ELEC 221 Lecture 12
The discrete-time Fourier transform

Tuesday 18 October 2022

Announcements

- No quiz today (quizzes resume next week)
- Assignment 4 will be made available this week
- Midterm grading underway

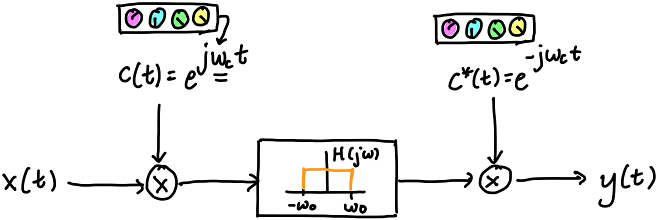
Midterm postmortem...

Last time

We saw the multiplication property of the CT Fourier transform:

$$\begin{aligned} y(t) &= h(t) * x(t) \\ Y(j\omega) &= H(j\omega)X(j\omega) \end{aligned}$$

$$\begin{aligned} r(t) &= s(t)p(t) \\ R(j\omega) &= \frac{1}{2\pi}\int_{-\infty}^{\infty} S(j\theta)P(j(\omega-\theta))d\theta \end{aligned}$$



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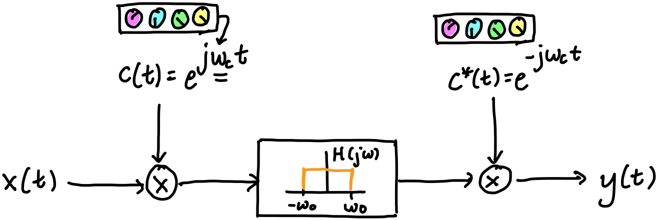


We saw how the CT Fourier spectrum behaves under differentiation and integration:

$$x(t) \quad \overset{\mathcal{F}}{\longleftrightarrow} \quad X(j\omega)$$

$$\frac{dx(t)}{dt} \quad \overset{\mathcal{F}}{\longleftrightarrow} \quad j\omega X(j\omega)$$

$$\int_{-\infty}^{t} x(\tau)d\tau \quad \overset{\mathcal{F}}{\longleftrightarrow} \quad \frac{1}{j\omega}X(j\omega) + \pi X(0)\delta(\omega)$$

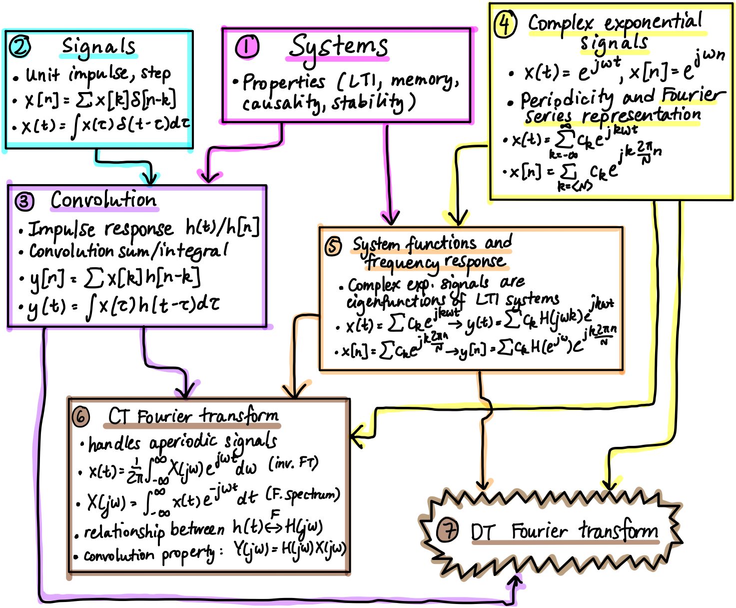
Last time

We leveraged differentiation/integration and the convolution property to compute impulse and frequency response for systems described by ODEs.

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

$$H(j\omega) = \frac{Y(j\omega)}{X(j\omega)} = \frac{\sum_{k=0}^{M} \beta_k (j\omega)^k}{\sum_{k=0}^{N} \alpha_k (j\omega)^k}$$

Where are we going?



Today

Learning outcomes:

- Compute the DT Fourier transform of non-periodic DT signals
- State key properties of the DTFT
- Leverage convolution properties of DTFT to analyze the behaviour of LTI systems

On Thursday and Tuesday:

- Learn how the fast Fourier transform algorithm works
- Hands-on with the NumPy FFT module: image processing

Recap: CT Fourier series and transform

Fourier series pair:

$$x(t) = \sum_{k=-\infty}^{\infty} c_k e^{jk\omega t} \qquad c_k = \frac{1}{T}\int_T x(t)e^{-j\omega t}dt$$

Fourier transform pair:

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

Recap: DT Fourier series

When a DT signal is periodic (with period N) it can be represented using only the integer harmonics at the same frequency.

DT synthesis equation:

$$x[n] = \sum_{k=\langle N \rangle} c_k e^{jk\frac{2\pi n}{N}}$$

DT analysis equation:

$$c_k = \frac{1}{N} \sum_{n=\langle N \rangle} x[n] e^{-jk\frac{2\pi n}{N}}$$

The discrete-time Fourier transform (DTFT) is the generalization of the Fourier series representation to **aperiodic** signals.

We derive it just like we did in CT:

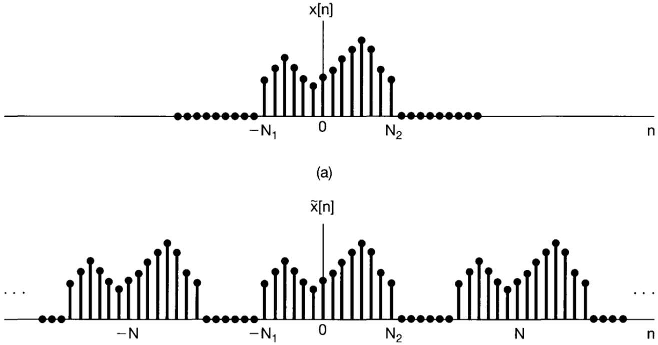


Image credit: Oppenheim chapter 5.1

The DT Fourier transform

Suppose $\tilde{x}[n]$ is a periodic extension of $x[n]$. We can write it as a DT Fourier series:

$$\tilde{x}[n] = \sum_{k=\langle N \rangle} c_k e^{jk\frac{2\pi n}{N}}$$

$$c_k = \frac{1}{N} \sum_{n=\langle N \rangle} \tilde{x}[n] e^{-jk\frac{2\pi n}{N}}$$

We could just as well change the bounds of the sum to include where our signal actually is:

$$\tilde{x}[n] = \sum_{k=-N_1}^{N_2} c_k e^{jk\frac{2\pi n}{N}}$$

$$c_k = \frac{1}{N} \sum_{n=-N_1}^{N_2} \tilde{x}[n] e^{-jk\frac{2\pi n}{N}}$$

Now, what happens if we make the period larger and larger (i.e., increase the spacing?)

$$c_k = \frac{1}{N} \sum_{n=-N_1}^{N_2} \tilde{x}[n] e^{-jk\frac{2\pi n}{N}}$$

If $N \to \infty$, for any finite n, our new signal $\tilde{x}[n]$ basically just looks like our old signal:

$$c_k = \frac{1}{N} \sum_{n=-N_1}^{N_2} x[n] e^{-jk\frac{2\pi n}{N}}$$

But since $x[n] = 0$ outside this range, we can change the bounds of the sum:

$$c_k = \frac{1}{N} \sum_{n=-\infty}^{\infty} x[n] e^{-jk\frac{2\pi n}{N}}$$

The DT Fourier transform

We have

$$c_k = \frac{1}{N} \sum_{n=-\infty}^{\infty} x[n] e^{-jk\frac{2\pi n}{N}}$$

Let's define

$$X(e^{j\omega}) = \sum_{n=-\infty}^{\infty} x[n] e^{-j\omega n} \quad (\omega = 2\pi/N)$$

Then

$$c_k = \frac{1}{N} X(e^{jk\omega})$$

Substituting

$$c_k = \frac{1}{N} X(e^{jk\omega})$$

back into the original synthesis equation for $\tilde{x}[n]$ yields

$$\begin{aligned}
\tilde{x}[n] &= \sum_{k=\langle N \rangle} \frac{1}{N} X(e^{jk\omega}) e^{jk\omega n} \\
&= \frac{1}{2\pi} \sum_{k=\langle N \rangle} X(e^{jk\omega}) e^{jk\omega n} \omega
\end{aligned}$$

Now what happens as $N \to \infty$?

The DT Fourier transform

As $N \to \infty$, $\omega \to 0$.

Consider what we are summing:

$$\tilde{x}[n] = \frac{1}{2\pi} \sum_{k=0}^{N-1} X(e^{jk\omega}) e^{jk\omega n} \omega$$

This is going to be a sum of terms like $X(e^{jk\omega}) e^{jk\omega n} \omega$ for very small ω. We can convert the sum to an integral:

$$\tilde{x}[n] = \frac{1}{2\pi} \int X(e^{jk\omega}) e^{jk\omega n} d\omega$$

Recall though that in this range, $\tilde{x}[n]$ is basically $x[n]$, and we only need to integrate from over 0 to 2π. The result is the **DT Fourier transform pair**.

Inverse DTFT (synthesis equation):

$$x[n] = \frac{1}{2\pi}\int_{2\pi} X(e^{jk\omega})e^{jk\omega n}d\omega$$

DTFT (analysis equation):

$$X(e^{j\omega}) = \sum_{n=-\infty}^{\infty} x[n]e^{-j\omega n}$$

Example: DTFT of a square pulse

Let's compute the DTFT of the DT signal

$$x[n] = \begin{cases} 1 & |n| \leq N_1 \\ 0 & |n| > N_1 \end{cases}$$

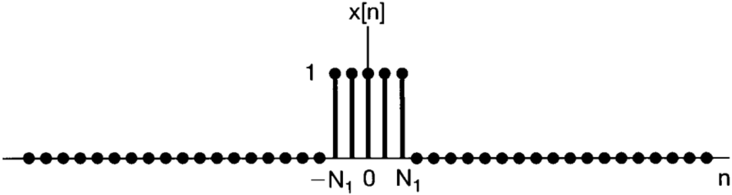


Image credit: Oppenheim chapter 5.1

$$x(t) = \begin{cases} 1 & |t| < T_1, \\ 0 & |t| > T_1 \end{cases}$$

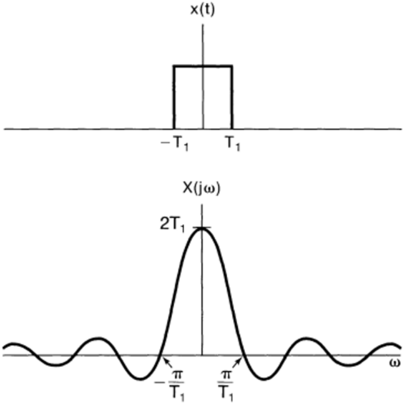


Image credit: Oppenheim chapter 4.1

Example: DTFT of a square pulse

$$x[n] = \begin{cases} 1 & |n| \leq N_1 \\ 0 & |n| > N_1 \end{cases}$$

Compute the DTFT:

$$\begin{aligned} X(e^{j\omega}) &= \sum_{n=-\infty}^{\infty} x[n] e^{-j\omega n} \\ &= \sum_{n=-N_1}^{N_1} e^{-j\omega n} \end{aligned}$$

How do we evaluate this sum?

Example: DTFT of a square pulse

Change variable in the summation to $m = n + N_1$

$$
\begin{aligned}
X(e^{j\omega}) &= \sum_{m=0}^{2N_1} e^{-j\omega(m-N_1)} \\
&= e^{j\omega N_1} \sum_{m=0}^{2N_1} e^{-j\omega m}
\end{aligned}
$$

Use our handy identity:

$$\sum_{k=0}^{N} z^k = \frac{1 - z^{N+1}}{1 - z}$$

$$\Rightarrow X(e^{j\omega}) = e^{j\omega N_1} \frac{1 - e^{-j\omega(2N_1+1)}}{1 - e^{-j\omega}}$$

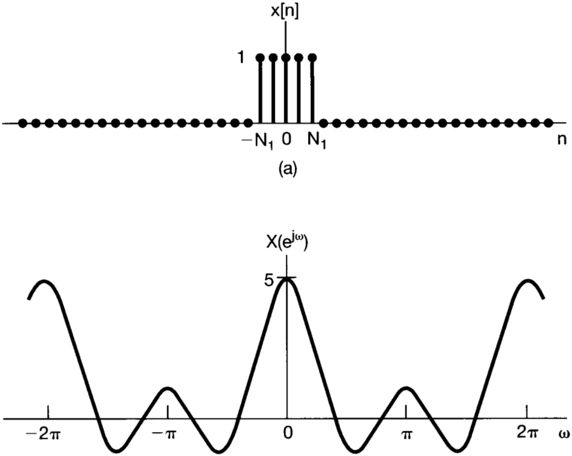
Example: DTFT of a square pulse

$$X(e^{j\omega}) = e^{j\omega N_1} \frac{1 - e^{-j\omega(2N_1+1)}}{1 - e^{-j\omega}}$$

Straightforward from here:

$$\begin{aligned}
X(e^{j\omega}) &= e^{j\omega N_1} \cdot \frac{e^{-j\omega(N_1+1/2)}}{e^{-j\omega/2}} \cdot \frac{e^{j\omega(N_1+1/2)} - e^{-j\omega(N_1+1/2)}}{e^{j\omega/2} - e^{-j\omega/2}} \\
&= \frac{\sin(\omega(N_1 + 1/2))}{\sin(\omega/2)}
\end{aligned}$$

Example: DTFT of a square pulse



Note that this function is periodic!

Image credit: Oppenheim chapter 5.1

Recall in CT we had Dirichlet criteria for both Fourier series and inverse Fourier transform representations:

$$x(t) = \sum_{k=-\infty}^{\infty} c_k e^{jk\omega t} \quad c_k = \frac{1}{T}\int_T x(t)e^{-jk\omega t}dt$$

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

Convergence criteria

We didn't have this issue for the DT Fourier series:

$$x[n] = \sum_{k=\langle N \rangle} c_k e^{jk\omega n} \qquad c_k = \frac{1}{N} \sum_{n=\langle N \rangle} x[n] e^{-jk\omega n}$$

What about for the DT Fourier transform?

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

Convergence criteria

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

The synthesis equation is fine; but the analysis equation has an infinite sum. One of the following must be satisfied:

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

Convolution works the same way as in CT:

$$\begin{aligned} y[n] &= h[n] * x[n] \\ Y(e^{j\omega}) &= H(e^{j\omega})X(e^{j\omega}) \end{aligned}$$

We also have the same relationship between impulse response and the frequency response:

$$\begin{aligned} h[n] &\overset{\mathcal{F}}{\longleftrightarrow} H(e^{j\omega}) \\ H(e^{j\omega}) &= \sum_{n=-\infty}^{\infty} h[n]e^{-j\omega n} \\ h[n] &= \frac{1}{2\pi}\int_{2\pi} H(e^{j\omega})e^{j\omega n}d\omega \end{aligned}$$

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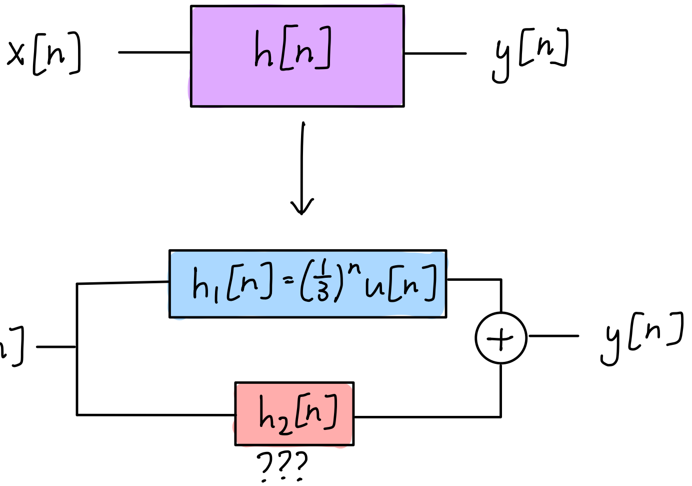
Example: convolution property

$$H(e^{j\omega}) = \frac{-12 + 5e^{-j\omega}}{12 - 7e^{-j\omega} + e^{-2j\omega}}$$



Example: convolution property

$$H(e^{j\omega}) = \frac{-12 + 5e^{-j\omega}}{12 - 7e^{-j\omega} + e^{-2j\omega}}$$

Hint:

$$a^n u[n] \stackrel{\mathcal{F}}{\longleftrightarrow} \frac{1}{1 - ae^{-j\omega}}, \quad |a| < 1$$

Example: convolution property

Many properties are the same as the CT analogs.

Linearity: If

$$\begin{aligned} x_1[n] &\overset{\mathcal{F}}{\longleftrightarrow} X_1(e^{j\omega}), \\ x_2[n] &\overset{\mathcal{F}}{\longleftrightarrow} X_2(e^{j\omega}) \end{aligned}$$

then

$$ax_1[n] + bx_2[n] \overset{\mathcal{F}}{\longleftrightarrow} aX_1(e^{j\omega}) + bX_2(e^{j\omega})$$

Many properties are the same as the CT analogs.

Time shift: If

$$x[n] \stackrel{\mathcal{F}}{\longleftrightarrow} X(e^{j\omega})$$

then

$$x[n-n_0] \stackrel{\mathcal{F}}{\longleftrightarrow} e^{-j\omega n_0} X(e^{j\omega})$$

Frequency shift:

$$e^{j\omega_0 n} x[n] \stackrel{\mathcal{F}}{\longleftrightarrow} X(e^{j(\omega-\omega_0)})$$

Properties of the DT Fourier transform

Conjugation: If

$$x[n] \overset{\mathcal{F}}{\longleftrightarrow} X(e^{j\omega})$$

then

$$x^*[n] \overset{\mathcal{F}}{\longleftrightarrow} X^*(e^{-j\omega})$$

If $x[n]$ is real,

$$X(e^{j\omega}) = X^*(e^{-j\omega})$$

Consequences for odd/even functions:

$$\begin{aligned}
\mathrm{Even}(x[n]) &\overset{\mathcal{F}}{\longleftrightarrow} \mathrm{Re}(X(e^{j\omega})) \\
\mathrm{Odd}(x[n]) &\overset{\mathcal{F}}{\longleftrightarrow} j\mathrm{Im}(X(e^{j\omega}))
\end{aligned}$$

Properties of the DT Fourier transform

Periodicity:

$$X(e^{j(\omega+2\pi)}) = X(e^{j\omega})$$

Differentiation in frequency:

$$\begin{aligned}
x[n] \quad &\overset{\mathcal{F}}{\longleftrightarrow} \quad X(e^{j\omega}) = \sum_{n=-\infty}^{\infty} x[n]e^{-j\omega n} \\
\frac{dX(e^{j\omega})}{d\omega} \quad &= \quad \sum_{n=-\infty}^{\infty} -jnx[n]e^{-j\omega n} \\
nx[n] \quad &\overset{\mathcal{F}}{\longleftrightarrow} \quad j\frac{dX(e^{j\omega})}{d\omega}
\end{aligned}$$

Differencing:

$$x[n] - x[n-1] \overset{\mathcal{F}}{\longleftrightarrow} (1 - e^{-j\omega})X(e^{j\omega})$$

Accumulating:

$$\sum_{m=-\infty}^{n} x[m] \overset{\mathcal{F}}{\longleftrightarrow} \frac{1}{1 - e^{-j\omega}} X(e^{j\omega}) + \pi X(e^{j0}) \sum_{k=-\infty}^{\infty} \delta(\omega - 2\pi k)$$

Parseval's relation:

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

Here $|X(e^{j\omega})|^2$ is called the *energy-density spectrum*.

Recap

Today's learning outcomes were:

- Compute the DT Fourier transform of non-periodic DT signals
- State key properties of the DTFT
- Leverage convolution properties of DTFT to analyze the behaviour of LTI systems

What topics did you find unclear today?

For next time

Content:

- The discrete Fourier transform (DFT) and the Fast Fourier Transform (FFT) algorithm

Action items:

1. Keep an eye out for Assignment 4

Recommended reading:

- From today's class: Oppenheim 5.0-5.7
- For next class: Oppenheim extension problems 5.53-5.54