Stationarity

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Based on
Probability, Random Variables and Random Signal Principles,
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Outline

1. First-Order Stationary Processes
2. Correlation and Covariance Functions

First Order Stationary

N Gaussian random variables

Definition

if the first order density function does not change with a shift in time origin

$$f_X(x_1;t_1) = f_X(x_1;t_1+\Delta)$$

must be true for any timet_1 and any real number Δ if $X(t)$ is to be a first-order stationary

Consequences of stationarity
N Gaussian random variables

Definition

$f_X(x, t_1)$is independent of t_1
the process mean value is a constant

$$m_X(t) = \overline{X} = constant$$

the process mean value

N Gaussian random variables

Definition

$$m_X(t) = \overline{X} = constant$$

$$m_X(t_1) = \int_{-\infty}^{\infty} x f_X(x; t_1) dx$$

$$m_X(t_2) = \int_{-\infty}^{\infty} x f_X(x; t_2) dx$$

$$m_X(t_1) = m_X(t_1 + \Delta)$$

Second-Order Stationary Process

N Gaussian random variables

Definition

if the second order density function does not change with a shift in time origin

$$f_X(x_1, x_2; t_1, t_2) = f_X(x_1, x_2; t_1 + \Delta, t_2 + \Delta)$$

must be true for any timet_1,t_2 and any real number Δ if $X(t)$ is to be a second-order stationary
Auto-correlation function

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

N^{th}-order Stationary Processes
N Gaussian random variables

Definition

if the second order density function does not change with a shift in time origin

$$f_X(x_1, \cdots, x_N; t_1, \cdots, t_N) = f_X(x_1, \cdots, x_N; t_1 + \Delta, \cdots, t_N + \Delta)$$

must be true for any time$t_1, ..., t_N$ and any real number Δ if $X(t)$ is to be a second-order stationary

Wide Sense Stationary Process

N Gaussian random variables

Definition

$$m_X(t) = \overline{X} = constant$$

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

The properties of autocorrelation functions (1)
N Gaussian random variables

Definition

$$|R_{XX}(\tau)| \le R_{XX}(0)$$

$$R_{XX}(-\tau) = R_{XX}(\tau)$$

$$R_{XX}(0) = E\left[X^2(t)\right]$$

$$P\left[|X(t+\tau) - X(t)| > \varepsilon\right] = \frac{2}{\varepsilon^2}\left(R_{XX}(0) - R_{XX}(\tau)\right)$$

The properties of autocorrelation functions (2)

N Gaussian random variables

Definition

if $X(t) = \overline{X} + N(t)$ where $N(t)$ is WSS, is zero-mean, and has autocorrelation function $R_{NN}(\tau) \to 0$ as $|\tau| \to \infty$, then

$$\lim_{|\tau|\to\infty} R_{XX}(\tau) = \overline{X}^2$$

if $X(t)$ is mean square periodic, i.e, there exists a $T \neq 0$ such that $E\left[(X(t+T) - X(t))^2\right] = 0$ for all t, then $R_{XX}(t)$ will have a periodic component with the same period

$R_{XX}(\tau)$ cannot have an arbitrary shape

Crosscorrelation functions (1)

N Gaussian random variables

Definition

$$R_{XY}(t_1, t_2) = E[X(t_1)Y(t_2)]$$

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

if

$$R_{XY}(t, t+\tau) = 0$$

then $X(t)$ and $Y(t)$ are called orthogonal processes

Crosscorrelation functions (2)

N Gaussian random variables

Definition

if X(t) and Y(t) are statistically independent

$$R_{XY}(t, t+\tau) = E[X(t)Y(t+\tau)] = m_X(t)m_X(t+\tau)$$

if X(t) and Y(t) are stistically independent and are at least WSS,

$$R_{XY}(\tau) = \overline{XY}$$

which is constant

The properties of crosscorrelation functions (1)

N Gaussian random variables

Definition

$$R_{XY}(\tau) = R_{XY}(-\tau)$$

$$|R_{XY}(\tau)| = \sqrt{R_{XX}(0)R_{YY}(0)}$$

$$|R_{XY}(\tau)| \leq \frac{1}{2}[R_{XX}(0) + R_{YY}(0)]$$

The properties of crosscorrelation functions (2)

N Gaussian random variables

Definition

$$R_{YX}(-\tau) = E[Y(t)X(t-\tau)] = E[Y(s+t)X(s)] = R_{XY}(\tau)$$

$$E\left[\{Y(t+\tau)+\alpha X(t)\}^2\right] \geq 0$$

the geometric mean of two positive numbers cannot exceed their arithmetic mean

The properties of crosscorrelation functions (3)

N Gaussian random variables

Definition

$$|R_{XY}(\tau)| \leq \frac{1}{2}[R_{XX}(0) + R_{YY}(0)]$$

$$\sqrt{R_{XX}(0)R_{YX}(0)} \leq \frac{1}{2}[R_{XX}(0) + R_{YY}(0)]$$

Covariance Functions
N Gaussian random variables

Definition

$$C_{XX}(t,t+\tau) = E\left[\{X(t)-m_X(t)\}\{X(t+\tau)-m_X(t+\tau)\}\right]$$
$$C_{XY}(t,t+\tau) = E\left[\{X(t)-m_X(t)\}\{Y(t+\tau)-m_Y(t+\tau)\}\right]$$
$$C_{XX}(t,t+\tau) = R_{XX}(t,t+\tau) - m_X(t)m_X(t+\tau)$$
$$C_{XY}(t,t+\tau) = R_{XY}(t,t+\tau) - m_X(t)m_Y(t+\tau)$$

at least jointly WSS

$$C_{XX}(\tau) = R_{XX}(\tau) - \overline{X}^2$$

$$C_{XY}(\tau) = R_{XY}(\tau) - \overline{X\,Y}$$

The properties of covariance functions
N Gaussian random variables

Definition

For a WSS process, variance does not depend on time and if $\tau = 0$

$$C_{XX}(0) = R_{XX}(0) - \overline{X}^2$$

$$\sigma_X^2 = E\left[\{X(t) - E[X(t)]\}^2\right] = C_{XX}(0)$$

it the two random processes uncorrelated

$$C_{XY}(t, t+\tau) = R_{XY}(t, t+\tau) - m_X(t)m_Y(t+\tau) = 0$$

$$R_{XY}(t, t+\tau) = m_X(t)m_Y(t+\tau)$$