Author: Dr. Shi Guo Email: guoshi1984@hotmail.com

1 Basic of Fourier Transform

If $f(x) = f(x+T)$ then $f(x)$ can be written as

$$f(x) = \sum_{-\infty}^{+\infty} c_k e^{\frac{2\pi ikx}{T}}$$

i is the imaginary unit, and k is an integer. The above expression is eligible

$$e^{\frac{2\pi ikx}{T}} = e^{\frac{2\pi ik(x+T)}{T}}$$

Each basis $e^{\frac{2\pi i}{T}}$ represents a signal with frequency $F_k = \frac{k}{T}$. So the interval between each adjacent frequency $\Delta F = \frac{1}{T}$.

Based on orthogonality,

$$c_k = \frac{1}{T}\int_0^T f(x)e^{-i\frac{2\pi kx}{T}}dx$$

The above is the Fourier transform in continuous case, in discrete case If $x = n\Delta t$, where n = 1...N, and $T = N\Delta t$, then the Fourier series can be written as

$$\begin{aligned} f(n) &= \sum_{-\infty}^{+\infty} c_k e^{\frac{2\pi ikn\Delta t}{N\Delta t}} \\ &= \sum_{-\infty}^{+\infty} c_k e^{\frac{2\pi ikn}{N}} \end{aligned}$$

$$c_k = \frac{1}{N\Delta t}\sum_{n=1}^{N} f(n\Delta t)e^{-i2\pi k\frac{1}{N\Delta t}n\Delta t}d(n\Delta t) = \frac{1}{N}\sum_{n=1}^{N} f(n)e^{-i2\pi k\frac{n}{N}}$$

This is the discrete Fourier transform.

$$\Delta F = \frac{1}{T} = \frac{1}{N\Delta t}$$

N is the total sample within time T.

Properties

1) To be eligible, f(x) has to be a period function with time T(with frequency $F = \frac{1}{T}$) in both continuous case and discrete case. The requirement in discrete case leads to uniform sampling theorem used in signal processing. The total sampling time $T_{sampling}$ has to be an integer multiple of T.

$$T_{sampling} = MT$$

while $T = \frac{N}{F_s}$ So

$$MT = N\delta t$$

if we let $\delta t = \frac{1}{F_s}$, where F_s is the sampling frequency, and $T = \frac{1}{F}$, we have

$$\frac{M}{F} = \frac{N}{F_s}$$

2) If $f(x)$ is real, which means $f(x) = f^*(x)$. We then substitute Fourier series for both $f(x)$ and $f*(x)$,

$$\sum_{-\infty}^{+\infty} c_k e^{2\pi i \frac{1}{T} kx} = \sum_{-\infty}^{+\infty} c_k^* e^{-2\pi i \frac{1}{T} kx} \tag{1}$$

Since the summation on the right hand side is from $-\infty$ to ∞, it is eligible to replace k with k.

$$\sum_{-\infty}^{+\infty} c_k^* e^{-2\pi i \frac{1}{T} kx} = \sum_{\infty}^{-\infty} c_{-k}^* e^{2\pi i \frac{1}{T} kx} \tag{2}$$

Combine the above two equations 1 and 2, we can see $c_k = c_{-k}^*$. This means they are complex conjugate: their magnitude are equal, their phase are opposite. Namely $||c_k|| = ||c_{-k}||$, $\phi(c_k) = \phi(c_{-k})$.
3) Connection between complex representation and real representation.
We have shown that for real signal $c_k = c_{-k}^*$ and $c_k = |c_k|e^{j\theta_k}$, $c_{-k} = |c_k|e^{-j\theta_k}$. And in complex representation, we can combine the term with index k and -k,

$$c_k e^{j2\pi k F_0 t} + c_{-k} e^{-j2\pi k F_0 t} = 2|c_k| cos(2\pi k F_0 t + \theta_k)$$

$$\begin{aligned} f(x) &= \sum_{-\infty}^{+\infty} c_k e^{\frac{2\pi i k x}{T}} \\ &= c_0 + 2\sum_{k=1}^{\infty} |c_k| cos(2\pi k F_0 t + \theta_k) \\ &= a_0 + \sum_{k=1}^{\infty} (a_k cos(2\pi k F_0 t) - b_k sin(2\pi k F_0 t)) \end{aligned}$$

where $a_0 = c_0$, $a_k = 2|c_k|cos\theta_k$, $b_k = 2|c_k|sin\theta_k$. 4) $c_k = c_{k+N}$. So when a signal contains frequency component no larger than B, in other words, the bandwidth of the signal is $2B(-B(to)B)$, then in order to capture the whole bandwidth of the signal, $N\Delta f > 2B$. This leads to Nyquist sampling theorem $F_s > 2B(bandwidth)$.

5) Power density

$$
\begin{aligned}
P_x &= \frac{1}{T}\int |x(t)|^2 dt \\
&= \frac{1}{T}\int x(t)\sum_{-\infty}^{\infty} c_k^* e^{-j2\pi k F_0 t} \\
&= \sum_{-\infty}^{\infty} c_k^* [\frac{1}{T}\int x(t) e^{-j2\pi k F_0 t}] \\
&= \sum_{-\infty}^{\infty} |c_k|^2
\end{aligned}
$$

When signal is real, then

$$
\begin{aligned}
P_x &= \sum_{-\infty}^{\infty} |c_k|^2 \\
&= a_0^2 + \frac{1}{2}\sum_{k=1}^{\infty}(a_k^2 + b_k^2)
\end{aligned}
$$

2 Fast Fourier Transform

$$X_k = \sum_{n=0}^{N-1} x_n e^{-i2\pi k \frac{n}{N}}$$

let

$$u_k = e^{-i2\pi k \frac{n}{N}}$$

then we have the basis orthogonality

$$u_{k1}^T u_{k2} = N\delta_{k_1,k_2}$$

We recognize we can write X_k with even index terms and odd index terms

$$\begin{aligned}
X_k = & \text{ Even index parts } + \text{ Odd index parts} \\
= & \sum_{m=0}^{N/2-1} x_{2m} e^{-\frac{2\pi i}{N} 2mk} + \sum_{m=0}^{N/2-1} x_{2m+1} e^{-\frac{2\pi i}{N}(2m+1)k} \\
= & \sum_{m=0}^{N/2-1} x_{2m} e^{-\frac{2\pi i}{N/2} mk}
\end{aligned}$$

(We can view this as Fourier Transform of N/2 even indexed points, where k is 0,1N/2)

$$+ e^{-\frac{2\pi i}{N} k}$$

$$\sum_{m=0}^{N/2-1} x_{2m+1} e^{-\frac{2\pi i}{N/2} mk}$$

(We can view this as Fourier Transform of N/2 odd indexed points, where k is 0,1N/2)

(Since each part is a Fourier transform of N/2 points, k has to be smaller than N/2)

$$= E_k + e^{-\frac{2\pi i}{N} k} O_k$$

As noted, the above derivation is for $k < N/2$, a very similar derivation for $N/2 <= k < N$ leads to

$$X_{k+N/2} = E_k - e^{-\frac{2\pi i}{N} k} O_k$$

Now we have divided the FFT of N points to two FFT with N/2 points Keep going till we reach the size to one, then combine together recursively.

2.1 Connection with Uncertainty Principle

Relationship between time length and frequency bandwidth
We consider a few examples
1) We consider a function g(t) which is infinitely long in time domain

$$g(t) = cos(2\pi f_0 t)$$

Its Fourier transform is

$$\begin{aligned}
F(f) &= \int \frac{e^{i2\pi f_0 t} + e^{-i2\pi f_0 t}}{2} e^{i2\pi f t} dt \\
&= \int \frac{1}{2} e^{i2\pi t(f_0+f)} dt + \int \frac{1}{2} e^{i2\pi t(f-f_0)} dt \\
&= \frac{1}{2}\delta(f+f_0) + \frac{1}{2}\delta(f-f_0)
\end{aligned}$$

The last line is based on $\int_{-\infty}^{\infty} e^{i2\pi f t} = \delta(f)$.
Since the delta function has width zero, so the the bandwidth in frequency domain is zero. We see a signal which is infinitely long in time domain has zero bandwidth in frequency domain. 2) We consider a function g(t) which has zero

width in time, namely an impulse function.

$$g(t) = \delta(t)$$

Since this function is not a periodic function, we assume its period is infinity. Its Fourier transform is

$$F(f) = \int_{-\infty}^{\infty} \delta(t)e^{-2\pi ft} = 1$$

Now we see a signal which has zero width in time has infinitely long frequency bandwidth. This leads to the uncertainty principle.
Uncertainty Principle In quantum mechanics, if there is a particle with position x and momentum p, then uncertainty principle states

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

Similar relationship holds for time t and Energy.

$$\Delta t \Delta E \geq \frac{\hbar}{2}$$

We can modify this expression to get the time and frequency relationship in our Fourier transform. Since $E = \hbar\omega$. Then

$$\Delta t \Delta \omega \geq \frac{1}{2}$$