

Power Density Spectrum - Continuous Time

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Based on
Probability, Random Variables and Random Signal Principles,
P.Z. Peebles,Jr. and B. Shi

Energy and average power in time domain

for continuous time signals

Energy, Average Power – deterministic, time domain

a deterministic signal $x(t)$

$$x_T(t) = \begin{cases} x(t) & -T < t < T \\ 0 & \text{otherwise} \end{cases}$$

the energy

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

the average power

$$P(T) = \frac{1}{2T} \int_{-T}^{+T} x^2(t) dt = \frac{1}{2T} \int_{-\infty}^{+\infty} x_T^2(t) dt$$

Fourier transform

for continuous time signals

Fourier Transform Pair $x(t) \longleftrightarrow X(\omega)$

Fourier transform

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

a deterministic signal $x(t)$

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

Fourier transform of $x_T(t)$

for continuous time signals

bounded duration, bounded variation

for a finite T , $x_T(t)$ is assumed to have bounded variation

$$\int_{-T}^{+T} |x(t)| dt < \infty$$

the Fourier transform of $x_T(t)$

$$\begin{aligned} X_T(\omega) &= \int_{-\infty}^{+\infty} x_T(t) e^{-j\omega t} dt \\ &= \int_{-T}^{+T} x(t) e^{-j\omega t} dt \end{aligned}$$

Fourier transforms of $x_T(t)$ and $X_T(t)$

for continuous time signals

deterministic $X_T(\omega)$ v.s. random $X_T(\omega)$

a **deterministic** sample signal $x_T(t)$

$$x_T(t) \iff X_T(\omega)$$

a **random process** signal $X_T(t)$

$$X_T(t) \iff X_T(\omega)$$

Parseval's theorem (I)

for continuous time signals

for a deterministic $x_T(t)$

a **deterministic** sample signal $x_T(t)$

$$\int_{-\infty}^{+\infty} x_T(\tau)x_T^*(\tau)d\tau = \frac{1}{2\pi} \int_{-\infty}^{+\infty} X_T(\omega)X_T^*(\omega)d\omega$$

$$\int_{-\infty}^{+\infty} |x_T(\tau)|^2 d\tau = \frac{1}{2\pi} \int_{-\infty}^{+\infty} |X_T(\omega)|^2 d\omega$$

Parseval's theorem (II)

for continuous time signals

for a deterministic $x_T(t)$ v.s. a random $X_T(t)$

- a **deterministic** signal $x_T(t) \iff X_T(\omega)$

$$\int_{-\infty}^{+\infty} |x_T(t)|^2 dt = \frac{1}{2\pi} \int_{-\infty}^{+\infty} |X_T(\omega)|^2 d\omega$$

- a **random** signal $X_T(t) \iff X_T(\omega)$

$$\int_{-\infty}^{+\infty} E \left[|X_T(t)|^2 \right] dt = \frac{1}{2\pi} \int_{-\infty}^{+\infty} E \left[|X_T(\omega)|^2 \right] d\omega$$

Energy and average power in frequency domain for continuous time signals

Energy, Average Power – Parseval's theorem applied

a deterministic signal $x_T(t)$

$$x_T(t) = \begin{cases} x(t) & -T < t < T \\ 0 & \text{otherwise} \end{cases} \quad x_T(t) \iff X_T(\omega)$$

the **energy** by Parseval's theorem

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

the **average power** by Parseval's theorem

$$P(T) = \frac{1}{2T} \int_{-T}^{+T} x^2(t) dt = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \frac{|X_T(\omega)|^2}{2T} d\omega$$

$E(T)$ and $P(T)$ in frequency domain – deterministic case for continuous time signals

deterministic $x_T(t) \iff X_T(\omega)$

the **energy** for the **deterministic** $X_T(\omega)$ in $x_T(t) \iff X_T(\omega)$

$$E(T) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} |X_T(\omega)|^2 d\omega$$

the **average power** for the **deterministic** $X_T(\omega)$

$$P(T) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \frac{|X_T(\omega)|^2}{2T} d\omega$$

the **power density spectrum** for the **deterministic** $X_T(\omega)$

$$\lim_{T \rightarrow \infty} \frac{|X_T(\omega)|^2}{2T}$$

$E(T)$ and $P(T)$ in frequency domain – random case for continuous time signals

random $X_T(t) \iff X_T(\omega)$

the **energy** for the **random** $X_T(\omega)$ in $X_T(t) \iff X_T(\omega)$

$$E(T) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} E[|X_T(\omega)|^2] d\omega$$

the **average power** for the **random** $X_T(\omega)$

$$P(T) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \frac{E[|X_T(\omega)|^2]}{2T} d\omega$$

the **power density spectrum** for the **random** $X_T(\omega)$

$$\lim_{T \rightarrow \infty} \frac{E[|X_T(\omega)|^2]}{2T}$$

Average power $P(T)$ – bounded duration $(-T, +T)$ for continuous time signals

$$P(T) = \frac{1}{2T} \int_{-T}^{+T} x^2(t) dt$$

- not the average power in a **random process**
only the power in **one** sample function
 - to obtain the **average power** over all possible realizations,
replace $x(t)$ by $X(t)$
take the **expected value** of $x^2(t)$, that is $E[X^2(t)]$
 - then, the **average power** is a **random variable**
with respect to the **random process** $X(t)$
- not the average power in an **entire** sample function
 - take $T \rightarrow \infty$ to include all power in the **ensemble** member

Average power P_{XX} – unbounded duration $(-\infty, +\infty)$ for continuous time signals

$$P(T) = \frac{1}{2T} \int_{-T}^{+T} x^2(t) dt$$

- replace $x(t)$ by the **random variable** $X(t)$
- take the **expected value** of $x^2(t)$, that is $E[X^2(t)]$

$$P(T) = \frac{1}{2T} \int_{-T}^{+T} E[X^2(t)] dt$$

- take $T \rightarrow \infty$ to include all power

$$P_{XX} = \lim_{T \rightarrow \infty} P(T) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^{+T} E[X^2(t)] dt$$

Average power P_{XX} – time average $A[\bullet]$

for continuous time signals

The time average

$$A_T[\bullet] = \frac{1}{2T} \int_{-T}^T [\bullet] dt \quad A[\bullet] = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T [\bullet] dt$$

time average and sample average operations

$$\begin{aligned} P_{XX} = \lim_{T \rightarrow \infty} P(T) &= \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^{+T} E[X^2(t)] dt \\ &= \lim_{T \rightarrow \infty} A_T[E[X^2(t)]] \\ &= A[E[X^2(t)]] \end{aligned}$$

Measuring average power

for continuous time signals

for deterministic and random signals

the **average power** $P(T)$ for a deterministic signal $x(t)$

$$P(T) = \frac{1}{2T} \int_{-T}^{+T} x^2(t) dt$$

the **average power** P_{XX} for a random process $X(t)$

$$\begin{aligned} P_{XX} &= \lim_{T \rightarrow \infty} P(T) \\ &= \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^{+T} E[X^2(t)] dt \\ &= A[E[X^2(t)]] \end{aligned}$$

Power density spectrum $S_{XX}(\omega)$

for continuous time signals

the average power via power density

the average power P_{XX} for the random process $X_T(\omega)$

$$\begin{aligned} P_{XX} &= \frac{1}{2\pi} \int_{-\infty}^{+\infty} \boxed{\lim_{T \rightarrow \infty} \frac{E[|X_T(\omega)|^2]}{2T}} d\omega \\ &= \frac{1}{2\pi} \int_{-\infty}^{+\infty} \boxed{S_{XX}(\omega)} d\omega \end{aligned}$$

the power density spectrum $S_{XX}(\omega)$

$$\boxed{S_{XX}(\omega)} = \boxed{\lim_{T \rightarrow \infty} \frac{E[|X_T(\omega)|^2]}{2T}}$$

Properties of Power Spectrum

for continuous time signals

- $S_{XX}(\omega) \geq 0$
- $S_{XX}(-\omega) = S_{XX}(\omega)$ $X(t)$ real
- $S_{XX}(\omega)$ real
- $\frac{1}{2\pi} \int_{-\infty}^{+\infty} S_{XX}(\omega) d\omega = A [E [X^2(t)]]$
- $S_{\dot{X}\dot{X}}(\omega) = \omega^2 S_{XX}(\omega)$
- $\frac{1}{2\pi} \int_{-\infty}^{+\infty} S_{XX}(\omega) e^{j\omega t} d\omega = A [R_{XX}(t, t + \tau)]$
- $S_{XX}(\omega) = \int_{-\infty}^{+\infty} A [R_{XX}(t, t + \tau)] e^{-j\omega\tau} d\tau$

Equations involving $S_{XX}(\omega)$

for continuous time signals

the average power P_{XX} and the inverse Fourier transform of $S_{XX}(\omega)$

the **average power** related equation

$$\frac{1}{2\pi} \int_{-\infty}^{+\infty} S_{XX}(\omega) d\omega = A [E [X^2(t)]]$$

the **autocorrelation** related equation

$$\frac{1}{2\pi} \int_{-\infty}^{+\infty} S_{XX}(\omega) e^{j\omega t} d\omega = A [R_{XX}(t, t + \tau)]$$

Average power related equation

for continuous time signals

the average power P_{xx}

the average power related equation

$$\frac{1}{2\pi} \int_{-\infty}^{+\infty} S_{XX}(\omega) d\omega = A [E [X^2(t)]]$$

- a random process $X(t)$ in time domain
- a random process $X(\omega)$ in frequency domain
- Parseval's theorem over $X_T(t) \iff X_T(\omega)$

$$X(t) = \lim_{T \rightarrow \infty} X_T(t)$$

$$X(\omega) = \lim_{T \rightarrow \infty} X_T(\omega)$$

Average power P_{XX} in time / frequency domain

for continuous time signals

Definition

Using a random process $X(t)$ in time domain

$$\begin{aligned} P_{XX} &= \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^{+T} E[X^2(t)] dt \\ &= \lim_{T \rightarrow \infty} A_T [E[X^2(t)]] = A[E[X^2(t)]] \end{aligned}$$

Using a random process $X_T(\omega)$ in frequency domain

$$\begin{aligned} P_{XX} &= \frac{1}{2\pi} \int_{-\infty}^{+\infty} \lim_{T \rightarrow \infty} \frac{E[|X_T(\omega)|^2]}{2T} d\omega \\ &= \frac{1}{2\pi} \int_{-\infty}^{+\infty} S_{XX}(\omega) d\omega \end{aligned}$$

Autocorrelation related equation

for continuous time signals

the Inverse Fourier transform of $S_{XX}(\omega)$

the average power related equation

$$\frac{1}{2\pi} \int_{-\infty}^{+\infty} S_{XX}(\omega) e^{j\omega t} d\omega = A[R_{XX}(t, t + \tau)]$$

- auto-correlation function

$$R_{XX}(t, t + \tau) = E[X(t)X(t + \tau)] \Rightarrow R_{XX}(\tau)$$

- a random process $X(t)$ in time domain
- a random process $X_T(\omega)$ in frequency domain

Fourier transforms of autocorrelation functions for continuous time signals

Definition

Fourier transform of an autocorrelation functions

$$S_{XX}(\omega) = \int_{-\infty}^{+\infty} R_{XX}(\tau) e^{-j\omega\tau} d\tau$$

$$S_{\dot{X}\dot{X}}(\omega) = \int_{-\infty}^{+\infty} R_{\dot{X}\dot{X}}(\tau) e^{-j\omega\tau} d\tau$$

- auto-correlation function

$$R_{XX}(t, t + \tau) = E[X(t)X(t + \tau)] \Rightarrow R_{XX}(\tau)$$

$$R_{\dot{X}\dot{X}}(t, t + \tau) = E[\dot{X}(t)\dot{X}(t + \tau)] \Rightarrow R_{\dot{X}\dot{X}}(\tau)$$

- a random process $X(t)$ in time domain
- $\dot{X}(t) = \frac{d}{dt}X(t)$: the derivative of $X(t)$

Fourier transform of a derivative function for continuous time signals

Definition

Fourier transform of an autocorrelation functions

$$x(t) \iff X(\omega)$$
$$\frac{d^n}{dt^n} x(t) \iff (j\omega)^n X(\omega)$$

Power Density Spectrum and Auto-correlation

for continuous time signals

Definition

$$S_{XX}(\omega) = \int_{-\infty}^{+\infty} A[R_{XX}(t, t + \tau)] e^{-j\omega\tau} d\tau$$
$$\frac{1}{2\pi} \int_{-\infty}^{+\infty} S_{XX}(\omega) e^{j\omega t} d\omega = A[R_{XX}(t, t + \tau)]$$

for a WSS $X(t)$, $A[R_{XX}(t, t + \tau)] = R_{XX}(\tau)$

$$S_{XX}(\omega) = \int_{-\infty}^{+\infty} R_{XX}(\tau) e^{-j\omega\tau} d\tau$$
$$R_{XX}(\tau) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} S_{XX}(\omega) e^{+j\omega\tau} d\omega$$

Power Spectrum and Auto-Correlation Functions

for continuous time signals

Definition

the power spectrum

$$S_{XX}(\omega) = \int_{-\infty}^{+\infty} R_{XX}(\tau) e^{-j\omega\tau} d\tau$$

the auto-correlation function

$$R_{XX}(\tau) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} S_{XX}(\omega) e^{+j\omega\tau} d\omega$$

RMS Bandwidth

for continuous time signals

Definition

the standard deviation is
a measure of the spread in a density function.
the analogous quantity for the normalized power spectrum is
a measure of its spread that we call the rms bandwidth
(root-mean-square)

$$W_{rms}^2 = \frac{\int_{-\infty}^{+\infty} \omega^2 S_{XX}(\omega) d\omega}{\int_{-\infty}^{+\infty} S_{XX}(\omega) d\omega}$$

RMS Bandwidth and Mean Frequency

for continuous time signals

Definition

the mean frequency $\bar{\omega}_0$

$$\bar{\omega}_0 = \frac{\int_{-\infty}^{+\infty} \omega S_{XX}(\omega) d\omega}{\int_{-\infty}^{+\infty} S_{XX}(\omega) d\omega}$$

the rms bandwidth

$$W_{rms}^2 = \frac{4 \int_{-\infty}^{+\infty} (\omega - \bar{\omega}_0)^2 S_{XX}(\omega) d\omega}{\int_{-\infty}^{+\infty} S_{XX}(\omega) d\omega}$$

