## TOPIC 3: Elementary Properties of Z transforms

### Linearity Property

The Z - Transform is linear

i) $Z\{af(n)+bg(n)\} = aZ\{F(n)\} + bZ\{g(n)\}$

ii) $Z\{af(t)\pm bg(t)\} = aZ\{f(t)\} \pm bZ\{g(t)\}$

Proof i):

W.K.T. $Z[f(n)] = \sum_{n=0}^{\infty} f(n) z^{-n}$

$$Z\{af(n)+bg(n)\} = \sum_{n=0}^{\infty} \{af(n)+bg(n)\} z^{-n}$$

$$= a\sum_{n=0}^{\infty} f(n) z^{-n} + b\sum_{n=0}^{\infty} g(n) z^{-n}$$

Proof:

w.k.T. $Z[f(t)] = \sum_{n=0}^{\infty} f(nT) z^{-n}$

$$Z[a f(t) \pm b g(t)] = \sum_{n=0}^{\infty} [a f(nT) \pm b g(nT)] z^{-n}$$

$$= \sum_{n=0}^{\infty} a f(nT) z^{-n} \pm b g(nT) z^{-n}$$

$$= a \sum_{n=0}^{\infty} f(nT) z^{-n} \pm b \sum_{n=0}^{\infty} g(nT) z^{-n}$$

$$= a Z[f(t)] \pm b Z[g(t)]$$

## First Shifting Theorem

i, If $Z\{f(t)\} = F(z)$, then

$$Z\{e^{-at} f(t)\} = F[z e^{aT}]$$

ii, If $Z\{f(t)\} = F(z)$ then,

$$Z\{e^{at} f(t)\} = F[z e^{-aT}]$$

iii, $Z\{f(t)\} = F(z)$ then, $Z\{a^n f(t)\} = F[z/a]$

iv, $Z\{f(n)\} = F(z)$ then, $Z\{a^n f(n)\} = F[z/a]$

Proof:

i, Given, $F(z) = Z\{f(t)\} = \sum_{n=0}^{\infty} f(nT) z^{-n}$

$$Z\{e^{-at} f(t)\} = \sum_{n=0}^{\infty} e^{-anT} f(nT) z^{-n}$$

$$= \sum_{n=0}^{\infty} f(nT) (e^{aT})^{-n} z^{-n}$$

$$= \sum_{n=0}^{\infty} f(nT) (z e^{at})^{-n}$$

$$= Z[f(t)]_{z \to z e^{at}}$$

$$= F[z]_{z \to z e^{at}}$$

ii, Given, $F(z) = z\{f(t)\} = \sum_{n=0}^{\infty} f(nT)\, z^{-n}$

$$z\{e^{at} f(t)\} = \sum_{n=0}^{\infty} e^{anT} f(nT)\, z^{-n}$$

$$= \sum_{n=0}^{\infty} f(nT)\, (e^{-aT})^{-n}\, z^{-n}$$

$$= \sum_{n=0}^{\infty} f(nT)\, (ze^{-aT})^{-n}$$

$$= z[f(t)]_{z \to ze^{-aT}}$$

$$= F(z)_{z \to ze^{-aT}}$$

$$= F[ze^{-aT}]$$

$$\therefore z\{e^{at} f(t)\} = F[ze^{-aT}]$$

iii, Given, $F(z) = z\{f(t)\} = \sum_{n=0}^{\infty} f(nT)\, z^{-n}$

$$z\{a^n f(t)\} = \sum_{n=0}^{\infty} a^n f(nT)\, z^{-n}$$

$$= \sum_{n=0}^{\infty} f(nT)\, \frac{z^{-n}}{a^{-n}}$$

$$= \sum_{n=0}^{\infty} f(nT)\, (z/a)^{-n}$$

$$= z\{f(t)\}_{z \to z/a}$$

$$= F[z]_{z \to z/a}$$

$$= F[z/a]$$

iv, Given,

$$F(z) = z\{f(n)\} = \sum_{n=0}^{\infty} f(n) z^{-n}$$

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

$$= \sum_{n=0}^{\infty} f(n) \frac{z^{-n}}{a^{-n}}$$

$$= \sum_{n=0}^{\infty} f(n) \left(\frac{z}{a}\right)^{-n}$$

$$= z\{f(n)\}_{z \to z/a}$$

$$= F[z]_{z \to z/a}$$

$$= F[z/a]$$

$$\therefore z\{a^n f(n)\} = F[z/a]$$

## Differentiation in the Z - Domain

i, $z\{n f(t)\} = -z \frac{d}{dz} F(z)$

ii, $z\{n f(n)\} = -z \frac{d}{dz} F(z)$

**Proof:**

i, $z\{n f(t)\} = -z \frac{d}{dz} F(z)$

W.K.T. $F(z) = z\{f(t)\}$

$$F(z) = \sum_{n=0}^{\infty} f(nT) z^{-n}$$

$$\frac{d}{dz} F(z) = \sum_{n=0}^{\infty} f(nT) (-n) z^{-n-1}$$

$$\frac{d}{dz} F(z) = -\sum_{n=0}^{\infty} f(nT)\; n \cdot \frac{z^{-n}}{z}$$

$$-z \frac{d}{dz} F(z) = \sum_{n=0}^{\infty} f(nT)\; n\, z^{-n}$$

$$-z \frac{d}{dz} F(z) = z\{n f(t)\}$$

$$\therefore -z \frac{d}{dz} F(z) = z\{n f(t)\}$$

ii) $z\{n f(n)\} = -z \frac{d}{dz} F(z)$

w.k.T

$$F(z) = z\{f(t)\}$$

$$F(z) = \sum_{n=0}^{\infty} f(n) z^{-n}$$

$$\frac{d}{dz} F(z) = \sum_{n=0}^{\infty} f(n) \cdot -n \cdot z^{-n} \cdot z^{-1}$$

$$= -\sum_{n=0}^{\infty} f(n) \cdot n \frac{z^{-n}}{z}$$

$$-z \frac{d}{dz} F(z) = \sum_{n=0}^{\infty} f(n) \cdot n z^{-n}$$

$$= z\{n f(n)\}$$

$$\therefore -z \frac{d}{dz} F(z) = z\{n f(n)\}$$

## Second Shifting Theorem

i, If $z[f(t)] = F(z)$ then,

$$z[f(t+T)] = z\,F(z) - z\,f(0)$$

Proof:

$$z\{f(t)\} = \sum_{n=0}^{\infty} f(nT)\, z^{-n}$$

$$z[f(t+T)] = \sum_{n=0}^{\infty} f(nT+T)\, z^{-n}$$

$$= \sum_{n=0}^{\infty} \left(f\,(n+1)T\right) z^{-n}$$

$$= \sum_{n=0}^{\infty} \left(f\,(n+1)T\right) z^{-n}\, z^{1}\cdot z^{-1}$$

$$= z\sum_{n=0}^{\infty} \left(f\,(n+1)T\right) z^{-(n+1)} \qquad \boxed{\because m = n+1}$$

$$= z\sum_{m=1}^{\infty} f(mT)\, z^{-m}$$

$$= z\left[\sum_{n=0}^{\infty} f(mT)\, z^{-m} - f(0)\right]$$

$$= z\left[F(z) - f(0)\right]$$

$$= z\,F(z) - z\,f(0)$$

$$\therefore z[f(t+T)] = z\,F(z) - z\,f(0)$$

ii, $Z\{f(n+1)\} = F(z) - z f(0)$

Proof:

w.k.t. $F(z) = Z\{f(n)\} = \sum_{n=0}^{\infty} f(n) z^{-n}$

$$Z\{f(n+1)\} = \sum_{n=0}^{\infty} f(n+1) z^{-n}$$

$$= \sum_{n=0}^{\infty} f(n+1)\, z^{-n} \cdot z^{1} \cdot z^{-1}$$

$$= z \sum_{n=0}^{\infty} f(n+1)\, z^{-(n+1)} \quad (\text{Take } m = n+1)$$

$$= z \sum_{m=1}^{\infty} f(m)\, z^{-m}$$

$$= z \sum_{m=0}^{\infty} \left[ f(m)\, z^{-m} - f(0) \right]$$

$$= z \left[ F(z) - f(0) \right]$$

$$= z F(z) - z f(0)$$

NOTE 1:

$Z[f(t)] = F(z)$ then,

$$Z\, f(t+kT) = Z\left[ f(n+k)T \right]$$

$$= z^{k} \left[ f(z) - f(0T) - \frac{F(1 \cdot T)}{z} - \frac{F(2 \cdot T)}{z^2} - \dots + \frac{f(k-1)T}{z^{k-1}} - \right]$$

NOTE 2:

$$Z\left[f(n+2)\right] = z^{2}\left[ f(z) - f(0) - f(1) z^{-1} \right]$$