1-\alpha^{-1}z^{-1}}$	$ \alpha  < z < \left \frac{1}{\alpha}\right $

## Interconnection of LTI Systems

Connection	Time	Laplace/Z
Series	$[h_1 * h_2](t)$	$H_1(s)H_2(s)$
Parallel	$h_1(t) + h_2(t)$	$H_1(s) + H_2(s)$

## Partial Fraction Decomposition

Fraction	Partial Fraction	Solution
$\frac{px+q}{(x-a)(x-b)}$	$\frac{A}{x-a} + \frac{B}{x-b}$	$A = \frac{pa+q}{a-b} \quad B = \frac{pb+q}{b-a}$
$\frac{px+q}{(x-a)^2}$	$\frac{A}{x-a} + \frac{B}{(x-a)^2}$	$A = p \quad B = pa+q$
$\frac{px^2+qx+r}{(x-a)(x-b)(x-c)}$	$\frac{A}{x-a} + \frac{B}{x-b} + \frac{C}{x-c}$	$A = \frac{pa^2+qa+r}{(a-b)(a-c)} \quad B = \frac{pb^2+qb+r}{(b-a)(b-c)} \quad C = \frac{pc^2+qc+r}{(c-a)(c-b)}$
$\frac{px^2+qx+r}{(x-a)^2(x-b)}$	$\frac{A}{x-a} + \frac{B}{(x-a)^2} + \frac{C}{x-b}$	
$\frac{px^2+qx+r}{(x-a)(x^2+bx+c)}$	$\frac{A}{x-a} + \frac{Bx+C}{x^2+bx+c}$	

## Misc. Identities

$$\sum_{k=0}^n x^k = \frac{1-x^{n+1}}{1-x} \xrightarrow{n \rightarrow \infty \text{ and } x < 1} \frac{1}{1-x}$$

$$\cos \theta = \frac{e^{j\theta} + e^{-j\theta}}{2}$$

$$\sin \theta = \frac{e^{j\theta} - e^{-j\theta}}{2j}$$