Ve 216: Introduction to Signals and Systems

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Based on Lecture Notes by Prof. Jeffrey A. Fessler

Outline

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1. 4. The Fourier Transform
   - Introduction
   - Definition of FT (4.1.1)
   - Convergence of FT (4.1.2)
   - Examples of FT pairs (4.1.3)
   - FT of periodic signals (4.2)
   - Properties of the CT FT (4.3)
   - Convolution property and LTI systems (4.4)
   - Parseval's relation
   - Time-domain multiplication (4.5)
   - Application of the FT to RLC circuits (4.7)
     - Finding response $y(t)$ of RLC circuit to a simple input
     - Frequency response of RLC circuits
   - Summary

Fourier series

The Fourier series analysis described previously provides several useful tools.

1. It allows us to analyze the frequency content of periodic signals by decomposing them into a linear combination of complex exponential signals (or sinusoids).
2. It also helps us understand conceptually what happens to periodic signals when passed through LTI systems (each frequency component gets a new amplitude and phase depending on frequency response of the system).
3. It gives us a simple mathematical expression for the response of an LTI system to a periodic input signal without performing convolution.

We would like to have similar tools for aperiodic signals as well. (Like speech or music.)

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Roadmap

	Signal	
Transform	Continuous Time	Discrete Time
Continuous Frequency	Fourier Transform	DTFT (periodic in frequency)
Discrete Frequency	Fourier Series (periodic in time)	DTFS or DFT (periodic in time and frequency) FFT

Fourier transform

Fourier himself recognized the utility of representing aperiodic signals in the frequency domain, and to a large extent our development follows his original approach of treating an aperiodic signal as the limiting case of a set of periodic signals whose periods increase to infinity.

The primary focus of this chapter is on the “signals” part (frequency content of signals). The “systems” part will be emphasized further in the next chapter in the context of filtering.

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Overview

- Definition
- Existence
- Examples
- Properties
- Convolution / filtering
- Multiplication / modulation (app: all electronic communication systems)
- Application to diffeq systems (app: RLC circuits)
- Partial fraction expansion (PFE)
- Finally: easy answer to $\cos(\omega t)\, u(t) \xrightarrow{\text{LTI}} y(t) =?$ and related problems

Outline

Aperiodic signal

- Suppose we have an aperiodic, time-limited signal $f(t)$, and we would like to analyze its frequency content, either to better understand the signal itself, or to analyze what will happen to the signal when it passes through some type of filter, or both.
- As in most math and engineering fields, we develop such an analysis by building on what we already know.
- We know how to analyze the frequency content of periodic signals, so let us construct a periodic signal from $f(t)$, and then examine what happens to the frequency content of the periodic signal as the period increases.

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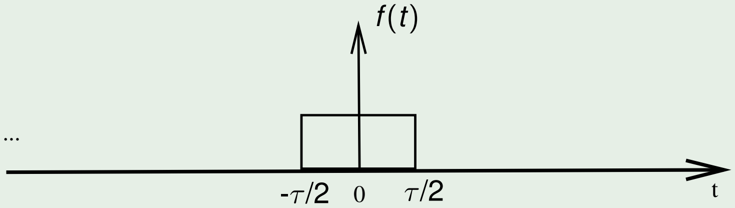
Example: rectangular function

Example

consider the rectangular signal

$$f(t) = \text{rect}\left(\frac{t}{\tau}\right).$$



Question

Is this an energy or power signal?

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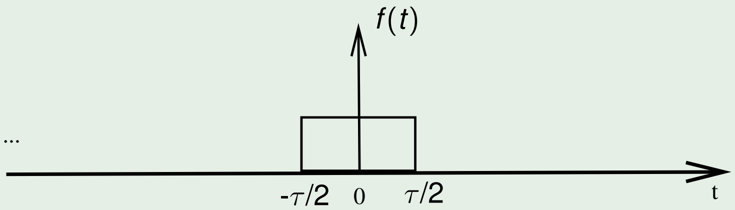

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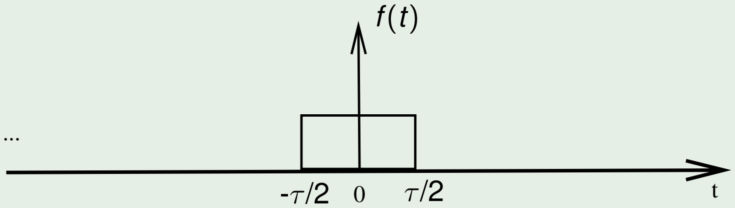


Question

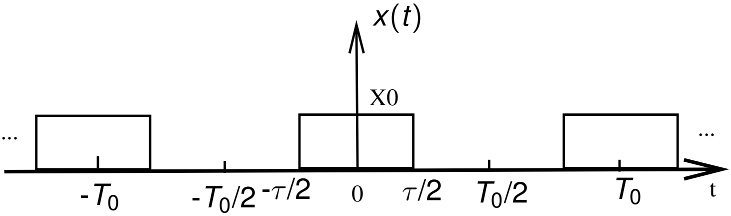
Is this an energy or power signal?

Energy.

Constructed periodic signal

Define a periodic signal

$$x_{T_0}(t) \triangleq \sum_{n=-\infty}^{\infty} f(t-nT_0) = \sum_{n=-\infty}^{\infty} \mathrm{rect}\left(\frac{t-nT_0}{\tau}\right)$$



Question

1. *What is this signal called?*
2. *Is it an energy or power signal?*
3. *What is the name of the special function that we defined to describe the c_k's of $x_{T_0}(t)$?*

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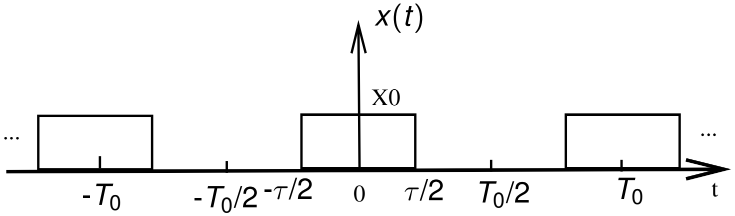

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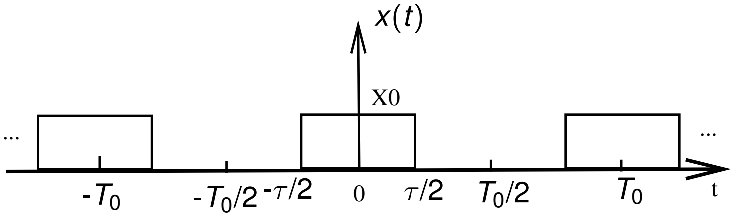

Question

1. *What is this signal called?* Rectangular pulse train
2. *Is it an energy or power signal?* Power
3. *What is the name of the special function that we defined to describe the c_k's of $x_{T_0}(t)$?* Sinc

Increasing the period

We have previously shown that this signal has a Fourier series representation with coefficients

$$c_k = \frac{1}{T_0}\int_{-T_0/2}^{T_0/2} x_{T_0}(t)e^{-jk\omega_0 t}\,dt = \frac{1}{T_0}\tau\,\mathrm{sinc}\left(\tau\frac{k\omega_0}{2\pi}\right).$$

(Chap. 3, p.215)

- In the time domain, as T_0 increases, $x_{T_0}(t)$ approaches $f(t)$ for any given finite t.
- let us examine what happens in the frequency domain as T_0 increases.

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Definition of FT (4)

$$\boxed{c_k = \frac{1}{T_0}\tau \operatorname{sinc}\left(\tau \frac{k\omega_0}{2\pi}\right)}$$

When increasing T_0,

- The first thing we see is that $c_k \to 0$.
- This is due to the $1/T_0$ term, and reflects the fact that $x_{T_0}(t)$ is a power signal, whereas $f(t)$ is an energy signal (and hence has 0 power).
- So we normalize out the $1/T_0$ and instead look at what happens $T_0 c_k$ as the period T_0 increases.

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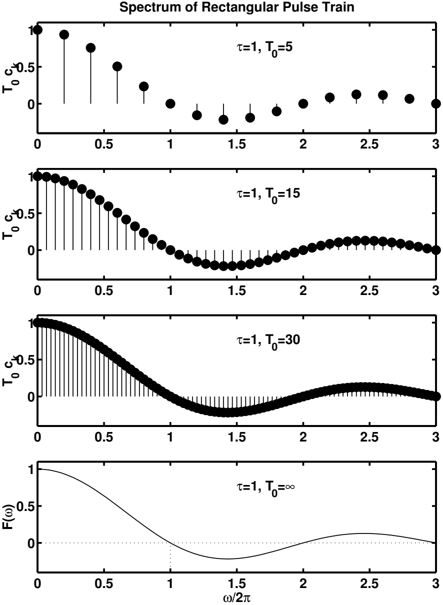
Spectrum



Spectrum of Rectangular Pulse Train
τ=1, T0=5
τ=1, T0=15
τ=1, T0=30
τ=1, T0=∞
T0 ck
F(ω)
ω/2π
0
0.5
1
1.5
2
2.5
3

The envelop

The spectral lines of $x(t)$ become closer and closer, and in the limit as $T_0 \to \infty$, become a continuum described by the envelope.

Question

What is the envelope?

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What is the envelope?

Observe that another way of writing the c_k formula is:

$$T_0 c_k = \tau \operatorname{sinc}\left(\tau \frac{\omega}{2\pi}\right)\Big|_{\omega = k\omega_0},$$

so the envelope is the formula $\boxed{\tau \operatorname{sinc}\left(\tau \frac{\omega}{2\pi}\right)}$.

This formula describes the frequency content of the aperiodic signal $f(t)$.

Video: MIT Lecture 8, 11.58 min

Definition of FT (1)

Question

Where did this sinc(·) *formula originate?*

Returning to the c_k formula:

$$
\begin{aligned}
T_0 c_k &= \int_{-T_0/2}^{T_0/2} x_{T_0}(t) e^{-jk\omega_0 t}\, dt \\
&= \int_{-T_0/2}^{T_0/2} f(t) e^{-jk\omega_0 t}\, dt \\
&= \int_{-\infty}^{\infty} f(t) e^{-jk\omega_0 t}\, dt \\
&= \int_{-\infty}^{\infty} f(t) e^{-j\omega t}\, dt \Big|_{\omega = k\omega_0}
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Definition of FT (2)

So if we define

$$F(\omega) \triangleq \int_{-\infty}^{\infty} f(t)e^{-j\omega t}\,dt$$

then

$$T_0 c_k = F(\omega)|_{\omega=k\omega_0} \Longrightarrow c_k = \frac{1}{T_0} F(\omega)|_{\omega=k\omega_0}$$

where the c_k's are the FS coefficients of the periodic signal $x_{T_0}(t)$, but the $F(\omega)$ is solely related to the aperiodic signal $f(t)$.

General treatment (1)

- We have seen that we can represent periodic function $x(t)$ with period T_0 by the complex Fourier series

$$x(t) = \sum_{k=-\infty}^{\infty} c_k e^{jk\omega_0 t} \quad \text{where} \quad c_k = \frac{1}{T_0} \int_{-T_0/2}^{T_0/2} x(t) e^{-jk\omega_0 t} \, dt,$$

where $\omega_0 = 2\pi / T_0$.

- The coefficients c_k define the spectrum of $x(t)$, and since the only frequency components present are at the harmonics $k\omega_0$, the spectrum is a discrete or line spectrum consisting of lines of height $|c_k|$ (with corresponding phase $\angle c_k$) at the frequencies $k\omega_0 = k\frac{2\pi}{T_0}$.

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General treatment (2)

What happens as the period T_0 increases? The spacing of the lines decreases, and in the limit as $T_0 \to \infty$ we can think of the spectra as continuous curves (one for magnitude, one for phase), rather than discrete lines.

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General treatment (3)

- Consider a "pulse" train

$$x_{T_0}(t) = \sum_{n=-\infty}^{\infty} f(t - nT_0),$$

  for some "pulse like" (energy) signal $f(t)$.
- As T_0 increases, the gap between the center pulse and the next pulse widens, and in the limit as $T_0 \to \infty$, eventually all that is left is central pulse. Formally:

$$\lim_{T_0 \to \infty} x_{T_0}(t) = f(t).$$

Since $f(t)$ is the limit of the $x_{T_0}(t)$ signals, it is natural to think that we should be able to define some type of spectrum for $f(t)$ by taking some type of limit of the FS expressions above.

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General treatment (4)

- Since $x_{T_0}(t)$ is periodic, it is a power signal, whereas $f(t)$ is aperiodic and (at least in this typical example) is an energy signal.
- We need to scale the FS coefficients by a factor of T_0, since there is such a difference in the definitions of energy and power.

Energy and power

Recall

- The **energy** of a signal $x(t)$ is defined as

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

  If E is finite ($E < \infty$) then $x(t)$ is called an **energy signal** and $P = 0$.

- The **average power** of a signal is defined as

$$P \triangleq \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} |x(t)|^2 \, dt.$$

  If P is finite and nonzero, then $x(t)$ is called a **power signal**.

General treatment (5)

Define:

$$F_{T_0}(k\omega_0) \triangleq T_0 c_k = \int_{-T_0/2}^{T_0/2} f(t) e^{-jk\omega_0 t}\, dt,$$

then

$$F_{T_0}(\omega) = \int_{-T_0/2}^{T_0/2} f(t) e^{-j\omega t}\, dt.$$

Although $F_{T_0}(\cdot)$ is only valid for the values $\omega = k\omega_0$, as T_0 increases these values become ever closer together, so there are "more and more" valid values. In the limit we have the following expression, valid for all ω:

$$\boxed{\lim_{T_0 \to \infty} F_{T_0}(\omega) \triangleq F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t}\, dt.}$$

General treatment (6)

$$\boxed{F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t}\,dt}$$

This integral relationship, which defines a function $F(\omega)$ given a signal $f(t)$, is called the **Fourier transform** of $f(t)$.

In EE the convention is to use capital letters to denote the Fourier transform of a signal denoted with lower case letters, *e.g.* $Y(\omega)$ would be the FT of $y(t)$, defined of course by

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General treatment (7)

So we see how to compute a FT $F(\omega)$ from an aperiodic signal $f(t)$. But this would be of limited utility if we could not also recover $f(t)$ from $F(\omega)$. Fortunately, we can!

For a periodic signal, such as our $x_{T_0}(t)$, we can recover it from its coefficients by summing:

$$x_{T_0}(t) = \sum_{k=-\infty}^{\infty} c_k e^{jk\omega_0 t}$$

$$= \sum_{k=-\infty}^{\infty} \frac{F_{T_0}(k\omega_0)}{T_0} e^{jk\omega_0 t}$$

$$= \frac{1}{2\pi} \sum_{k=-\infty}^{\infty} F_{T_0}(k\omega_0) e^{jk\omega_0 t} \omega_0$$

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To summarize, for an aperiodic signal $f(t)$, we have derived the following relationships:

$$\boxed{f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)e^{j\omega t}\,d\omega, \quad F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t}\,dt}$$

The functions $f(t)$ and $F(\omega)$ are called **Fourier transform pairs** and we write

$$f(t) \stackrel{\mathcal{F}}{\longleftrightarrow} F(\omega).$$

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The annoying asymmetry (extra 2π) is due to our choice to use ω in radians/unit time as the frequency variable. If instead we had used cycles/unit time (*e.g.* Hz), then the 2π out front disappears.

Systems perspective for FT formula

$$x(t) = e^{j\omega t} \rightarrow \boxed{\text{LTI}} \rightarrow H(\omega)e^{j\omega t}$$

where

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FT: Example (1)

Example

Find the FT of a rectangular signal $f(t) = \mathrm{rect}(t/\tau)$.

Solution

$$F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t}\, dt = \int_{-\tau/2}^{\tau/2} 1\, e^{-j\omega t}\, dt$$

$$= \begin{cases} \tau, & \omega = 0 \\ \int_{-\tau/2}^{\tau/2} \cos(\omega t) - j\sin(\omega t)\, dt, & \omega \neq 0 \end{cases}$$

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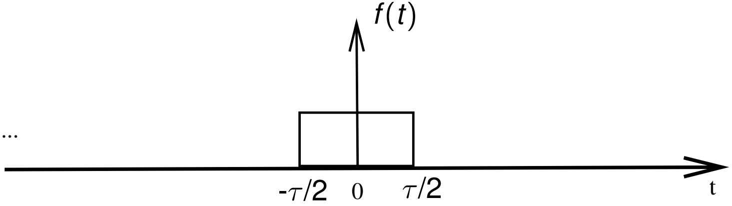
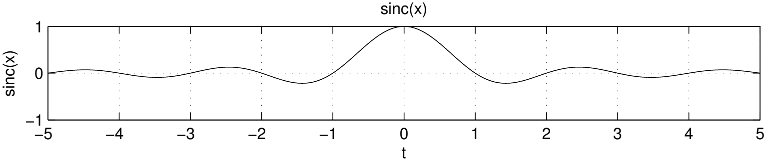
FT: Example (2)

$$\mathrm{sinc}(x) \triangleq \begin{cases} 1, & x = 0 \\ \frac{\sin \pi x}{\pi x}, & x \neq 0. \end{cases}$$

Thus we have derived our first FT pair

$$\boxed{\mathrm{rect}(t/\tau) \overset{\mathcal{F}}{\longleftrightarrow} \tau \,\mathrm{sinc}\left(\tau \frac{\omega}{2\pi}\right).}$$





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Where do $F(\omega) = \tau\,\mathrm{sinc}\left(\tau\frac{\omega}{2\pi}\right)$ *have its peak of* τ *and zeros?*

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- *Peak at* $\omega = 0$.
- *Zeros at*

$$\tau\frac{\omega}{2\pi} = \pm k \Longrightarrow \omega = (\pm k2\pi)/\tau, k = 1, 2, \ldots$$

Outline

Conditions for existence of the CT FT

In the rect signal example above, we could easily perform the integral. But any time we see infinite sums or integrals, we must consider existence of the sum or integral.

Example

$\sum_{k=0}^{n}(-1)^k$ is well defined for any finite integer n. But $\sum_{k=0}^{\infty}(-1)^k$ is undefined!

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When in general will the FT exist?

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Square integrable signals

If $f(t)$ is an energy signal, also known as **square integrable**, *i.e.* if $\int_{-\infty}^{\infty} |f(t)|^2 \, dt < \infty$, then

- $F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t} \, dt$ exists and is finite, since by the triangle inequality: $|F(\omega)|^2 \leq \int_{-\infty}^{\infty} |f(t)e^{-j\omega t}|^2 \, dt < \infty$.
- If we "reconstruct" $\tilde{f}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega)e^{j\omega t} \, d\omega$, then the error signal will have zero energy, *i.e.* $\int_{-\infty}^{\infty} |\tilde{f}(t) - f(t)|^2 \, dt = 0$.

This is completely adequate for engineering purposes, so we write $f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega)e^{j\omega t} \, d\omega$ throughout the rest of the course, even though strictly speaking the "equality" in that expression only holds in an L_2 sense rather than in the strict mathematical sense.

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- Unfortunately, square integrable is a little bit too restrictive of a condition for many engineering problems.
- The **Dirichlet conditions** are a set of sufficient conditions on $f(t)$ that have been shown to ensure that the FT exists.
- There are various versions of these conditions that appear in different books. Here is one set of sufficient conditions.
  - $f(t)$ is absolutely integrable: $\int_{-\infty}^{\infty} |f(t)|\, dt < \infty$
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Rule of thumb:
if you can draw a complete picture of $f(t)$, then its FT exists.

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Unit impulse (in time)(1)

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Find FT of unit impulse function. (not square integrable, not bounded, but FT still can be defined.)

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by the sifting property. *Thus*

$$\boxed{\delta(t - t_0) \overset{\mathcal{F}}{\longleftrightarrow} e^{-j\omega t_0}}$$

and in particular

$$\boxed{\delta(t) \overset{\mathcal{F}}{\longleftrightarrow} 1}$$

Unit impulse (in time) (2)

$$\boxed{\delta(t - t_0) \overset{\mathcal{F}}{\longleftrightarrow} e^{-j\omega t_0}}$$

Note that

- $|F(\omega)| = 1$, *so the unit impulse function has equal energy (density) in all frequencies!*
- $\angle F(\omega) = -\omega t_0$, *which decreases linearly with* ω.

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A unit impulse signal has a unity FT. What signal corresponds to a spectrum consisting of a single impulse at $\omega = 0$*?*

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***Dual relationships*:**

$$\delta(t) \overset{\mathcal{F}}{\longleftrightarrow} 1, \quad 1 \overset{\mathcal{F}}{\longleftrightarrow} \delta\left(\frac{\omega}{2\pi}\right) = 2\pi\delta(\omega)$$

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- *Signals with impulses in the spectrum are power signals.*
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This is a particularly important FT pair, since $e^{-at}u(t)$ is important in the solution of diffeq systems!

Decaying exponential function (2)

The ***energy density spectrum*** *of this signal is*

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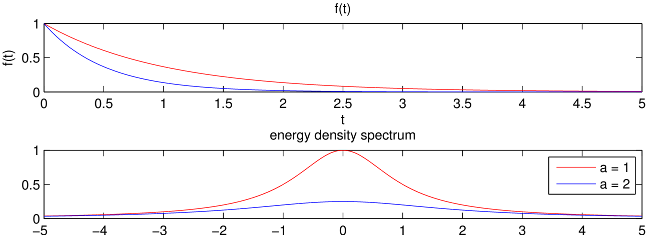

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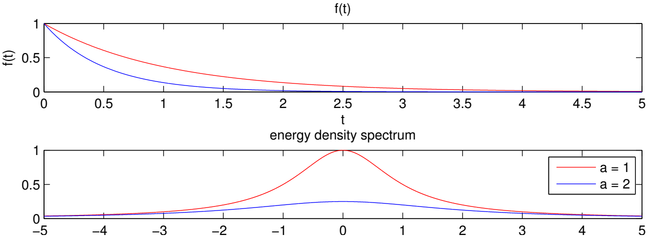

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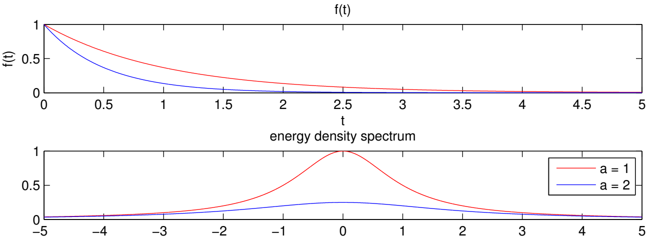


Question

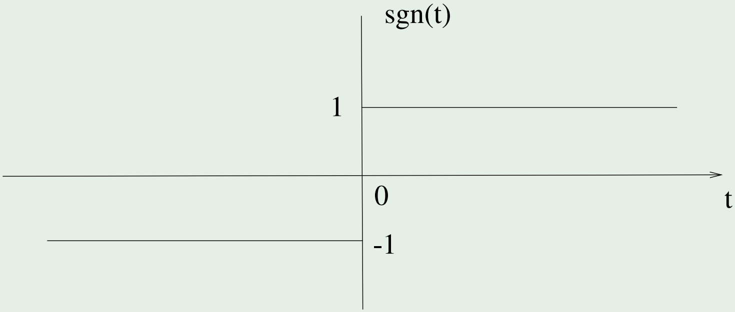
What happens as a increases?

Signal decays faster (more impulse like), and spectrum broadens.

Sign function (1)

Example

$$f(t) = \operatorname{sgn}(t) \triangleq \begin{cases} 1, & t > 0 \\ -1, & t < 0 \end{cases}$$
$$= u(t) - u(-t) = 2u(t) - 1.$$



Is it absolutely integrable? Is it square integrable?

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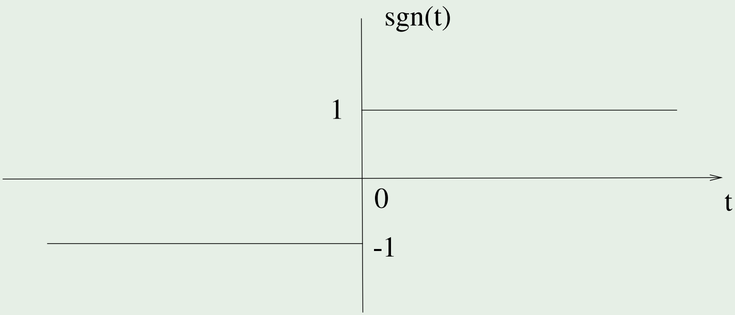
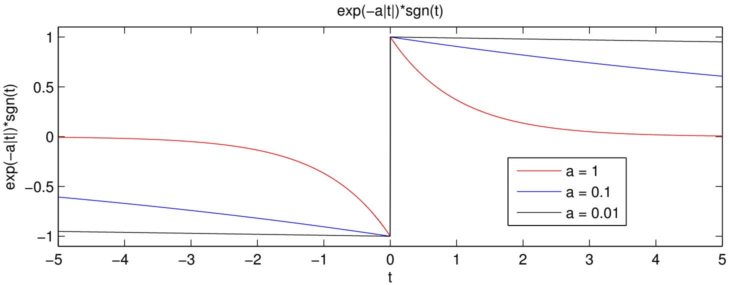


Is it absolutely integrable? *No* Is it square integrable? *No*

Sign function (2)

To find its FT, consider

$$\lim_{a \to 0} g(t), \quad g(t) = e^{-a|t|}\,\mathrm{sgn}(t)$$



Sign function (3)

$\omega \neq 0$

$$G(\omega) = \int_{-\infty}^{\infty} e^{-a|t|}\,\mathrm{sgn}(t)\, e^{-j\omega t}\, dt$$

$$= \int_{-\infty}^{0} -\,e^{at} e^{-j\omega t}\, dt + \int_{0}^{\infty} e^{-at} e^{-j\omega t}\, dt$$

$$= \int_{\infty}^{0} +e^{-at'} e^{j\omega t'}\, dt' + \int_{0}^{\infty} e^{-at} e^{-j\omega t}\, dt \quad (t' = -t)$$

$$= \underbrace{\int_{0}^{\infty} -e^{-at'} e^{j\omega t'}\, dt'}_{\text{swapping the bounds for definite integrals}} + \int_{0}^{\infty} e^{-at} e^{-j\omega t}\, dt,$$

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Sign function (4)

$$
\begin{aligned}
F(\omega) &= \lim_{a\to 0} G(\omega) = \begin{cases} 0, & \omega = 0 \\ \lim_{a\to 0}\left[\frac{-1}{-j\omega+a} + \frac{1}{j\omega+a}\right], & \omega \neq 0. \end{cases} \\
&= \begin{cases} 0, & \omega = 0 \\ \frac{2}{j\omega}, & \omega \neq 0. \end{cases} = \frac{2}{j\omega} + 0\delta(\omega) = \frac{2}{j\omega}
\end{aligned}
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Thus

$$\boxed{\mathrm{sgn}(t) \overset{\mathcal{F}}{\longleftrightarrow} \frac{2}{j\omega}}$$

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Outline

FT of periodic signals (1)

- We already have a perfectly-sized tool for analyzing periodic signals: the Fourier series.
- So strictly speaking, analysis of periodic signals by FT methods is redundant.
- However, when considering signals that have mixed periodic and aperiodic components, such as AM (amplitude modulation) signals "with carrier" (Chap. 1, p.128), it is convenient to be able to use one tool to handle both the periodic and aperiodic component.
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FT of periodic signals (2)

- One cannot directly calculate the FT of a periodic signal because a periodic signal (which has infinite energy) is neither square integrable nor absolutely integrable.
- We use an alternate representation of the periodic signal as a Fourier series and then employ known properties of the Dirac delta function and Fourier transform to obtain the FT of periodic signals.
- Unlike Fourier transforms of finite-energy functions, the Fourier transforms of periodic functions are not ordinary functions but rather distributions which have a literature of their own.

FT from FS (1)

Suppose $x(t)$ is periodic with period T_0 and fundamental frequency $\omega_0 = 2\pi/T_0$. We saw earlier that we can represent $x(t)$ by its Fourier series:

$$x(t) = \sum_{k=-\infty}^{\infty} c_k e^{jk\omega_0 t}$$

Question

What is the FT of $x(t)$?

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FT from FS (2)

Solution

1. *FT of a complex exponential signal*
2. *Superposition property*

FT from FS (2)

Solution

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$$e^{j\omega_0 t} \overset{\mathcal{F}}{\longleftrightarrow} 2\pi\delta(\omega - \omega_0)$$

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$$\sum_n x_n(t) \overset{\mathcal{F}}{\longleftrightarrow} \sum_n X_n(\omega)$$

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Unit impulse in spectrum

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What signal corresponds to a spectrum consisting of a single impulse?

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If $X(\omega) = 2\pi\delta(\omega - \omega_0)$ *then*

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Thus we have shown the following FT pair:

$$\boxed{e^{j\omega_0 t} \xleftrightarrow{\mathcal{F}} 2\pi\delta(\omega - \omega_0).}$$

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This makes sense, since a complex exponential signal has a single frequency component at ω_0.

Linearity of FT

Linearity of FT:

$$f(t) = a_1 f_1(t) + a_2 f_2(t) \xleftrightarrow{\mathcal{F}} F(\omega) = a_1 F_1(\omega) + a_2 F_2(\omega)$$

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Show the linearity property of FT.

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$$\begin{aligned} F(\omega) &= \int_{-\infty}^{\infty} f(t)e^{-j\omega t}\,dt = \int_{-\infty}^{\infty} [a_1 f_1(t) + a_2 f_2(t)]e^{-j\omega t}\,dt \\ &= a_1 \left[\int_{-\infty}^{\infty} f_1(t)e^{-j\omega t}\,dt\right] + a_2 \left[\int_{-\infty}^{\infty} f_2(t)e^{-j\omega t}\,dt\right] \\ &= a_1 F_1(\omega) + a_2 F_2(\omega). \end{aligned}$$

Superposition of FT

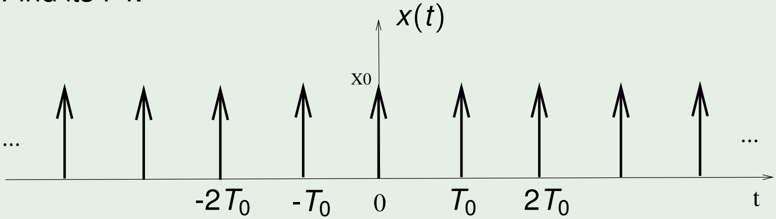
The linearity property is easily extended to the superposition property

$$\boxed{\sum_n x_n(t) \stackrel{\mathcal{F}}{\longleftrightarrow} \sum_n X_n(\omega)}$$

FT from FS: Example (1)

Example

What is the periodic signal $x(t) = \sum_{n=-\infty}^{\infty} \delta(t - nT_0)$ called? Find its FT.



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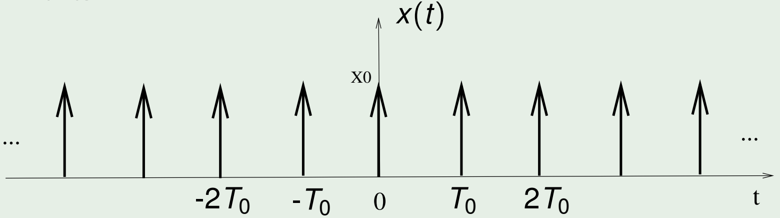


Impulse train signal.

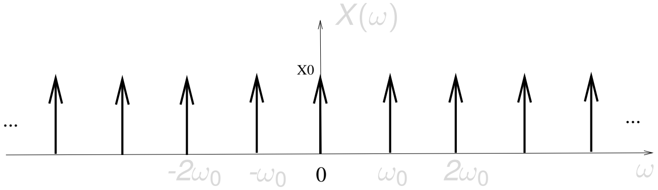
Solution

We previously found its Fourier series coefficients to be $c_k = 1/T_0$*, so*

$$x(t) = \sum_{k=-\infty}^{\infty} \frac{1}{T_0} e^{jk\omega_0 t}.$$

Thus the FT of $x(t)$ *is*

$$\boxed{X(\omega) = \sum_{k=-\infty}^{\infty} \frac{1}{T_0} 2\pi\delta(\omega - k\omega_0) = \sum_{k=-\infty}^{\infty} \omega_0 \delta(\omega - k\omega_0).}$$



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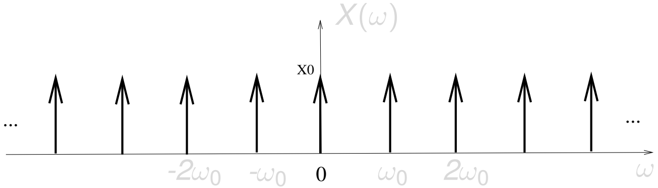

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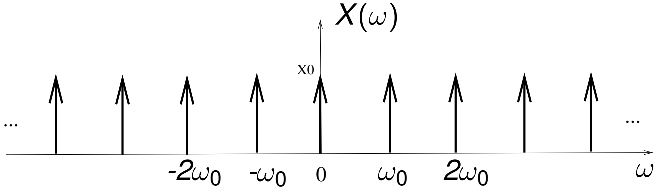

FT from FS: Example (2)

Example

For the 0.5Hz pervious square wave

$$x(t) = \sum_{n=-\infty}^{\infty} \text{rect}(t - 1/2 - 2n) \text{ with } c_k = \begin{cases} 1/2, & k = 0 \\ \frac{1}{jk\pi}, & k \text{ odd} \\ 0, & \text{otherwise} \end{cases}$$

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and $\omega_0 = \pi$, find its FT.

$$X(\omega) = \sum_{k=-\infty}^{\infty} c_k 2\pi\delta(\omega - k\omega_0) = \boxed{\pi\delta(\omega) + \sum_{k,\ \text{odd}} \frac{2}{jk}\delta(\omega - k\pi)}$$

Outline

Motivation

Fourier transform pairs:

$$\boxed{F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t}\, dt, \quad f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) e^{j\omega t}\, d\omega}$$

We would like to be able to find $F(\omega)$ and $f(t)$ without recomputing everything. Another motivation is to avoid inverse FT via integration. Thus we study properties of the FT.

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Linearity (1)

Property

Linearity property:

$$f(t) = a_1 f_1(t) + a_2 f_2(t) \xleftrightarrow{\mathcal{F}} F(\omega) = a_1 F_1(\omega) + a_2 F_2(\omega)$$

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Find FT of $f(t) = \cos \omega_0 t$.

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Find FT of $f(t) = \cos \omega_0 t$.

$$f(t) = \cos \omega_0 t = e^{j\omega_0 t}/2 + e^{-j\omega_0 t}/2$$

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Linearity (2)

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$$
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\cos(\omega_0 t + \phi) &= e^{j(\omega_0 t + \phi)}/2 + e^{-j(\omega_0 t + \phi)}/2 \\
&= \frac{e^{j\phi}}{2} e^{j\omega_0 t} + \frac{e^{-j\phi}}{2} e^{-j\omega_0 t}
\end{aligned}
$$

$$
\boxed{\cos(\omega_0 t + \phi) \overset{\mathcal{F}}{\longleftrightarrow} \pi e^{j\phi}\delta(\omega - \omega_0) + \pi e^{-j\phi}\delta(\omega + \omega_0).}
$$

Time-transformations

Property

Time transforms:

$$f(at+b) \xleftrightarrow{\mathcal{F}} \frac{1}{|a|} e^{j\omega b/a} F(\omega/a), \quad \text{for } a \neq 0$$

Time-transformations: proof

If $y(t) = f(at+b)$ *then*

1. *for* $a > 0$ *(using* $t' = at + b$*):*

$$
\begin{aligned}
Y(\omega) &= \int_{-\infty}^{\infty} f(at+b)e^{-j\omega t}\,dt = \frac{1}{a}\int_{-\infty}^{\infty} f(t')e^{-j\omega(t'-b)/a}\,dt' \\
&= \frac{e^{j\omega b/a}}{a}\int_{-\infty}^{\infty} f(t')e^{-j\omega/at'}\,dt' = \frac{e^{j\omega b/a}}{a}F(\omega/a).
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2. *Similar for case where* $a < 0$ *(using* $t' = at + b$*),*

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Time-shift

Property

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$$f(at+b) \overset{\mathcal{F}}{\longleftrightarrow} \frac{1}{|a|} e^{j\omega b/a} F(\omega/a), \quad \textit{for} \;\; a \neq 0$$

Property

Time-shift (use $a=1$ and $b=-t_0$)

$$\boxed{f(t-t_0) \overset{\mathcal{F}}{\longleftrightarrow} e^{-j\omega t_0} F(\omega)} \textit{(phase shift)}$$

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Property

Time-scale (use $b=0$)

$$\boxed{f(at) \overset{\mathcal{F}}{\longleftrightarrow} \frac{1}{|a|} F\left(\frac{\omega}{a}\right), \; a \neq 0}$$

Time-scale

Property

Time transforms:

$$f(at+b) \overset{\mathcal{F}}{\longleftrightarrow} \frac{1}{|a|} e^{j\omega b/a} F(\omega/a), \quad \text{for } a \neq 0$$

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Time-scale (use $b = 0$)

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Time-reversal

Property

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$$f(at+b) \overset{\mathcal{F}}{\longleftrightarrow} \frac{1}{|a|} e^{j\omega b/a} F(\omega/a), \quad \textit{for} \;\; a \neq 0$$

Property

Time-reversal (use $a = -1$ and $b = 0$)

$$f(-t) \overset{\mathcal{F}}{\longleftrightarrow} F(-\omega)$$

Time-reversal

Property

Time transforms:

$$f(at+b) \overset{\mathcal{F}}{\longleftrightarrow} \frac{1}{|a|} e^{j\omega b/a} F(\omega/a), \quad \textit{for} \;\; a \neq 0$$

Property

Time-reversal (use $a=-1$ and $b=0$)

$$f(-t) \overset{\mathcal{F}}{\longleftrightarrow} F(-\omega)$$

Even signals

Property

If $x(t)$ is an even signal, i.e.,

$$f(t) = f(-t)$$

then its FT is also even, i.e.,

$$F(\omega) = F(-\omega)$$

Even signals: proof

Recall if $f(t)$ is even, i.e.,

$$f(t) = f(-t),$$

Recall time-reversal

$$f(-t) \xleftrightarrow{\mathcal{F}} F(-\omega)$$

So

$$F(\omega) = F(-\omega), \quad \textit{(spectrum is also even)}$$

Even signals: proof

Recall if $f(t)$ is even, i.e.,

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$$f(-t) \stackrel{\mathcal{F}}{\longleftrightarrow} F(-\omega)$$

So

$$F(\omega) = F(-\omega), \quad \textit{(spectrum is also even)}$$

Conjugation

Property

Conjugation:

$$f^*(t) \xleftrightarrow{\mathcal{F}} F^*(-\omega)$$

Conjugation: proof

$$F^*(-\omega) = \left[\int_{-\infty}^{\infty} f(t)e^{-j(-\omega)t}\,dt\right]^*$$

$$= \underbrace{\int_{-\infty}^{\infty} f^*(t)e^{-j\omega t}\,dt}_{FT\ of\ f^*(t)}$$

So

$$F^*(-\omega) \xleftrightarrow{\mathcal{F}} f^*(t)$$

Conjugation: proof

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So

$$F^*(-\omega) \overset{\mathcal{F}}{\longleftrightarrow} f^*(t)$$

Hermitian symmetric

Property

If $f(t)$ is real, i.e.,

$$f(t) = f^*(t)$$

then

$$F(\omega) = F^*(-\omega)$$

so the spectrum of a real signal is ***Hermitian symmetric****.*

Furthermore

- $\angle F(\omega) = \angle F^*(-\omega) = -\angle F(-\omega)$
- $|F(\omega)| = |F^*(-\omega)| = |F(-\omega)|$

It can be easily proved using the conjugation property.

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It can be easily proved using the conjugation property.

Hermitian symmetric: example

Example

Show the Hermitian symmetry property for $f(t) = e^{-t}u(t)$.

Solution

$$f(t) = e^{-t}u(t) \xleftrightarrow{\mathcal{F}} F(\omega) = \frac{1}{j\omega + 1}$$

$$F(-\omega) = \frac{1}{-j\omega + 1}$$

$$F^*(-\omega) = \frac{1}{j\omega + 1} = F(\omega)$$

$$\boxed{F(\omega) = F^*(-\omega)}$$

Solution

$$f(t) = e^{-t}u(t) \overset{\mathcal{F}}{\longleftrightarrow} F(\omega) = \frac{1}{j\omega + 1}$$

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Real and even signals

Property

If $f(t)$ is real and even $F(\omega)$ is also real and even.

Property

If $f(t)$ is real and odd, then $F(\omega)$ is purely imaginary and odd.

Real and even signals

Property

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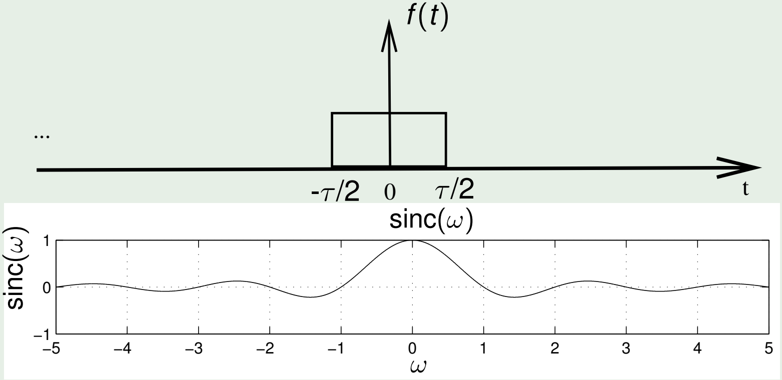
Real and even signals: example

Example

$$\mathrm{rect}(t) \stackrel{\mathcal{F}}{\longleftrightarrow} \mathrm{sinc}\left(\frac{\omega}{2\pi}\right)$$



Real and even signals: proof

Combining the preceding two properties for real and even signals

$$
\begin{array}{ccccccc}
f(t) & = & f(-t) & = & f^*(t) & = & f^*(-t) \\
\updownarrow & & \updownarrow & & \updownarrow & & \updownarrow \\
F(\omega) & = & F(-\omega) & = & F^*(-\omega) & = & F^*(\omega)
\end{array}
$$

Duality

Question

We have shown that

$$\mathrm{rect}(t) \xleftrightarrow{\mathcal{F}} \mathrm{sinc}\left(\frac{\omega}{2\pi}\right).$$

If we want to find the FT of $\mathrm{sinc}(t)$*, do we have to start from scratch?*

No!

Property

The principle of duality says that FT pairs have the following dual relationship. If

$$f(t) \xleftrightarrow{\mathcal{F}} F(\omega)$$

then

$$x(t) = F(t) \xleftrightarrow{\mathcal{F}} X(\omega) = 2\pi f(-\omega)$$

Duality

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Duality: proof

$$\begin{aligned}\int_{-\infty}^{\infty} F(t)e^{-j\omega t}\,dt &= 2\pi \underbrace{\frac{1}{2\pi}\int_{-\infty}^{\infty} F(t)e^{jt(-\omega)}\,dt}_{\text{(inverse FT) } f(t)=\frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)e^{j\omega t}\,d\omega} \\ &= 2\pi f(-\omega)\end{aligned}$$

Time differentiation

Property

Time differentiation

$$\frac{\mathrm{d}}{\mathrm{d}t} f(t) \xleftrightarrow{\mathcal{F}} j\omega F(\omega)$$

- DC component vanishes (derivative of a constant is zero).
- Higher frequencies are amplified! (Usually causes undesirable noise amplification (MIT Lecture 9-10).)

Filtering (ideal lowpass filter and differentiator), Video (MIT, Lecture 9, 28:40min)

Time differentiation

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Filtering (ideal lowpass filter and differentiator), Video (MIT, Lecture 9, 28:40min)

Time differentiation: proof

Easily shown from inverse FT formula:

$$\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t} f(t) &= \frac{\mathrm{d}}{\mathrm{d}t} \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) e^{j\omega t}\, d\omega \\
&= \frac{1}{2\pi} \int_{-\infty}^{\infty} j\omega F(\omega) e^{j\omega t}\, d\omega
\end{aligned}$$

Question

What happens if we differentiate again?

Time differentiation: proof

Easily shown from inverse FT formula:

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}f(t) &= \frac{\mathrm{d}}{\mathrm{d}t}\frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)e^{j\omega t}\,d\omega \\ &= \frac{1}{2\pi}\int_{-\infty}^{\infty} j\omega F(\omega)e^{j\omega t}\,d\omega\end{aligned}$$

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Question

What happens if we differentiate again?

$$\boxed{\frac{d^k}{dt^k}f(t) \stackrel{\mathcal{F}}{\longleftrightarrow} (j\omega)^k F(\omega)}$$

Time differentiation: example (1)

Example

$f(t) = e^{-at}u(t)$, with real$\{a\} > 0$. Find the FT of $\frac{\mathrm{d}}{\mathrm{d}t} f(t)$.

Time differentiation: example (1)

Example

$f(t) = e^{-at}u(t)$, with real$\{a\} > 0$. Find the FT of $\frac{\mathrm{d}}{\mathrm{d}t}f(t)$.

Previously showed

$$F(\omega) = \frac{1}{j\omega + a}$$

So

$$\frac{\mathrm{d}}{\mathrm{d}t}f(t) \overset{\mathcal{F}}{\longleftrightarrow} \frac{j\omega}{j\omega + a} = \boxed{1 - a\frac{1}{j\omega + a}}.$$

Time differentiation: example (1)

Example

$f(t) = e^{-at}u(t)$, with real$\{a\} > 0$. Find the FT of $\frac{\mathrm{d}}{\mathrm{d}t}f(t)$.

Sanity check

$$
\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t}f(t) &= (\frac{\mathrm{d}}{\mathrm{d}t}e^{-at})u(t) + e^{-at}\frac{\mathrm{d}}{\mathrm{d}t}u(t) \\
&= -ae^{-at}u(t) + e^{-at}\delta(t) \\
&= -ae^{-at}u(t) + \delta(t) \\
&\overset{\mathcal{F}}{\longleftrightarrow} \boxed{1 - a\frac{1}{j\omega + a}},
\end{aligned}
$$

as expected.

Time differentiation: example (2)

Example

Find the FT of $f(t) = \text{sgn}(t)$.

Time differentiation: example (2)

Example

Find the FT of $f(t) = \mathrm{sgn}(t)$.

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathrm{sgn}(t) = 2\delta(t), \quad \text{and} \quad \delta(t) \xleftrightarrow{\mathcal{F}} 1 \Rightarrow j\omega F(\omega) = 2$$

Time differentiation: example (2)

Example

Find the FT of $f(t) = \text{sgn}(t)$.

$$\frac{\mathrm{d}}{\mathrm{d}t}\text{sgn}(t) = 2\delta(t), \quad \text{and} \quad \delta(t) \overset{\mathcal{F}}{\longleftrightarrow} 1 \Rightarrow j\omega F(\omega) = 2$$

For this result, it is determined that

$$F(\omega) = \frac{2}{j\omega} + k\delta(\omega),$$

where the term $k\delta(\omega)$ is nonzero only at $\omega = 0$ and accounts for the time-averaged value of $f(t)$.

Time differentiation: example (3)

$$F(\omega) = \frac{2}{j\omega} + k\delta(\omega)$$

- In the general case, this $k\delta(\omega)$ term must be included; otherwise the time-derivative operation implied by the expression $j\omega F(\omega)$ would cause a loss of this information about the time-averaged value of $f(t)$.
- In this particular case, the time-averaged value of $\mathrm{sgn}(t)$ is zero. Therefore, $k = 0$.

$$\boxed{\mathrm{sgn}(t) \xleftrightarrow{\mathcal{F}} \frac{2}{j\omega}}$$

Time differentiation: example (3)

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$$\boxed{\mathrm{sgn}(t) \stackrel{\mathcal{F}}{\longleftrightarrow} \frac{2}{j\omega}}$$

Frequency differentiation

Property

Frequency differentiation:

$$(-jt)f(t) \overset{\mathcal{F}}{\longleftrightarrow} \frac{d}{d\omega}F(\omega)$$

$$(-jt)^n f(t) \overset{\mathcal{F}}{\longleftrightarrow} \frac{d^n}{d\omega^n}F(\omega)$$

Frequency differentiation: proof

Proof:

$$\begin{aligned}
\frac{d}{d\omega} F(\omega) &= \frac{d}{d\omega} \int_{-\infty}^{\infty} f(t) e^{-j\omega t}\, dt \\
&= \int_{-\infty}^{\infty} f(t)(-jt) e^{-j\omega t}\, dt \\
&= \underbrace{\int_{-\infty}^{\infty} [-jtf(t)] e^{-j\omega t}\, dt}_{(FT)\ F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t}\, dt} .
\end{aligned}$$

$$\boxed{(-jt) f(t) \overset{\mathcal{F}}{\longleftrightarrow} \frac{d}{d\omega} F(\omega)}$$

Frequency differentiation: proof

Proof:

$$\begin{aligned}\frac{d}{d\omega}F(\omega) &= \frac{d}{d\omega}\int_{-\infty}^{\infty} f(t)e^{-j\omega t}\,dt \\ &= \int_{-\infty}^{\infty} f(t)(-jt)e^{-j\omega t}\,dt \\ &= \underbrace{\int_{-\infty}^{\infty} [-jtf(t)]e^{-j\omega t}\,dt}_{(FT)\ F(\omega)=\int_{-\infty}^{\infty} f(t)e^{-j\omega t}\,dt} .\end{aligned}$$

$$\boxed{(-jt)f(t) \overset{\mathcal{F}}{\longleftrightarrow} \frac{d}{d\omega}F(\omega)}$$

$\omega = 0$ & $t = 0$

Property

$\omega = 0$ *(DC) value*

$$F(0) = F(\omega)|_{\omega=0} = \int_{-\infty}^{\infty} f(t)e^{-j\omega t}\,dt\Big|_{\omega=0} = \int_{-\infty}^{\infty} f(t)\,dt$$

Property

$t = 0$ *value*

$$f(0) = f(t)|_{t=0} = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)e^{j\omega t}\,d\omega\Big|_{t=0} = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)\,d\omega$$

$\omega = 0$ & $t = 0$

Property

$\omega = 0$ (DC) value

$$F(0) = F(\omega)\big|_{\omega=0} = \int_{-\infty}^{\infty} f(t)e^{-j\omega t}\,dt\bigg|_{\omega=0} = \int_{-\infty}^{\infty} f(t)\,dt$$

Property

$t = 0$ value

$$f(0) = f(t)\big|_{t=0} = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)e^{j\omega t}\,d\omega\bigg|_{t=0} = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)\,d\omega$$

Outline

Convolution

Property

Convolution (particularly useful for LTI systems)

$$y(t) = h(t) * x(t) \overset{\mathcal{F}}{\longleftrightarrow} Y(\omega) = H(\omega)X(\omega)$$

Convolution: proof

$$Y(\omega) = \int_{-\infty}^{\infty} y(t)e^{-j\omega t}\,dt = \int_{-\infty}^{\infty} (x(t) * h(t))e^{-j\omega t}\,dt$$

$$= \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\infty} x(t-\tau)h(\tau)\,d\tau\right] e^{-j\omega t}\,dt$$

$$= \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\infty} x(t-\tau)e^{-j\omega t}\,dt\right] h(\tau)\,d\tau$$

$$= \int_{-\infty}^{\infty} X(\omega)e^{-j\omega\tau} h(\tau)\,d\tau \quad \textit{(time-shift property)}$$

$$= X(\omega)\int_{-\infty}^{\infty} h(\tau)e^{-j\omega\tau}\,d\tau$$

$$= X(\omega)H(\omega)$$

Convolution: proof

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Convolution: example

Example

eigenfunction revisited

$$x(t) = e^{j\omega_0 t} \rightarrow \boxed{\text{LTI } h(t)} \rightarrow y(t)$$

$$Y(\omega) = H(\omega)X(\omega) = H(\omega)2\pi\delta(\omega-\omega_0) = H(\omega_0)2\pi\delta(\omega-\omega_0),$$

by the sampling property of impulse functions. So

$$Y(\omega) = H(\omega_0)2\pi\delta(\omega-\omega_0) \overset{\mathcal{F}}{\longleftrightarrow} \boxed{y(t) = H(\omega_0)e^{j\omega_0 t}}$$

as we have seen previously.

Convolution: example

Example

eigenfunction revisited

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$$Y(\omega) = H(\omega)X(\omega) = H(\omega)2\pi\delta(\omega - \omega_0) = H(\omega_0)2\pi\delta(\omega - \omega_0),$$

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Convolution: example

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eigenfunction revisited

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as we have seen previously.

Practical use of the convolution property

The convolution property says

$$x(t) \rightarrow \boxed{\text{LTI } h(t)} \rightarrow y(t) = h(t) * x(t)$$

so

$$y(t) \overset{\mathcal{F}}{\longleftrightarrow} Y(\omega) = H(\omega)X(\omega)$$

$$e^{j\omega_0 t} \rightarrow \boxed{h(t)} \rightarrow y(t) = h(t) * e^{j\omega_0 t} = H(\omega_0)e^{j\omega_0 t}$$

Practical use of the convolution property

The convolution property says

$$x(t) \rightarrow \boxed{\text{LTI } h(t)} \rightarrow y(t) = h(t) * x(t)$$

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$$e^{j\omega_0 t} \rightarrow \boxed{h(t)} \rightarrow y(t) = h(t) * e^{j\omega_0 t} = H(\omega_0)e^{j\omega_0 t}$$

Interchangeable notation

$H(\omega)$ and $H(j\omega)$ are interchangeable notation

$$H(\omega) = H(j\omega) = \int_{-\infty}^{\infty} h(t)e^{-j\omega t}\,dt$$

- $H(\omega)$: **frequency response**
- $|H(\omega)|$: **magnitude response**
- $\angle H(\omega)$: **phase response**

Time integration

Property

time integration

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

Time integration: proof

$$\int_{-\infty}^{t} f(\tau)\, d\tau = f(t) * u(t)$$

$$\int_{-\infty}^{t} f(\tau)\, d\tau \xleftrightarrow{\mathcal{F}} F(\omega)U(\omega) = F(\omega)\left(\pi\delta(\omega) + \frac{1}{j\omega}\right)$$

so

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Note that $|1/(jw)| = |1/\omega|$ *is a lowpass filter.*

Time integration: proof

$$\int_{-\infty}^{t} f(\tau)\, d\tau = f(t) * u(t)$$

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Finding LTI system response via FT methods

Skill: ***Finding LTI system response (output signal) via FT methods***

Recipe:

1. Find input spectrum $X(\omega)$ (often using FT table)
2. Find system frequency response $H(\omega)$ (often using FT table)
3. Multiply: $Y(\omega) = H(\omega)X(\omega)$
4. Take inverse FT to get $y(t)$ (often using PFE and FT table).

Basic Fourier Transform Pairs (Text TABLE 4.2, p.329)

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Basic Fourier Transform Pairs (Text TABLE 4.2, p.329)

Example (1)

Example

Suppose the aperiodic input signal $x(t) = \cos(t) + \cos(2\pi t)$ is applied to an LTI system with impulse response $h(t) = \text{sinc}(t/2)$. Determine the output signal $y(t)$.

Example (2)

1. Find input spectrum

$$X(\omega) = \pi\delta(\omega - 1) + \pi\delta(\omega + 1) + \pi\delta(\omega - 2\pi) + \pi\delta(\omega + 2\pi)$$

2. Find system frequency response

$$h(t) = \mathrm{sinc}(t/2) \xleftrightarrow{\mathcal{F}} H(\omega) = 2\,\mathrm{rect}\left(\frac{\omega}{\pi}\right)$$

3. Multiply

$$Y(\omega) = H(\omega)X(\omega) = 2[\pi\delta(\omega - 1) + \pi\delta(\omega + 1)]$$

4. Take inverse FT to get $y(t)$

$$y(t) = \boxed{2\cos(t)}$$

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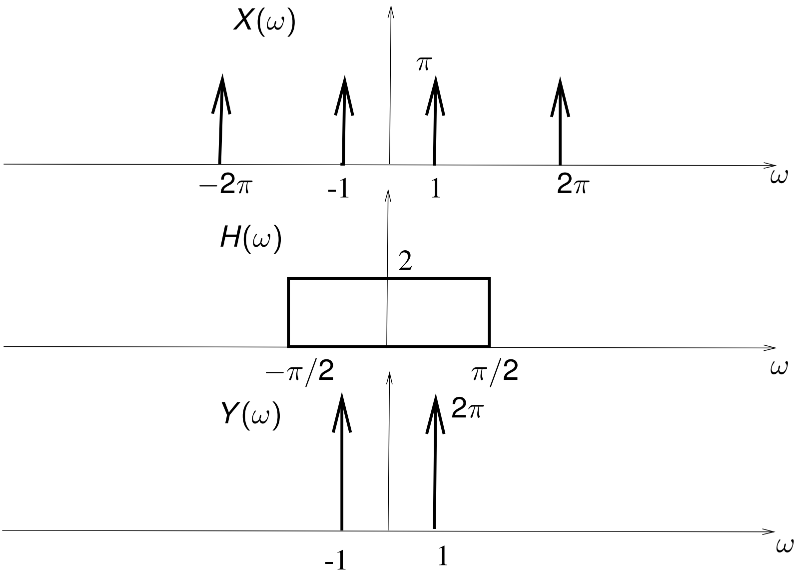
$X(\omega)$
π
-2π
-1
1
2π
ω
$H(\omega)$
2
$-\pi/2$
$\pi/2$
ω
$Y(\omega)$
2π
-1
1
ω

Taking an inverse FT

The final step of this process involves taking an inverse FT.
There are several ways to do this:

- Table lookup
- Inverse FT formula (integration)
- Use of FT properties (along with table)
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Taking an inverse FT: example (1)

Example

Find $y(t) = [e^{-at}u(t)] * [e^{-at}u(t)]$.

Taking an inverse FT: solution (1)

$$y(t) \stackrel{\mathcal{F}}{\longleftrightarrow} Y(\omega) = \frac{1}{j\omega + a}\frac{1}{j\omega + a} = \left(\frac{1}{j\omega + a}\right)^2$$

Using FT table (textbook, TABLE 4.2)

$$y(t) = te^{-at}u(t)$$

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Taking an inverse FT: example (2)

Example

Find $y(t) = [e^{-t}u(t)] * [e^{-2t}u(t)]$.

Taking an inverse FT: solution (2)

$$y(t) = [e^{-t}u(t)] * [e^{-2t}u(t)] \xleftrightarrow{\mathcal{F}} Y(\omega) = \frac{1}{j\omega+1}\frac{1}{j\omega+2}$$

$$Y(\omega) = Y(s) = \left.\frac{1}{s+1}\frac{1}{s+2}\right|_{s=j\omega}$$

partial fraction expansion (PFE)

$$Y(s) = \frac{1}{s+1}\frac{1}{s+2} = \frac{r_1}{s+1} + \frac{r_2}{s+2}$$

The next step is to determine r_1 and r_2.

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Taking an inverse FT: solution (3)

Multiplying both sides by $s+1$

$$(s+1)Y(s) = r_1 + \frac{r_2(s+1)}{s+2}$$

and now evaluate at $s=-1$*;*

$$(s+1)Y(s)\big|_{s=-1} = r_1 + \left.\frac{r_2(s+1)}{s+2}\right|_{s=-1}$$

$$\implies r_1 = \frac{1}{-1+2} = 1$$

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Taking an inverse FT: solution (4)

Similarly multiplying both sides by $s+2$

$$(s+2)Y(s) = \frac{r_1(s+2)}{s+1} + r_2$$

and now evaluate at $s=-2$;

$$(s+2)Y(s)|_{s=-2} = \left.\frac{r_1(s+2)}{s+1}\right|_{s=-2} + r_2$$

$$\Longrightarrow r_2 = \frac{1}{-2+1} = -1$$

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Taking an inverse FT: solution (5)

$$Y(\omega) = Y(s)|_{s=j\omega} = \frac{1}{j\omega+1} + \frac{-1}{j\omega+2}.$$

$$\boxed{y(t) = e^{-t}u(t) - e^{-2t}u(t)}$$

This example illustrates the PFE method, which applies when one needs to find the inverse FT of a spectrum that is a rational function of $j\omega$.

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Taking an inverse FT: example (3)

Example

Find the FT of $y(t) = \text{tri}(t)$.

Taking an inverse FT: solution (6)

We have seen that

$$\mathrm{tri}(t) = \mathrm{rect}(t) * \mathrm{rect}(t).$$

We know that

$$\mathrm{rect}(t) \overset{\mathcal{F}}{\longleftrightarrow} \mathrm{sinc}\left(\frac{\omega}{2\pi}\right)$$

Thus

$$Y(\omega) = \mathrm{sinc}\left(\frac{\omega}{2\pi}\right)\mathrm{sinc}\left(\frac{\omega}{2\pi}\right).$$

So

$$\boxed{\mathrm{tri}(t) \overset{\mathcal{F}}{\longleftrightarrow} \mathrm{sinc}^2\left(\frac{\omega}{2\pi}\right).}$$

Convolution and LTI systems (1)

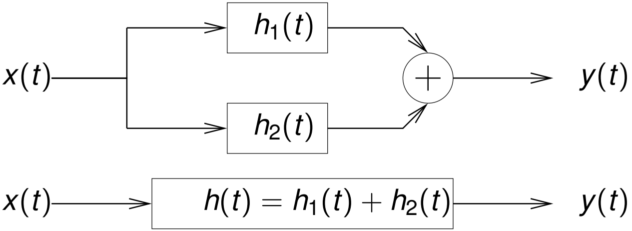
We have seen that when two LTI systems are connected in parallel, *i.e.*

$$y(t) = [h_1(t) * x(t)] + [h_2(t) * x(t)],$$

the output signal is

$$y(t) = h(t) * x(t), \quad \text{where} \quad h(t) = h_1(t) + h_2(t).$$

Distributive



Convolution and LTI systems (2)

$$h(t) = h_1(t) + h_2(t)$$

Thus the overall frequency response of two LTI systems connected in parallel is given by the sum of the frequency responses of the individual systems:

$$H(\omega) = H_1(\omega) + H_2(\omega).$$

Convolution and LTI systems (3)

When two LTI systems are connected in series, *i.e.*

$$y(t) = h_2(t) * [h_1(t) * x(t)], ,$$

the output signal is

$$y(t) = h(t) * x(t), \quad \text{where} \quad h(t) = h_1(t) * h_2(t).$$

$$x(t) \longrightarrow \boxed{h_1(t)} \longrightarrow \boxed{h_2(t)} \longrightarrow y(t)$$

Associative

$$x(t) \longrightarrow \boxed{h(t) = h_1(t) * h_2(t)} \longrightarrow y(t)$$

Convolution and LTI systems (4)

$$h(t) = h_1(t) * h_2(t)$$

Thus the overall frequency response of two LTI systems connected in series is given by the product of the frequency responses of the individual systems:

$$H(\omega) = H_1(\omega)H_2(\omega).$$

Since multiplication is commutative, the order of serial interconnection of LTI subsystems has no effect on the overall frequency response of the system.

$$h(t) = h_1(t) * h_2(t) = h_2(t) * h_1(t)$$

Commutative property of convolution.

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Outline

Energy signal

We have previously defined the energy of a CT signal $x(t)$ to be

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

- If $E < \infty$ then we say $x(t)$ is an energy signal.
- If $x(t)$ has finite duration or if $x(t)$ decays to zero rapidly enough as $|t| \to \infty$, then $x(t)$ will be an energy signal.

The above definition is for the time domain. How can we measure energy in the frequency domain? Answered by Parseval!

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Parseval's relation

Property

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

time-domain energy vs frequency domain!

For this reason, $|X(\omega)|^2$ is sometimes called the **energy density spectrum**.

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Parseval's relation: proof

$$\int_{-\infty}^{\infty} x(t)x^*(t)\,dt = \int_{-\infty}^{\infty} x(t)\left[\frac{1}{2\pi}\int_{-\infty}^{\infty} X(\omega)e^{j\omega t}\,d\omega\right]^* dt$$

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Energy density spectrum

Generally, since $Y(\omega) = H(\omega)X(\omega)$, we have

$$|Y(\omega)|^2 = |H(\omega)|^2|X(\omega)|^2$$

This expression relates the energy density spectrum of the output of an LTI system to the energy density spectrum of its input.

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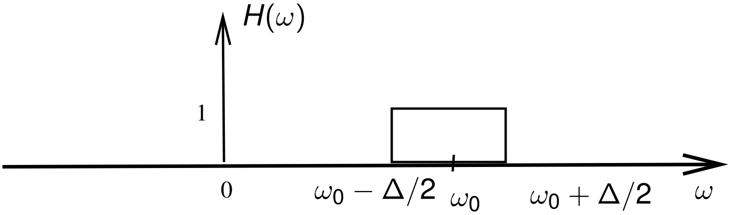
Physical interpretation

Physical interpretation.
Imagine passing a signal $x(t)$ through a bandpass filter with a narrow passband centered at some ω_0, *i.e.*

$$H(\omega) = \text{rect}\left(\frac{\omega - \omega_0}{\Delta}\right)$$



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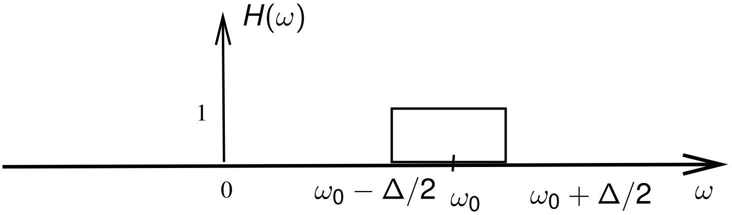

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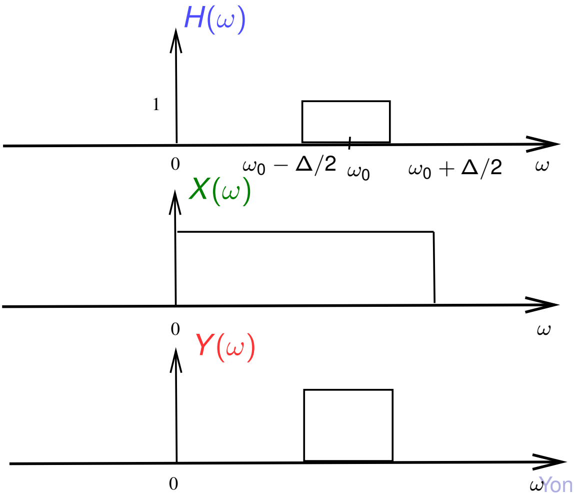

Total energy of the output

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

$$= \lim_{T\to\infty} \frac{1}{T} \int_{-\infty}^{\infty} |f_T(t)|^2 \, dt$$

where

$$f_T(t) \triangleq x(t) \, \mathrm{rect}(t/T)$$

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This is a time-domain expression. How do we express power in the frequency domain?

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$$P_f(\omega) \triangleq \lim_{T\to\infty} \frac{1}{T} |F_T(\omega)|^2$$

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Periodic signals

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$$x(t) = \sum_{k=-\infty}^{\infty} c_k e^{jk\omega t}.$$

We have shown previously that

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Periodic signals and LTI systems

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$$x(t) \to \boxed{\mathrm{H}} \to y(t)$$

then

$$\boxed{P_y(\omega) = |H(\omega)|^2 P_x(\omega).}$$

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Cross correlation

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Property

Cross Correlation

$$r_{xy}(t) = x(t) * y^*(-t) \overset{\mathcal{F}}{\longleftrightarrow} S_{xy}(\omega) = X(\omega)Y^*(\omega)$$

If $x(t)$ and $y(t)$ real, then

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Autocorrelation

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$$r_{xx}(t) = x(t) * x^*(-t) \xleftrightarrow{\mathcal{F}} S_{xx}(\omega) = |X(\omega)|^2$$

Outline

Time-domain multiplication

Property

Time-domain multiplication

$$f_1(t)f_2(t) \xleftrightarrow{\mathcal{F}} \frac{1}{2\pi}F_1(\omega) * F_2(\omega)$$

Time-domain multiplication: proof

skip

$$
\begin{aligned}
F(\omega) &= \int_{-\infty}^{\infty} f(t) e^{-j\omega t}\, dt = \int_{-\infty}^{\infty} f_1(t) f_2(t) e^{-j\omega t}\, dt \\
&= \int_{-\infty}^{\infty} \left[\frac{1}{2\pi} \int_{-\infty}^{\infty} F_1(\lambda) e^{j\lambda t}\, d\lambda \right] f_2(t) e^{-j\omega t}\, dt \\
&= \frac{1}{2\pi} \int_{-\infty}^{\infty} F_1(\lambda) \left[\int_{-\infty}^{\infty} f_2(t) e^{-j(\omega-\lambda)t} \right] d\lambda \\
&= \frac{1}{2\pi} \int_{-\infty}^{\infty} F_1(\lambda) F_2(\omega - \lambda)\, d\lambda \\
&= \frac{1}{2\pi} F_1(\omega) * F_2(\omega).
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Frequency shift

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Frequency shift (complex modulation)

$$e^{j\omega_0 t} f(t) \xleftrightarrow{\mathcal{F}} F(\omega - \omega_0)$$

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Proof:

1. *use the time-domain multiplication property*
2. *use the inverse FT formula*

Frequency shift proof (1)

Method 1 (use the time-domain multiplication property)

Since

$$e^{j\omega_0 t} \xleftrightarrow{\mathcal{F}} 2\pi\delta(\omega - \omega_0)$$

from the time-domain multiplication property we have

$$e^{j\omega_0 t} f(t) \xleftrightarrow{\mathcal{F}} \frac{1}{2\pi}[2\pi\delta(\omega - \omega_0)] * F(\omega) = \delta(\omega - \omega_0) * F(\omega) = F(\omega - \omega_0)$$

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Frequency shift proof (2)

Method 2 (use the inverse FT formula)

$$F(\omega - \omega_0) \xleftrightarrow{\mathcal{F}} \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega - \omega_0) e^{j\omega t}\, d\omega$$

$$= \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega') e^{j(\omega' + \omega_0)t}\, d\omega' \quad (\omega' = \omega - \omega_0)$$

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Modulation: example

Example

Find the FT of $f(t)\cos\omega_0 t$.

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$$\cos\omega_0 t = \frac{1}{2}e^{j\omega_0 t} + \frac{1}{2}e^{-j\omega_0 t}$$

By frequency shift property and linearity.

$$\boxed{f(t)\cos\omega_0 t \overset{\mathcal{F}}{\longleftrightarrow} \frac{F(\omega-\omega_0)+F(\omega+\omega_0)}{2}}$$

Summary

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1. Convolution in time domain corresponds to multiplication in frequency domain.
2. Multiplication in time domain corresponds to convolution in frequency domain (with an extra $1/2\pi$).

Time-domain multiplication: example(1)

Example

1. Find FT of a causal cosine $x(t) = \cos(\omega_0 t)\, u(t)$.
2. Find the FT of a causal cosine $x(t) = \cos(\omega_0 t + \phi)\, u(t)$.

Time-domain multiplication: example(1)

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Hints: Apply the delay property to the cosine part:

$$x(t) = \cos(\omega_0 t + \phi)\, u(t) = \cos(\omega_0(t + \phi/\omega_0))u(t)$$

$$f(t - t_0) \xleftrightarrow{\mathcal{F}} e^{-j\omega t_0} F(\omega)$$

Time-domain multiplication: solution(1)

$$X(\omega) = \frac{1}{2\pi}[\pi\delta(\omega - \omega_0) + \pi\delta(\omega + \omega_0)] * \left[\pi\delta(\omega) + \frac{1}{j\omega}\right]$$

$$= \frac{\pi}{2}[\delta(\omega - \omega_0) + \delta(\omega + \omega_0)] + \frac{1}{2}\left[\frac{1}{j(\omega - \omega_0)} + \frac{1}{j(\omega + \omega_0)}\right]$$

Simplifying yields

$$\boxed{\cos(\omega_0 t)\, u(t) \xleftrightarrow{\mathcal{F}} \frac{\pi}{2}[\delta(\omega - \omega_0) + \delta(\omega + \omega_0)] + \frac{j\omega}{(j\omega)^2 + \omega_0^2}.}$$

As a sanity check, when $\omega_0 = 0$ *we get*

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as expected.

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$x(t) = \cos(\omega_0 t + \phi)\, u(t) = \cos(\omega_0(t + \phi/\omega_0))u(t)$. *Applying the delay property to the cosine part:*

$$
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X(\omega) &= \frac{1}{2\pi} e^{j(\phi/\omega_0)\omega}[\pi\delta(\omega - \omega_0) + \pi\delta(\omega + \omega_0)] * \left[\pi\delta(\omega) + \frac{1}{j\omega}\right] \\
&= \frac{1}{2}[e^{j\phi}\delta(\omega - \omega_0) + e^{-j\phi}\delta(\omega + \omega_0)] * \left[\pi\delta(\omega) + \frac{1}{j\omega}\right] \\
&= \frac{\pi}{2}[e^{j\phi}\delta(\omega - \omega_0) + e^{-j\phi}\delta(\omega + \omega_0)] + \frac{1}{2}\left[\frac{e^{j\phi}}{j(\omega - \omega_0)} + \frac{e^{-j\phi}}{j(\omega + \omega_0)}\right]
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Time-domain multiplication

Property

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Pulsed cosine (1)

Example

pulsed cosine.

Find FT of

$$f(t) = \mathrm{rect}(t/T)\cos(\omega_0 t)\,.$$

Plot its signal spectrum and energy density spectrum.

Pulsed cosine (2)

$$f(t) = \mathrm{rect}(t/T)\cos(\omega_0 t) = f_1(t/T)f_2(t)$$

$$f_1(t) \triangleq \mathrm{rect}(t), \quad f_2(t) \triangleq \cos(\omega_0 t)$$

Using time-scaling and time-domain multiplication properties

$$F(\omega) = \frac{1}{2\pi} T F_1(\omega T) * F_2(\omega)$$

$$= \frac{1}{2\pi} T \,\mathrm{sinc}\left(T\frac{\omega}{2\pi}\right) * \{\pi[\delta(\omega - \omega_0) + \delta(\omega + \omega_0)]\}$$

$$\boxed{= \frac{1}{2}\left[T\,\mathrm{sinc}\left(T\frac{\omega - \omega_0}{2\pi}\right) + T\,\mathrm{sinc}\left(T\frac{\omega + \omega_0}{2\pi}\right)\right]}$$

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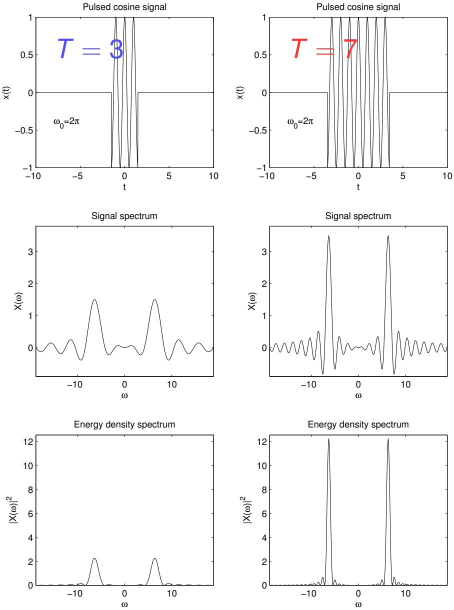
Pulsed cosine (3)



Pulsed cosine (4)

- As T increases, the spectrum becomes more concentrated at the center frequency ω_0.
- Recall that a pure periodic signal only has frequency components at multiples of the fundamental.
- Even thought the $f(t)$ above is not periodic, its spectrum is "similar" to that of a periodic signal in that most of its energy is near the frequency component ω_0.

Pulsed cosine (4)

This type of signal is used in digital communications.
The following practical tradeoff is unavoidable:

> increasing T will narrow the spectrum (use less bandwidth), but the corresponding signal is then longer in the time domain.

Outline

Application of the FT to RLC circuits

Using properties of the FT, we can solve many problems associated with diffeq systems in general and RLC circuits in particular.

- Find frequency response $H(\omega)$.
- Find impulse response $h(t)$.
- Determine response $y(t)$ to a given input signal $x(t)$

The key properties of the FT are:

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Finding response $y(t)$ of RLC circuit (1)

Finding response $y(t)$ of RLC circuit to a simple input.

Example

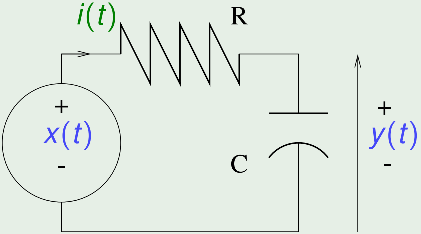
We showed that for the following RC circuit we have

$$h(t) = (1/RC)e^{-t/RC}u(t)$$

and

$$H(\omega) = \frac{1}{1 + j\omega RC}.$$

Find the step response of this system via FT methods.



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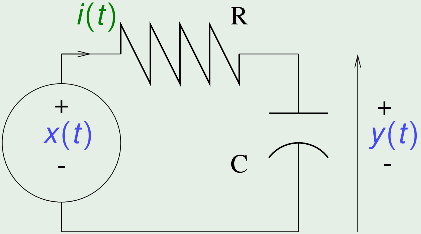

Finding response $y(t)$ of RLC circuit (2)

$$Y(\omega) = H(\omega)X(\omega) = \frac{1}{1 + j\omega RC}[\pi\delta(\omega) + 1/j\omega]$$

$$= \underbrace{\frac{1}{1 + j\omega RC}\pi\delta(\omega)}_{\text{sampling property}} + \underbrace{\frac{1}{j\omega}\frac{1}{1 + j\omega RC}}_{\text{PFE for simple inverse FT}}$$

$$= \pi\delta(\omega) + \frac{1}{j\omega}\frac{1 + j\omega RC - j\omega RC}{1 + j\omega RC}$$

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Taking the inverse FT by table lookup, we get the following system step response:

$$\boxed{y(t) = u(t) - e^{-t/RC}u(t) = (1 - e^{-t/RC})u(t)}$$

This example is simple enough that both the time-domain and frequency-domain approaches were comparable effort. But for more complicated systems, the frequency-domain method is usually easier than solving diffeqs and/or convolution!

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Basic idea

Prior to this point, to find $H(\omega)$ for a diffeq system or RLC circuit, we had to first find the diffeq for the circuit (time domain). Now we can work in the frequency domain.

Basic idea:

$$X(\omega) \to \boxed{\text{LTI } H(\omega)} \to Y(\omega) = H(\omega)X(\omega)$$

we can rearrange above formula to get

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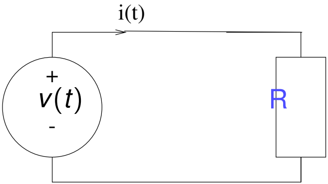
Resister



Resistor:

$$v(t) = i(t)R$$

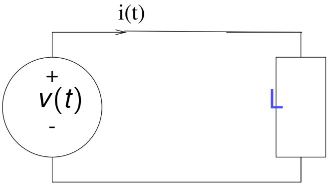
so

$$V(\omega) = I(\omega)R$$

or

$$\boxed{\frac{V(\omega)}{I(\omega)} = R}$$

Inductor



Inductor:

$$v(t) = L\frac{\mathrm{d}}{\mathrm{d}t}i(t)$$

So by the differentiation property

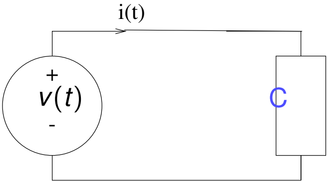
$$V(\omega) = Lj\omega I(\omega)$$

Thus

$$\boxed{\frac{V(\omega)}{I(\omega)} = j\omega L}$$

This is the **complex impedance** of an inductor derived by FT methods!

Capacitor



Capacitor:

$$i(t) = C\frac{\mathrm{d}}{\mathrm{d}t}v(t)$$

so by the differentiation property.

$$I(\omega) = Cj\omega V(\omega)$$

Thus

$$\boxed{\frac{V(\omega)}{I(\omega)} = \frac{1}{j\omega C}}$$

Impedance

$$
\begin{aligned}
\text{Resistor} &: \quad \frac{V(\omega)}{I(\omega)} = R \\
\text{Inductor} &: \quad \frac{V(\omega)}{I(\omega)} = j\omega L \\
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- In the frequency domain, diffeq's become simply ratios!
- Usual rules for combining resistances in series and parallel apply to impedances.
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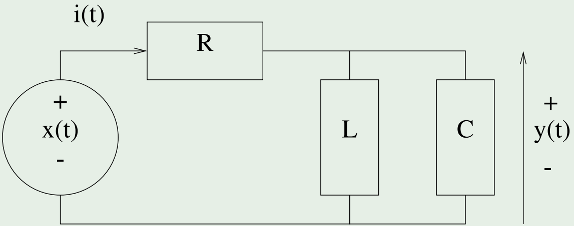
Example (1)

Example

Find frequency response $H(\omega)$, diffeq, and impulse response $h(t)$ for the following circuit.



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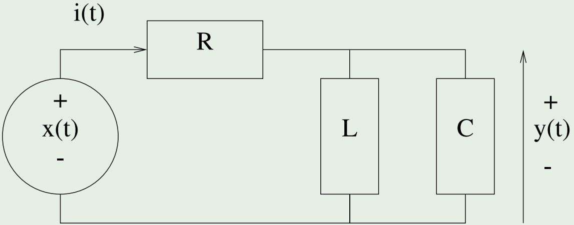
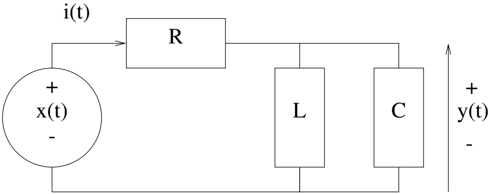


1. *Time domain approach using diffeq*
2. *Frequency domain approach using complex impedances.*

Time domain approach (1)

Time domain approach using diffeq



1. $i(t)$ on R

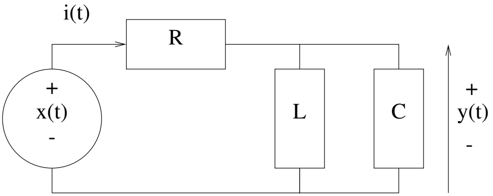
$$i(t) = \frac{x(t) - y(t)}{R} \Longrightarrow I(\omega) = \frac{X(\omega) - Y(\omega)}{R}$$

2. $i(t)$ on L and C

$$i(t) = i_L(t) + i_C(t) \Longrightarrow I(\omega) = I_L(\omega) + I_C(\omega) = \frac{Y(\omega)}{j\omega L} + Y(\omega)(j\omega C)$$

Time domain approach (1)

Time domain approach using diffeq



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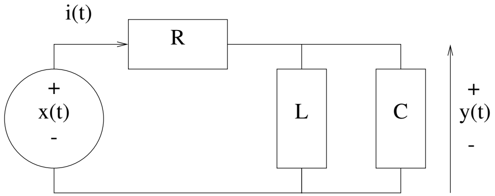
Time domain approach using diffeq



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Time domain approach (2)

Equating:

$$\frac{X(\omega) - Y(\omega)}{R} = \frac{Y(\omega)}{j\omega L} + Y(\omega)(j\omega C)$$

$$\implies \quad Y(\omega)\left(\frac{1}{R} + \frac{1}{j\omega L} + j\omega C\right) = \frac{X(\omega)}{R}$$

Thus

$$H(\omega) = \frac{Y(\omega)}{X(\omega)} = \frac{1/R}{1/R + 1/(j\omega L) + j\omega C}$$

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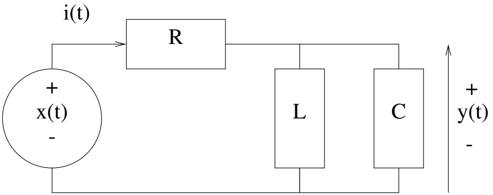
Frequency domain approach (1)

Frequency domain approach using complex impedances.



Equivalent impedance of parallel combination of inductor and capacitor:

$$Z(\omega) = \left[(j\omega L)^{-1} + j\omega C\right]^{-1}.$$

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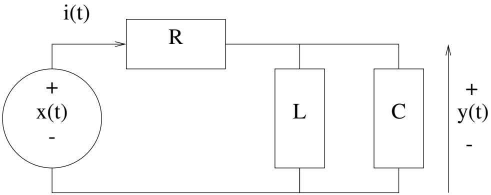
Frequency domain approach using complex impedances.



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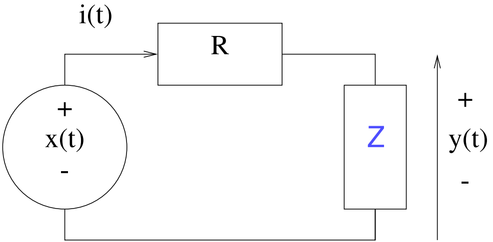

Considering equivalent circuit above as a (complex) voltage divider:

$$H(\omega) = \frac{Y(\omega)}{X(\omega)} = \frac{Z(\omega)}{Z(\omega)+R} = \frac{1}{1+R/Z(\omega)}$$

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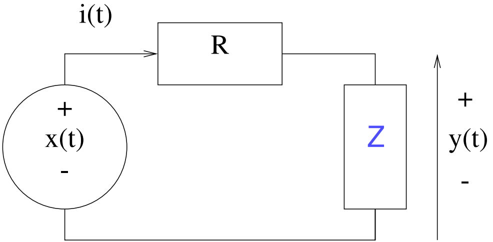
Frequency domain approach (2)



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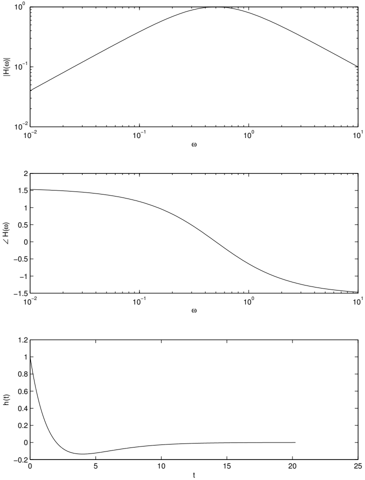
$$= \frac{1}{1 + R\left[(j\omega L)^{-1} + j\omega C\right]} = \frac{j\omega}{R/L + j\omega + (j\omega)^2 RC}$$

Frequency response from RLC circuits: Example (3)

Now it is trivial to plot magnitude and phase response using MATLAB's `freqs` command for given RLC values.



MATLAB code (1)

```
a = [1 1 1/4]; %RC = 1; R/L = 1/4
b = [1 0]; %start from higher-order coefficients
[H,o]= freqs(b,a);
sys = tf(b,a);
[h,t] = impulse(sys);
plot(h,t)

subplot(311)
loglog(o, abs(H))
xlabel('\omega'), ylabel('|H(\omega)|')
subplot(312)
semilogx(o, angle(H))
xlabel('\omega'), ylabel('\angle H(\omega)')
subplot(313)
plot(t, h)
xlabel('t'), ylabel('h(t)')
```

MATLAB code (2)

- [H, w] = freqs(b,a) evaluates the complex frequency response of the analog filter specified by coefficient vectors b and a at auto-generated angular frequencies (200 points by default) in rad/s specified in real vector w.
- sys = tf(b, a) creates a continuous-time transfer function with numerator(s) and denominator(s) specified by b and a.
- [y,t] = impulse(sys) returns the output response y and the time vector t used for simulation (if not supplied as an argument to impulse).
- loglog(X,Y) creates a plot using a logarithmic scale for both the x-axis and the y-axis.
- semilogx(X,Y) creates a plot with a logarithmic scale for the x-axis and a linear scale for the y-axis.

Find $H(\omega)$ experimentally

The analysis above is the mathematical approach.

Question

How would one find $H(\omega)$ experimentally?

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$$\cos(\omega_0 t) \rightarrow \boxed{LTI} \rightarrow |H(\omega_0)|\cos(\omega_0 t + \angle H(\omega_0))$$

Diffeq from $H(\omega)$(1)

Question

How to find the diffeq from $H(\omega)$?

$$H(\omega) = \frac{j\omega}{R/L + j\omega + (j\omega)^2 RC}.$$

Diffeq from $H(\omega)$(2)

We know that

$$H(\omega) = \frac{Y(\omega)}{X(\omega)} = \frac{j\omega}{R/L + j\omega + (j\omega)^2 RC}.$$

Cross multiplying yields

$$[R/L + j\omega + (j\omega)^2 RC]Y(\omega) = j\omega X(\omega).$$

Thus, by the time-domain differentiation property of the FT, the corresponding diffeq is

$$\boxed{\frac{R}{L}y(t) + \frac{\mathrm{d}}{\mathrm{d}t}y(t) + RC\frac{d^2}{dt^2}y(t) = \frac{\mathrm{d}}{\mathrm{d}t}x(t)}$$

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Impulse response from $H(\omega)$

- In principle, $h(t)$ is "simply" the inverse FT of $H(\omega)$.
- But you will not find this particular $H(\omega)$ in most FT tables, and trying to find the inverse FT by integration will be challenging!
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Impulse response from $H(\omega)$: example (1)

General idea. First note that

$$H(\omega) = \frac{j\omega}{R/L + j\omega + (j\omega)^2 RC} = \left.\frac{s}{s^2 RC + s + R/L}\right|_{s=j\omega}.$$

Suppose $RC = 1$ and $R/L = 1/4$. Then

$$H(\omega) = \left.\frac{s}{s^2 + s + 1/4}\right|_{s=j\omega} = \left.\frac{s}{(s+1/2)^2}\right|_{s=j\omega} = \frac{j\omega}{(j\omega + 1/2)^2}.$$

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$$te^{-t/2}u(t) \overset{\mathcal{F}}{\longleftrightarrow} 1/(j\omega + 1/2)^2$$

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Impulse response from $H(\omega)$: example (2)

The extra $j\omega$ in $H(\omega)$ is equivalent to differentiating in the time domain. Thus

$$h(t) = \boxed{\frac{\mathrm{d}}{\mathrm{d}t} te^{-t/2}u(t) = (1 - t/2)e^{-t/2}u(t)}.$$

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- *How do we do this in general?*

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Question

- *How did we do this in this case?*
  We managed to manipulate $H(\omega)$ into a form where we recognized the inverse transform.
- *How do we do this in general?*
  PFE

Outline

Summary

- Defined FT and inverse FT by limits of FS
- Existence of FT
- FT of many important signals
- FT properties (!)
- FT of periodic signals
- Parseval's relation (Energy density spectrum)
- convolution property and LTI systems
- Application of FT to RLC and diffeq systems