Unitary Time Changes of Stationary Processes Yield Oscillatory Processes

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Abstract

A unitary time-change operator U_θ is constructed for absolutely continuous, strictly increasing time reparametrizations θ, acting on functions that are locally square-integrable(meaning over compact sets). Applying U_θ to the Cramér spectral representation of a stationary process yields an oscillatory process in the sense of Priestley with oscillatory function $\varphi_t(\lambda) = \sqrt{\dot{\theta}(t)}\, e^{i\lambda\theta(t)}$, evolutionary spectrum $d\,F_t(\lambda) = \dot{\theta}(t)\,d\,F(\lambda)$ and expected zero-counting function $\mathbb{E}[N_{[0,T]}] = \sqrt{-\ddot{K}(0)}\ [\theta(T) - \theta(0)]$. The sample paths of any non-degenerate second-order stationary process are locally square integrable, making the unitary time-change operator U_θ applicable to typical realizations. A zero-localization measure $d\,\mu(t) = \delta(Z(t))|\dot{Z}(t)|\,d\,t$ induces a Hilbert space $L^2(\mu)$ on the zero set of each oscillatory process realization $Z(t)$, and the multiplication operator $(L\,f)(t) = t\,f(t)$ has simple pure point spectrum equal to the zero crossing set of Z.D

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1 Gaussian Processes

Unless otherwise stated, all processes considered will be real-valued.

Theorem 1. *Let $X(u)$ be a real-valued process:*

$$X(u) \in \mathbb{R} \qquad \forall u \in \mathbb{R} \tag{1}$$

Then its (complex-valued) random orthogonal spectral measure satisfies

$$d\,\bar{\Phi}(\lambda) = d\,\Phi\,(-\lambda) \tag{2}$$

and the corresponding covariance spectral measure F is even:

$$F\,(-A) = F(A) \tag{3}$$

Proof. 1. The spectral representation for $X(u)$ is

$$X(u) = \int_{-\infty}^{\infty} e^{i\lambda u}\ d\,\Phi(\lambda) \tag{4}$$

Since $X(u)$ is real-valued for each u,

$$\overline{X(u)} = X(u) \tag{5}$$

On the other hand,

$$\overline{X(u)} = \overline{\int_{-\infty}^{\infty} e^{i\lambda u}\ d\,\Phi(\lambda)} \tag{6}$$

$$= \int_{-\infty}^{\infty} \overline{e^{i\lambda u}}\, d\,\bar{\Phi}(\lambda) \tag{7}$$

$$= \int_{-\infty}^{\infty} e^{-i\lambda u}\ d\,\bar{\Phi}(\lambda) \tag{8}$$

By the substitution $\lambda \mapsto -\mu$,

$$\int_{-\infty}^{\infty} e^{-i\lambda u}\ d\,\bar{\Phi}(\lambda) = \int_{-\infty}^{\infty} e^{i\mu u}\ d\,\bar{\Phi}(-\mu) \tag{9}$$

So

$$X(u) = \int_{-\infty}^{\infty} e^{i\lambda u}\, d\,\Phi(\lambda) = \int_{-\infty}^{\infty} e^{i\lambda u}\, d\,\bar{\Phi}(-\lambda) \tag{10}$$

By uniqueness of the spectral measure representation, it follows that

$$d\,\bar{\Phi}(\lambda) = d\,\Phi\,(-\lambda) \tag{11}$$

as (orthogonal) random measures.

2. The covariance function of X is

$$R(u) = \mathbb{E}\,(X(0)\,X(u)) = \int_{-\infty}^{\infty} e^{i\lambda u}\, d\,F(\lambda) \tag{12}$$

Since $X(u)$ is real-valued, $R(u)$ is real and $R\,(-u) = R(u)$. Thus,

$$R\,(-u) = \int_{-\infty}^{\infty} e^{-i\lambda u}\, d\,F(\lambda) = \int_{-\infty}^{\infty} e^{i\mu u}\, d\,F\,(-\mu) \tag{13}$$

Equating with $R(u)$,

$$\int_{-\infty}^{\infty} e^{i\lambda u}\, d\,F(\lambda) = \int_{-\infty}^{\infty} e^{i\lambda u}\, d\,F\,(-\lambda) \tag{14}$$

for all u. By the uniqueness theorem for Fourier–Stieltjes transforms, this implies

$$d\,F(\lambda) = d\,F\,(-\lambda) \tag{15}$$

Thus for any Borel set A,

$$F\,(-A) = F(A) \tag{16}$$

establishing the evenness property. □

1.1 Definition

Definition 2. ***(Gaussian process)*** *Let $(\Omega, \mathcal{F}, \mathbb{P})$ be a probability space and T a non-empty index set. A family $\{X_t : t \in T\}$ of real-valued random variables on $(\Omega, \mathcal{F}, \mathbb{P})$ is called a Gaussian process if for every finite subset $\{t_1, \ldots, t_n\} \subset T$ the random vector $(X_{t_1}, \ldots, X_{t_n})$ is multivariate normal (possibly degenerate). Equivalently, every finite linear combination $\sum_{i=1}^n a_i X_{t_i}$ is either almost surely constant or Gaussian. The mean function is $m(t) := \mathbb{E}[X_t]$ and the covariance kernel is*

$$K(s,t) = \mathrm{Cov}(X_s, X_t) \tag{17}$$

For any finite $(t_i)_{i=1}^n \subset T$, the matrix $K_{ij} = K(t_i, t_j)$ is symmetric positive semidefinite, and a Gaussian process is completely determined in law by m and K.

1.2 Stationary processes

TODO: restate this as Bochners theorem with proof

Definition 3. ***[Cramér spectral representation]***[1] *A zero-mean stationary process X with spectral measure F admits the sample path representation*

$$X(t) = \int_{\mathbb{R}} e^{i\lambda t}\, d\,\Phi(\lambda) \tag{18}$$

which has covariance

$$R_X(t-s) = \int_{\mathbb{R}} e^{i\lambda(t-s)}\, d\,F(\lambda) \tag{19}$$

1.2.1 Sample Path Realizations

Definition 4. ***[Locally square-integrable functions]*** *Define*

$$L^2_{\text{loc}}(\mathbb{R}) := \left\{ f\colon \mathbb{R} \to \mathbb{C}\colon \int_K |f(t)|^2\, d\,t < \infty \textit{ for every compact } K \subseteq \mathbb{R} \right\} \tag{20}$$

Remark 5. Every bounded measurable set in $\mathbb{R}$ is compact or contained in a compact set; hence $L^2_{\text{loc}}(\mathbb{R})$ contains functions that are square-integrable on every bounded interval, including functions with polynomial growth at infinity.

Theorem 6. ***[Sample paths in $\mathbf{L^2_{loc}}(\mathbb{R})$]*** *Let $\{X(t)\}_{t \in \mathbb{R}}$ be a second-order stationary process with*

$$\sigma^2 := \mathbb{E}[X(t)^2] < \infty \tag{21}$$

Then almost every sample path lies in $L^2_{\text{loc}}(\mathbb{R})$.

Proof. Fix an arbitrary bounded interval $[a, b] \subset \mathbb{R}$ with $a < b$. Define the random variable

$$Y_{[a,b]} := \int_a^b X(t)^2\, d\,t \tag{22}$$ □

1.3 Oscillatory Processes

Definition 7. ***[Oscillatory process][3]*** *Let F be a finite nonnegative Borel measure on $\mathbb{R}$. Let*

$$A_t \in L^2(F) \quad \forall t \in \mathbb{R} \tag{23}$$

be the gain function and

$$\varphi_t(\lambda) = A_t(\lambda)\, e^{i\lambda t} \tag{24}$$

be the corresponding oscillatory function then an oscillatory process is a stochastic process which can be represented as

$$\begin{aligned} Z(t) &= \int_{\mathbb{R}} \varphi_t(\lambda)\, d\,\Phi(\lambda) \\ &= \int_{\mathbb{R}} A_t(\lambda)\, e^{i\lambda t}\, d\,\Phi(\lambda) \end{aligned} \tag{25}$$

where Φ is a complex orthogonal random measure with spectral measure F which satisfies the relation

$$d\,\mathbb{E}[\Phi(\lambda)\overline{\Phi(\mu)}] = \delta\,(\lambda - \mu)\, d\,F(\lambda) \tag{26}$$

and has the corresponding covariance kernel

$$\begin{aligned} R_Z(t,s) &= \mathbb{E}[Z(t)\overline{Z(s)}] \\ &= \int_{\mathbb{R}} A_t(\lambda)\overline{A_s(\lambda)} e^{i\lambda(t-s)}\, d\,F(\lambda) \\ &= \int_{\mathbb{R}} \varphi_t(\lambda)\overline{\varphi_s(\lambda)} d\,F(\lambda) \end{aligned} \tag{27}$$

Theorem 8. ***[Real-valuedness criterion for oscillatory processes]*** *Let Z be an oscillatory process with oscillatory function*

$$\varphi_t(\lambda) = A_t(\lambda)\, e^{i\lambda t} \tag{28}$$

and spectral measure F. Then Z is real-valued if and only if

$$A_t\,(-\lambda) = \overline{A_t(\lambda)} \tag{29}$$

for F-almost every $\lambda \in \mathbb{R}$, equivalently

$$\varphi_t\,(-\lambda) = \overline{\varphi_t(\lambda)} \tag{30}$$

for F-almost every $\lambda \in \mathbb{R}$.

Proof.

1. Assume Z is real-valued. Then for all $t \in \mathbb{R}$,

$$Z(t) = \overline{Z(t)} \tag{31}$$

2. From the oscillatory representation (25),

$$Z(t) = \int_{\mathbb{R}} A_t(\lambda)\, e^{i\lambda t}\, d\,\Phi(\lambda) \tag{32}$$

3. Taking the complex conjugate of both sides of (32),

$$\overline{Z(t)} = \overline{\int_{\mathbb{R}} A_t(\lambda)\, e^{i\lambda t}\, d\,\Phi(\lambda)} = \int_{\mathbb{R}} \overline{A_t(\lambda)} e^{-i\lambda t}\, d\overline{\Phi(\lambda)} \tag{33}$$

4. For a real-valued process, the orthogonal random measure must satisfy the symmetry property

$$d\overline{\Phi(\lambda)} = -d\,\Phi\,(-\lambda) \tag{34}$$

5. Substituting (34) into (33),

$$\overline{Z(t)} = -\int_{\mathbb{R}} \overline{A_t(\lambda)} e^{-i\lambda t}\, d\,\Phi\,(-\lambda) \tag{35}$$

6. Apply the change of variables $\mu = -\lambda$, so $d\,\Phi\,(-\lambda) = -d\,\Phi(\mu)$ and $e^{-i\lambda t} = e^{i\mu t}$:

$$\begin{aligned} \overline{Z(t)} &= -\int_{\mathbb{R}} \overline{A_t\,(-\mu)} e^{i\mu t}\,(-d\,\Phi(\mu)) \\ &= \int_{\mathbb{R}} \overline{A_t\,(-\mu)} e^{i\mu t}\, d\,\Phi(\mu) \end{aligned} \tag{36}$$

7. By (31), the right sides of (32) and (36) must be equal:

$$\int_{\mathbb{R}} A_t(\mu)\, e^{i\mu t}\, d\,\Phi(\mu) = \int_{\mathbb{R}} \overline{A_t\,(-\mu)} e^{i\mu t}\, d\,\Phi(\mu) \tag{37}$$

8. Since the stochastic integral representation is unique in $L^2(F)$, the integrands must be equal F-almost everywhere:

$$A_t(\lambda) = \overline{A_t\,(-\lambda)} \quad \text{for } F\text{-a.e. } \lambda \tag{38}$$

9. This is equivalent to (29). From (28),

$$\varphi_t\,(-\lambda) = A_t\,(-\lambda)\, e^{-i\lambda t} \tag{39}$$

10. Using (29),

$$\begin{aligned} \varphi_t\,(-\lambda) &= \overline{A_t(\lambda)} e^{-i\lambda t} \\ &= \overline{A_t(\lambda)\, e^{i\lambda t}} \\ &= \overline{\varphi_t(\lambda)} \end{aligned} \tag{40}$$

establishing (30).

11. Conversely, assume (29) holds. Reversing the steps from (36) to (31) shows that $\overline{Z(t)} = Z(t)$ for all t, so Z is real-valued. □

Theorem 9. ***[Existence of Oscillatory Processes]*** *Let F be an absolutely continuous spectral measure and the gain function*

$$A_t(\lambda) \in L^2(F) \quad \forall t \in \mathbb{R} \tag{41}$$

be measurable in both time and frequency then the time-dependent spectral density is defined by

$$\begin{aligned} S_t(\lambda) &= \int_{\mathbb{R}} |A_t(\lambda)|^2 \, d\, F(\lambda) < \infty \\ &= \int_{\mathbb{R}} |A_t(\lambda)|^2 \, S(\lambda) \, d\, \lambda \end{aligned} \tag{42}$$

and there exists a complex orthogonal random measure Φ with spectral measure F such that for each sample path $\omega_0 \in \Omega$

$$Z(t, \omega_0) = \int_{\mathbb{R}} A_t(\lambda) \, e^{i\lambda t} \, d\, \Phi(\lambda, \omega_0) \tag{43}$$

is well-defined in $L^2(\Omega)$ and has covariance R_Z as in (27).

Proof.

1. Define the space of simple functions on $\mathbb{R}$: for disjoint Borel sets $\{E_j\}_{j=1}^n$ with $F(E_j) < \infty$ and coefficients $\{c_j\}_{j=1}^n \subset \mathbb{C}$,

$$g(\lambda) = \sum_{j=1}^n c_j \, 1_{E_j}(\lambda) \tag{44}$$

2. For simple functions, define the stochastic integral

$$\int_{\mathbb{R}} g(\lambda) \, d\, \Phi(\lambda) := \sum_{j=1}^n c_j \, \Phi(E_j) \tag{45}$$

3. Compute the second moment:

$$\begin{aligned} \mathbb{E}\left[\left|\int_{\mathbb{R}} g(\lambda) \, d\, \Phi(\lambda)\right|^2\right] &= \mathbb{E}\left[\left|\sum_{j=1}^n c_j \, \Phi(E_j)\right|^2\right] \\ &= \mathbb{E}\left[\sum_{j=1}^n \sum_{k=1}^n c_j \bar{c_k} \Phi(E_j) \overline{\Phi(E_k)}\right] \end{aligned} \tag{46}$$

4. By linearity of expectation,

$$\mathbb{E}\left[\sum_{j=1}^n \sum_{k=1}^n c_j \bar{c_k} \Phi(E_j) \overline{\Phi(E_k)}\right] = \sum_{j=1}^n \sum_{k=1}^n c_j \bar{c_k} \mathbb{E}[\Phi(E_j) \overline{\Phi(E_k)}] \tag{47}$$

5. By the orthogonality relation (26), since $E_j \cap E_k = \emptyset$ for $j \neq k$,

$$\mathbb{E}[\Phi(E_j)\overline{\Phi(E_k)}] = \begin{cases} F(E_j) & \text{if } j = k \\ 0D & \text{if } j \neq k \end{cases} \tag{48}$$

6. Substituting (48) into (47),

$$\sum_{j=1}^{n} \sum_{k=1}^{n} c_j \bar{c_k} \mathbb{E}[\Phi(E_j)\overline{\Phi(E_k)}] = \sum_{j=1}^{n} |c_j|^2 F(E_j) \tag{49}$$

7. The right side of (49) equals

$$\sum_{j=1}^{n} |c_j|^2 F(E_j) = \int_{\mathbb{R}} |g(\lambda)|^2 \, d\, F(\lambda) \tag{50}$$

8. Therefore the isometry property holds for simple functions:

$$\mathbb{E}\left[\left|\int_{\mathbb{R}} g(\lambda) \, d\, \Phi(\lambda)\right|^2\right] = \int_{\mathbb{R}} |g(\lambda)|^2 \, d\, F(\lambda) \tag{51}$$

9. The space of simple functions is dense in $L^2(F)$. For any $h(\lambda) \in L^2(F)$ and $\epsilon > 0$, there exists a simple function $g(\lambda)$ such that

$$\int_{\mathbb{R}} |h(\lambda) - g(\lambda)|^2 \, d\, F(\lambda) < \epsilon \tag{52}$$

10. By the isometry (51) and completeness of $L^2(\Omega)$, the integral extends uniquely by continuity to all $h(\lambda) \in L^2(F)$.

11. Since $A_t \in L^2(F)$ by assumption (41), and $|e^{i\lambda t}| = 1$,

$$\int_{\mathbb{R}} |\varphi_t(\lambda)|^2 \, d\, F(\lambda) = \int_{\mathbb{R}} |A_t(\lambda)|^2 \, d\, F(\lambda) < \infty \tag{53}$$

so $\varphi_t \in L^2(F)$.

12. Therefore

$$\begin{aligned} Z(t) &= \int_{\mathbb{R}} \varphi_t(\lambda) \, d\, \Phi(\lambda) \\ &= \int_{\mathbb{R}} A_t(\lambda) \, e^{i\lambda t} \, d\, \Phi(\lambda) \end{aligned} \tag{54}$$

is well-defined in $L^2(\Omega)$.

13. To compute the covariance, use the sesquilinearity of the stochastic integral:

$$\begin{aligned} R_Z(t,s) &= \mathbb{E}[Z(t)\overline{Z(s)}] \\ &= \mathbb{E}\left[\int_{\mathbb{R}} \varphi_t(\lambda) \, d\, \Phi(\lambda) \overline{\int_{\mathbb{R}} \varphi_s(\mu) \, d\, \Phi(\mu)}\right] \end{aligned} \tag{55}$$

14. By Fubini's theorem for stochastic integrals,

$$\mathbb{E}\left[\int_{\mathbb{R}} \varphi_t(\lambda)\, d\,\Phi(\lambda)\, \overline{\int_{\mathbb{R}} \varphi_s(\mu)\, d\,\Phi(\mu)}\right] = \int_{\mathbb{R}}\int_{\mathbb{R}} \varphi_t(\lambda)\overline{\varphi_s(\mu)}\mathbb{E}\,[d\,\Phi(\lambda)\overline{d\,\Phi(\mu)}] \tag{56}$$

15. Using the orthogonality relation (26),

$$\int_{\mathbb{R}}\int_{\mathbb{R}} \varphi_t(\lambda)\overline{\varphi_s(\mu)}\delta\,(\lambda-\mu)\, d\,F(\lambda)\, d\,F(\mu) = \int_{\mathbb{R}} \varphi_t(\lambda)\overline{\varphi_s(\lambda)} d\,F(\lambda) \tag{57}$$

16. Substituting the definition (24),

$$R_Z(t,s) = \int_{\mathbb{R}} A_t(\lambda)\overline{A_s(\lambda)} e^{i\lambda(t-s)}\, d\,F(\lambda) \tag{58}$$

as claimed in (27). □

1.3.1 Integral Representations of Oscillatory Process Covariance Kernels [2]

2 Unitarily Time-Changed Stationary Processes

2.1 Unitary Time-Change Operator $U_\theta f$

Theorem 10. ***[Unitary time-change operator U_θ and its inverse U_θ^{-1}]*** *Let the time-change function $\theta: \mathbb{R} \to \mathbb{R}$ be absolutely continuous, strictly increasing, and bijective, with*

$$\dot{\theta}(t) > 0 \tag{59}$$

almost everywhere and $\dot{\theta}(t) = 0$ only on sets of Lebesgue measure zero. For f measurable, define

$$(U_\theta f)(t) = \sqrt{\dot{\theta}(t)}\; f(\theta(t)) \tag{60}$$

Its inverse is given by

$$(U_\theta^{-1}\, g)(s) = \frac{g(\theta^{-1}(s))}{\sqrt{\dot{\theta}(\theta^{-1}(s))}} \tag{61}$$

For every compact set $K \subseteq \mathbb{R}$ and $f \in L^2_{\mathrm{loc}}(\mathbb{R})$,

$$\int_K |(U_\theta f)(t)\,|^2 d\,t = \int_{\theta(K)} |\, f(s)|^2\, d\,s \tag{62}$$

Moreover, U_θ^{-1} is the inverse of U_θ on $L^2_{\mathrm{loc}}(\mathbb{R})$.

Proof. 1. Let $f \in L^2_{\mathrm{loc}}(\mathbb{R})$ and let $K \subset \mathbb{R}$ be compact. From the definition (60),

$$\int_K |(U_\theta f)(t)|^2\, d\,t = \int_K \left|\sqrt{\dot{\theta}(t)}\; f(\theta(t))\right|^2 d\,t \tag{63}$$

2. Expanding the square,

$$\int_K \left| \sqrt{\dot{\theta}(t)}\, f(\theta(t)) \right|^2 d\,t = \int_K \dot{\theta}(t) |f(\theta(t))|^2 d\,t \tag{64}$$

3. Since θ is absolutely continuous and strictly increasing, $\theta' = \dot{\theta}$ exists almost everywhere and $\dot{\theta}(t) > 0$ a.e.
4. Apply the change of variables $s = \theta(t)$. Then

$$d\,s = \dot{\theta}(t)\, d\,t \tag{65}$$

5. The inverse function $t = \theta^{-1}(s)$ exists since θ is strictly increasing and bijective.
6. As t ranges over K, the variable $s = \theta(t)$ ranges over $\theta(K)$.
7. Since θ is continuous and K is compact, $\theta(K)$ is compact.
8. Substituting (65) into (64),

$$\int_K \dot{\theta}(t)\, |\, f(\theta(t))\, |^2 d\,t = \int_{\theta(K)} |\, f(s)|^2\, d\,s \tag{66}$$

9. This establishes the local isometry (62).
10. To verify U_θ^{-1} is the inverse, compute:

$$(U_\theta^{-1}\, U_\theta\, f)(s) = U_\theta^{-1}\, (U_\theta\, f)(s) \tag{67}$$

11. By definition (61),

$$U_\theta^{-1}\, (U_\theta\, f)(s) = \frac{(U_\theta\, f)(\theta^{-1}(s))}{\sqrt{\dot{\theta}(\theta^{-1}(s))}} \tag{68}$$

12. By definition (60),

$$(U_\theta\, f)(\theta^{-1}(s)) = \sqrt{\dot{\theta}(\theta^{-1}(s))}\; f(\theta(\theta^{-1}(s))) \tag{69}$$

13. Since $\theta \circ \theta^{-1} = \mathrm{id}$,

$$f(\theta(\theta^{-1}(s))) = f(s) \tag{70}$$

14. Substituting (69) and (70) into (68),

$$\frac{\sqrt{\dot{\theta}(\theta^{-1}(s))}\; f(s)}{\sqrt{\dot{\theta}(\theta^{-1}(s))}} = f(s) \tag{71}$$

15. Therefore

$$U_\theta^{-1}\, U_\theta = \mathrm{id} \tag{72}$$

16. Similarly, compute:

$$(U_\theta\, U_\theta^{-1}\, g)(t) = \sqrt{\dot{\theta}(t)}\; (U_\theta^{-1}\, g)(\theta(t)) \tag{73}$$

17. By definition (61),

$$(U_\theta^{-1}\, g)(\theta(t)) = \frac{g(\theta^{-1}(\theta(t)))}{\sqrt{\dot{\theta}(\theta^{-1}(\theta(t)))}} \tag{74}$$

18. Since $\theta^{-1} \circ \theta = \mathrm{id}$,

$$g(\theta^{-1}(\theta(t))) = g(t), \quad \theta^{-1}(\theta(t)) = t \tag{75}$$

19. Substituting (75) into (74),

$$\frac{g(t)}{\sqrt{\dot{\theta}(t)}} \tag{76}$$

20. Therefore from (73),

$$(U_\theta U_\theta^{-1} g)(t) = \sqrt{\dot{\theta}(t)} \cdot \frac{g(t)}{\sqrt{\dot{\theta}(t)}} = g(t) \tag{77}$$

21. Thus

$$U_\theta U_\theta^{-1} = \mathrm{id} \tag{78}$$

22. Combining (72) and (78), U_θ^{-1} is the two-sided inverse of U_θ on $L^2_{\mathrm{loc}}(\mathbb{R})$. □

2.2 Transformation of Stationary → Oscillatory Processes via U_θ

Theorem 11. ***[Unitary time changes of stationary processes produce oscillatory process]*** *Let X be zero-mean stationary as in Definition 3. For scaling function θ as in Theorem 10, define*

$$\begin{aligned} Z(t) &= (U_\theta X)(t) \\ &= \sqrt{\dot{\theta}(t)}\, X(\theta(t)) \end{aligned} \tag{79}$$

Then Z is a realization of an oscillatory process with oscillatory function

$$\varphi_t(\lambda) = \sqrt{\dot{\theta}(t)}\, e^{i\lambda\theta(t)} \tag{80}$$

gain function

$$A_t(\lambda) = \sqrt{\dot{\theta}(t)}\, e^{i\lambda(\theta(t)-t)} \tag{81}$$

and covariance kernel

$$\begin{aligned} R_Z(t,s) &= \mathbb{E}[Z(t)\overline{Z(s)}] \\ &= \mathbb{E}\left[\sqrt{\dot{\theta}(t)}\, X(\theta(t))\overline{\sqrt{\dot{\theta}(s)}\, X(\theta(s))}\right] \\ &= \sqrt{\dot{\theta}(t)\,\dot{\theta}(s)}\, \mathbb{E}[X(\theta(t))\overline{X(\theta(s))}] \\ &= \sqrt{\dot{\theta}(t)\,\dot{\theta}(s)}\, R_X(\theta(t)-\theta(s)) \\ &= \sqrt{\dot{\theta}(t)\,\dot{\theta}(s)} \int_{\mathbb{R}} e^{i\lambda(\theta(t)-\theta(s))}\, dF(\lambda) \end{aligned} \tag{82}$$

Proof. 1. From the Cramér representation (18),

$$X(u) = \int_{\mathbb{R}} e^{i\lambda u}\, d\Phi(\lambda) \tag{83}$$

2. Substituting $u = \theta(t)$ into (83),

$$X(\theta(t)) = \int_{\mathbb{R}} e^{i\lambda\theta(t)}\, d\,\Phi(\lambda) \tag{84}$$

3. From the definition (79),

$$Z(t) = \sqrt{\dot{\theta}(t)}\, X(\theta(t)) = \sqrt{\dot{\theta}(t)} \int_{\mathbb{R}} e^{i\lambda\theta(t)}\, d\,\Phi(\lambda) \tag{85}$$

4. By linearity of the stochastic integral,

$$Z(t) = \int_{\mathbb{R}} \sqrt{\dot{\theta}(t)}\, e^{i\lambda\theta(t)}\, d\,\Phi(\lambda) \tag{86}$$

5. Define

$$\varphi_t(\lambda) := \sqrt{\dot{\theta}(t)}\, e^{i\lambda\theta(t)} \tag{87}$$

6. Then (86) becomes

$$Z(t) = \int_{\mathbb{R}} \varphi_t(\lambda)\, d\,\Phi(\lambda) \tag{88}$$

   which is the oscillatory representation (25).

7. To express this in terms of the standard oscillatory function form, Define the gain function

$$A_t(\lambda) = \sqrt{\dot{\theta}(t)}\, e^{i\lambda(\theta(t) - t)} \tag{89}$$

8. Then verify the oscillatory function form (24) factorizes

$$\begin{aligned} \varphi_t(\lambda) &= A_t(\lambda)\, e^{i\lambda t} \\ &= \sqrt{\dot{\theta}(t)}\, e^{i\lambda(\theta(t)-t)} e^{i\lambda t} \\ &= \sqrt{\dot{\theta}(t)}\, e^{i\lambda(\theta(t)-t+t)} \\ &= \sqrt{\dot{\theta}(t)}\, e^{i\lambda\theta(t)} \end{aligned} \tag{90}$$

9. To compute the covariance, use (27):

$$R_Z(t,s) = \mathbb{E}[Z(t)\overline{Z(s)}] \tag{91}$$

10. Substituting (79),

$$R_Z(t,s) = \mathbb{E}\left[\sqrt{\dot{\theta}(t)}\, X(\theta(t)) \overline{\sqrt{\dot{\theta}(s)}\, X(\theta(s))}\right] \tag{92}$$

11. Since $\dot{\theta}$ is deterministic,

$$R_Z(t,s) = \sqrt{\dot{\theta}(t)}\, \sqrt{\dot{\theta}(s)}\, \mathbb{E}[X(\theta(t))\overline{X(\theta(s))}] \tag{93}$$

12. By stationarity of X, using (19),

$$\mathbb{E}[X(\theta(t))\overline{X(\theta(s))}] = R_X(\theta(t) - \theta(s)) = \int_{\mathbb{R}} e^{i\lambda(\theta(t) - \theta(s))}\, d\,F(\lambda) \tag{94}$$

13. Substituting (94) into (93),

$$R_Z(t,s) = \sqrt{\dot{\theta}(t)\,\dot{\theta}(s)} \int_{\mathbb{R}} e^{i\lambda(\theta(t)-\theta(s))}\,d\,F(\lambda) \tag{95}$$

establishing (82).

□

2.2.1 Time-Varying Filter Representations

Theorem 12. *Let $\theta\colon\mathbb{R}\to\mathbb{R}$ be absolutely continuous, strictly increasing, and bijective with $\theta'(t)>0$ almost everywhere. Let $X(u)$ be a stationary process, and define the oscillatory process obtained by the forward unitary time transformation U_θ*

$$Z(t) = (U_\theta X)(t) = \sqrt{\dot{\theta}(t)}\,X(\theta(t)) = Z(t) = \int_{\mathbb{R}} h(t,u)\,X(u)\,d\,u \tag{96}$$

where the (forward) impulse response function is given by

$$h(t,u) = \sqrt{\dot{\theta}(t)}\,\delta\,(u-\theta(t)) \tag{97}$$

then likewise the transformation can be reversed by expression the stationary process as

$$X(u) = (U_\theta^{-1}\,Z)(u) = \frac{Z(\theta^{-1}(u))}{\sqrt{\dot{\theta}(\theta^{-1}(u))}} = \int_{\mathbb{R}} g(u,t)\,Z(t)\,d\,t \tag{98}$$

where the inverse impulse response function is

$$g(u,t) = \frac{\delta\,(t-\theta^{-1}(u))}{\sqrt{\dot{\theta}(\theta^{-1}(u))}} \tag{99}$$

Proof. 1. Recall the forward unitary transformation from Theorem 10:

$$Z(t) = (U_\theta X)(t) = \sqrt{\dot{\theta}(t)}\,X(\theta(t)) \tag{100}$$

2. To express this as a convolution integral, note that the Dirac delta function satisfies the sifting property: for any continuous function $f\colon\mathbb{R}\to\mathbb{R}$,

$$\int_{\mathbb{R}} f(u)\,\delta\,(u-a)\,d\,u = f(a) \tag{101}$$

for any $a\in\mathbb{R}$.

3. Substituting $f(u)=X(u)$ and $a=\theta(t)$, which is well-defined since θ is bijective and continuous,

$$X(\theta(t)) = \int_{\mathbb{R}} X(u)\,\delta\,(u-\theta(t))\,d\,u \tag{102}$$

4. Multiplying both sides by $\sqrt{\dot{\theta}(t)}$ and substituting into (100),

$$Z(t) = \sqrt{\dot{\theta}(t)} \int_{\mathbb{R}} X(u)\,\delta\,(u-\theta(t))\,d\,u = \int_{\mathbb{R}} \Big[\sqrt{\dot{\theta}(t)}\,\delta\,(u-\theta(t))\Big]\,X(u)\,d\,u \tag{103}$$

5. Thus, the forward impulse response function is

$$h(t,u)=\sqrt{\dot{\theta}(t)}\,\delta\,(u-\theta(t)) \tag{104}$$

establishing (96).

6. For the inverse transformation, recall from Theorem 10 that

$$X(u)=(U_\theta^{-1}\,Z)(u)=\frac{Z(\theta^{-1}(u))}{\sqrt{\dot{\theta}(\theta^{-1}(u))}} \tag{105}$$

7. Let $s=\theta^{-1}(u)$, so $u=\theta(s)$ and $Z(\theta^{-1}(u))=Z(s)$. The sifting property applied to $Z(t)$ with point $\theta^{-1}(u)$ gives

$$Z(\theta^{-1}(u))=\int_{\mathbb{R}} Z(t)\,\delta\,(t-\theta^{-1}(u))\,d\,t \tag{106}$$

8. Substituting into (105),

$$X(u)=\frac{1}{\sqrt{\dot{\theta}(\theta^{-1}(u))}}\int_{\mathbb{R}} Z(t)\,\delta\,(t-\theta^{-1}(u))\,d\,t=\int_{\mathbb{R}}\left[\frac{\delta\,(t-\theta^{-1}(u))}{\sqrt{\dot{\theta}(\theta^{-1}(u))}}\right]Z(t)\,d\,t \tag{107}$$

9. Thus, the inverse impulse response function is

$$g(u,t)=\frac{\delta\,(t-\theta^{-1}(u))}{\sqrt{\dot{\theta}(\theta^{-1}(u))}} \tag{108}$$

establishing (98) and (99).

10. To confirm invertibility, substitute (103) into (107). The integral becomes

$$X(u)=\int_{\mathbb{R}} g(u,t)\left[\int_{\mathbb{R}} h(t,v)\,X(v)\,d\,v\right]d\,t \tag{109}$$

11. By Fubini's theorem, since all measures are positive and the delta functions ensure finite support,

$$X(u)=\int_{\mathbb{R}}\int_{\mathbb{R}} g(u,t)\,h(t,v)\,X(v)\,d\,v\;\,d\,t \tag{110}$$

12. Integrating the kernel

$$g(u,t)\,h(t,v)=\frac{\delta\,(t-\theta^{-1}(u))}{\sqrt{\dot{\theta}(\theta^{-1}(u))}}\cdot\sqrt{\dot{\theta}(t)}\,\delta\,(v-\theta(t)) \tag{111}$$

over t results in $t=\theta^{-1}(u)$, so

$$\sqrt{\dot{\theta}(t)}=\sqrt{\dot{\theta}(\theta^{-1}(u))} \tag{112}$$

and

$$\delta\,(v-\theta(t))=\delta\,(v-u) \tag{113}$$

yielding

$$\int_{\mathbb{R}} g(u,t)\,h(t,v)\,d\,t=\delta\,(v-u) \tag{114}$$

13. Thus, (110) simplifies to

$$\int_{\mathbb{R}} \delta\,(v-u)\,X(v)\,d\,v = X(u) \tag{115}$$

confirming the transformations are inverses.

□

Corollary 13. *The evolutionary spectrum is*

$$d\,F_t(\lambda) = \dot{\theta}(t)\,d\,F(\lambda) \tag{116}$$

Proof. 1. The evolutionary spectrum is defined by

$$d\,F_t(\lambda) = |A_t(\lambda)|^2\,d\,F(\lambda) \tag{117}$$

2. From (81),

$$|A_t(\lambda)|^2 = \left|\sqrt{\dot{\theta}(t)}\,e^{i\lambda(\theta(t)-t)}\right|^2 \tag{118}$$

3. Since $|e^{i\alpha}| = 1$ for all real α,

$$|e^{i\lambda(\theta(t)-t)}|^2 = 1 \tag{119}$$

4. Therefore

$$|A_t(\lambda)|^2 = \left(\sqrt{\dot{\theta}(t)}\right)^2 \cdot 1 = \dot{\theta}(t) \tag{120}$$

5. Substituting (120) into (117),

$$d\,F_t(\lambda) = \dot{\theta}(t)\,d\,F(\lambda) \tag{121}$$ □

2.3 Covariance operator conjugation

Proposition 14. *Let*

$$(T_K\,f)(t) := \int_{\mathbb{R}} K(|t-s|)\,f(s)\,d\,s \tag{122}$$

with stationary kernel

$$K(h) = \int_{\mathbb{R}} e^{i\lambda h}\,d\,F(\lambda) \tag{123}$$

Define the transformed kernel

$$K_\theta(s,t) := \sqrt{\dot{\theta}(t)\,\dot{\theta}(s)}\,K(|\theta(t)-\theta(s)|) \tag{124}$$

then the corresponding integral covariance operator is conjugated for all $f \in L^2_{\mathrm{loc}}(\mathbb{R})$ by

$$(T_{K_\theta}\,f)(t) = (U_\theta\,T_K\,U_\theta^{-1}\,f)(t) \tag{125}$$

Proof. 1. From (125), expand the right side:

$$(U_\theta\,T_K\,U_\theta^{-1}\,f)(t) = \sqrt{\dot{\theta}(t)}\,(T_K\,U_\theta^{-1}\,f)(\theta(t)) \tag{126}$$

2. By definition (122),

$$(T_K U_\theta^{-1} f)(\theta(t)) = \int_{\mathbb{R}} K(|\theta(t) - s|)\,(U_\theta^{-1} f)(s)\,d\,s \tag{127}$$

3. By definition (61),

$$(U_\theta^{-1} f)(s) = \frac{f(\theta^{-1}(s))}{\sqrt{\dot{\theta}(\theta^{-1}(s))}} \tag{128}$$

4. Substituting (128) into (127),

$$\int_{\mathbb{R}} K(|\theta(t) - s|) \frac{f(\theta^{-1}(s))}{\sqrt{\dot{\theta}(\theta^{-1}(s))}}\,d\,s \tag{129}$$

5. Apply the change of variables $s = \theta(u)$, so $d\,s = \dot{\theta}(u)\,d\,u$ and $\theta^{-1}(s) = u$:

$$\int_{\mathbb{R}} K(|\theta(t) - \theta(u)|) \frac{f(u)}{\sqrt{\dot{\theta}(u)}}\,\dot{\theta}(u)\,d\,u \tag{130}$$

6. Simplify:

$$\int_{\mathbb{R}} K(|\theta(t) - \theta(u)|) \frac{\dot{\theta}(u)}{\sqrt{\dot{\theta}(u)}}\,f(u)\,d\,u = \int_{\mathbb{R}} K(|\theta(t) - \theta(u)|) \sqrt{\dot{\theta}(u)}\,f(u)\,d\,u \tag{131}$$

7. Substituting (131) into (126),

$$\sqrt{\dot{\theta}(t)} \int_{\mathbb{R}} K(|\theta(t) - \theta(u)|) \sqrt{\dot{\theta}(u)}\,f(u)\,d\,u \tag{132}$$

8. Bring the constant inside the integral:

$$\int_{\mathbb{R}} \sqrt{\dot{\theta}(t)}\,\sqrt{\dot{\theta}(u)}\,K(|\theta(t) - \theta(u)|)\,f(u)\,d\,u \tag{133}$$

9. By definition (124),

$$\sqrt{\dot{\theta}(t)}\,\sqrt{\dot{\theta}(u)}\,K(|\theta(t) - \theta(u)|) = K_\theta(u, t) \tag{134}$$

10. Therefore

$$\int_{\mathbb{R}} K_\theta(u, t)\,f(u)\,d\,u = (T_{K_\theta} f)(t) \tag{135}$$

establishing (125). □

3 Zero Localization

Definition 15. *Let Z be real-valued with $Z \in C^1(\mathbb{R})$ having only simple zeros*

$$Z(t_0) = 0 \Rightarrow \dot{Z}(t_0) \neq 0 \tag{136}$$

Define, for Borel $B \subset \mathbb{R}$,

$$\mu(B) = \int_{\mathbb{R}} 1_B(t)\, \delta(Z(t)) |\dot{Z}(t)|\, dt \tag{137}$$

Theorem 16. *Under the assumptions of Definition 15, zeros are locally finite and one has*

$$\delta(Z(t)) = \sum_{t_0 : Z(t_0) = 0} \frac{\delta(t - t_0)}{|\dot{Z}(t_0)|} \tag{138}$$

whence

$$\mu = \sum_{t_0 : Z(t_0) = 0} \delta_{t_0} \tag{139}$$

Proof.

1. For any smooth test function ϕ with compact support, apply the standard change of variables formula for the delta function. Let $\{t_0^{(1)}, t_0^{(2)}, \ldots\}$ denote the zeros of Z.
2. By the change of variables formula for distributions,
$$\int_{\mathbb{R}} \phi(t)\, \delta(Z(t))\, dt = \sum_{t_0 : Z(t_0) = 0} \frac{\phi(t_0)}{|\dot{Z}(t_0)|} \tag{140}$$
3. The right side of (140) equals
$$\sum_{t_0 : Z(t_0) = 0} \frac{\phi(t_0)}{|\dot{Z}(t_0)|} = \sum_{t_0 : Z(t_0) = 0} \int_{\mathbb{R}} \phi(t) \frac{\delta(t - t_0)}{|\dot{Z}(t_0)|}\, dt \tag{141}$$
4. By Fubini's theorem (justified since the sum has locally finite terms due to C^1 regularity and simple zeros),
$$\sum_{t_0 : Z(t_0) = 0} \int_{\mathbb{R}} \phi(t) \frac{\delta(t - t_0)}{|\dot{Z}(t_0)|}\, dt = \int_{\mathbb{R}} \phi(t) \sum_{t_0 : Z(t_0) = 0} \frac{\delta(t - t_0)}{|\dot{Z}(t_0)|}\, dt \tag{142}$$
5. Comparing (140) and (142),
$$\int_{\mathbb{R}} \phi(t)\, \delta(Z(t))\, dt = \int_{\mathbb{R}} \phi(t) \sum_{t_0 : Z(t_0) = 0} \frac{\delta(t - t_0)}{|\dot{Z}(t_0)|}\, dt \tag{143}$$
6. Since ϕ is arbitrary,
$$\delta(Z(t)) = \sum_{t_0 : Z(t_0) = 0} \frac{\delta(t - t_0)}{|\dot{Z}(t_0)|} \tag{144}$$

establishing (138).

7. Substituting (144) into the definition (137),

$$\mu(B) = \int_{\mathbb{R}} 1_B(t) \sum_{t_0 : Z(t_0) = 0} \frac{\delta(t - t_0)}{|\dot{Z}(t_0)|} |\dot{Z}(t)| \, d t \tag{145}$$

8. By the sifting property of the delta function, $|\dot{Z}(t)|$ evaluated at $t = t_0$ gives $|\dot{Z}(t_0)|$:

$$\int_{\mathbb{R}} 1_B(t) \frac{\delta(t - t_0)}{|\dot{Z}(t_0)|} |\dot{Z}(t)| \, d t = \frac{1_B(t_0) |\dot{Z}(t_0)|}{|\dot{Z}(t_0)|} = 1_B(t_0) \tag{146}$$

9. Summing over all zeros,

$$\mu(B) = \sum_{t_0 : Z(t_0) = 0} 1_B(t_0) = \sum_{t_0 \in B : Z(t_0) = 0} 1 \tag{147}$$

10. This is precisely the atomic measure

$$\mu = \sum_{t_0 : Z(t_0) = 0} \delta_{t_0} \tag{148}$$

establishing (139). □

Definition 17. *Let $\mathcal{H} = L^2(\mu)$ be the Hilbert space with inner product*

$$\langle f, g \rangle = \int_{-\infty}^{\infty} f(t) \overline{g(t)} d \mu(t) \tag{149}$$

Proposition 18. ***[Atomic structure]*** *Let*

$$\mu = \sum_{t_0 : Z(t_0) = 0} \delta_{t_0} \tag{150}$$

then

$$\mathcal{H} \cong \left\{ f : \{t_0 : Z(t_0) = 0\} \to \mathbb{C} : \sum_{t_0 : Z(t_0) = 0} |f(t_0)|^2 < \infty \right\} \cong \ell^2 \tag{151}$$

with orthonormal basis $\{e_{t_0}\}_{t_0 : Z(t_0) = 0}$ where

$$e_{t_0}(t_1) = \delta_{t_0, t_1} \tag{152}$$

Proof. 1. By (150), μ is a purely atomic measure with atoms at the zero set.

2. For any $f \in L^2(\mu)$, the L^2 norm is

$$\|f\|_{L^2(\mu)}^2 = \int_{\mathbb{R}} |f(t)|^2 \, d \mu(t) \tag{153}$$

3. Substituting (150),

$$\int_{\mathbb{R}} |f(t)|^2 \, d\mu(t) = \int_{\mathbb{R}} |f(t)|^2 \sum_{t_0 : Z(t_0) = 0} \delta_{t_0}(dt) = \sum_{t_0 : Z(t_0) = 0} |f(t_0)|^2 \tag{154}$$

4. Therefore

$$\|f\|_{L^2(\mu)}^2 = \sum_{t_0 : Z(t_0) = 0} |f(t_0)|^2 \tag{155}$$

5. This is precisely the ℓ^2 norm on the zero set.

6. Define the map $\Psi : L^2(\mu) \to \ell^2$ by

$$\Psi(f) = (f(t_0))_{t_0 : Z(t_0) = 0} \tag{156}$$

7. From (155), Ψ is an isometry:

$$\|\Psi(f)\|_{\ell^2}^2 = \sum_{t_0 : Z(t_0) = 0} |f(t_0)|^2 = \|f\|_{L^2(\mu)}^2 \tag{157}$$

8. Ψ is surjective: for any sequence $(c_{t_0}) \in \ell^2$, define $f(t) = \sum_{t_0} c_{t_0} \delta_{t_0}(t)$, which is in $L^2(\mu)$.

9. Therefore Ψ is a Hilbert space isomorphism, establishing (151).

10. For the orthonormal basis, define e_{t_0} by (152).

11. Then

$$\langle e_{t_0}, e_{t_1} \rangle = \int_{\mathbb{R}} e_{t_0}(t) \overline{e_{t_1}(t)} d\mu(t) = \sum_{s : Z(s) = 0} \delta_{t_0, s} \delta_{t_1, s} = \delta_{t_0, t_1} \tag{158}$$

12. Therefore $\{e_{t_0}\}$ is an orthonormal set.

13. Since every $f \in L^2(\mu)$ can be written as

$$f = \sum_{t_0 : Z(t_0) = 0} f(t_0) \, e_{t_0} \tag{159}$$

the set $\{e_{t_0}\}$ is complete, hence an orthonormal basis. □

Definition 19. ***[Multiplication operator]*** *Define the linear operator*

$$L : \mathcal{D}(L) \subset \mathcal{H} \to \mathcal{H} \tag{160}$$

by

$$(Lf)(t) = t f(t) \tag{161}$$

on the support of μ with domain

$$\mathcal{D}(L) := \left\{ f \in \mathcal{H} : \int |t f(t)|^2 \, d\mu(t) < \infty \right\} \tag{162}$$

Theorem 20. ***[Self-adjointness and spectrum]*** *L is self-adjoint on $\mathcal{H}$ and has pure point, simple spectrum*

$$\sigma(L) = \overline{\{t \in \mathbb{R}: Z(t) = 0\}} \tag{163}$$

with eigenvalues $\lambda = t_0$ for each zero t_0 and corresponding eigenvectors e_{t_0}.

Proof.

1. For $f, g \in \mathcal{D}(L)$, compute the inner product:

$$\langle L f, g \rangle = \int_{\mathbb{R}} (L f)(t) \overline{g(t)} d\mu(t) \tag{164}$$

2. By definition (161),

$$\int_{\mathbb{R}} t f(t) \overline{g(t)} d\mu(t) \tag{165}$$

3. Since t is real-valued, $\bar{t} = t$, so

$$\int_{\mathbb{R}} t f(t) \overline{g(t)} d\mu(t) = \int_{\mathbb{R}} f(t) \overline{t g(t)} d\mu(t) \tag{166}$$

4. The right side of (166) is

$$\int_{\mathbb{R}} f(t) \overline{(L g)(t)} d\mu(t) = \langle f, L g \rangle \tag{167}$$

5. Therefore

$$\langle L f, g \rangle = \langle f, L g \rangle \tag{168}$$

   for all $f, g \in \mathcal{D}(L)$, establishing that L is symmetric.

6. Since L is a multiplication operator on $L^2(\mu)$, it is self-adjoint (by standard functional analysis).

7. To determine the spectrum, compute the action on basis vectors. From (161) and (152),

$$(L e_{t_0})(t) = t e_{t_0}(t) = t \delta_{t_0}(t) \tag{169}$$

8. By the sifting property,

$$t \delta_{t_0}(t) = t_0 \delta_{t_0}(t) = t_0 e_{t_0}(t) \tag{170}$$

9. Therefore

$$L e_{t_0} = t_0 e_{t_0} \tag{171}$$

10. This shows that each t_0 is an eigenvalue with eigenvector e_{t_0}.

11. Since the $\{e_{t_0}\}$ form a complete orthonormal basis (Proposition 18), the spectrum is pure point.

12. Each eigenspace is one-dimensional (spanned by e_{t_0}), so the spectrum is simple and given by the closure of the zero set

$$\sigma(L) = \{t_0: Z(t_0) = 0\} = \overline{\{t \in \mathbb{R}: Z(t) = 0\}} \tag{172}$$

□

3.1 The Kac-Rice Formula For The Expected Zero Counting Function

Theorem 21. (Expected Zero-Counting Function Of The Oscillatory Process Subclass of Unitarily Time-Changed Stationary Processes) *Let $\theta: \mathbb{R} \to \mathbb{R}$ be absolutely continuous, strictly increasing, and bijective with $\dot{\theta}(t) > 0$ almost everywhere. Let X be a centered stationary Gaussian process with spectral measure F and covariance function*

$$K(h) = \int_{\mathbb{R}} e^{i\omega h} \, dF(\omega) \tag{173}$$

twice differentiable at $h = 0$. Define the unitarily time-changed process

$$Z(t) = \sqrt{\dot{\theta}(t)} \; X(\theta(t)) \tag{174}$$

Then Z is a centered Gaussian process with covariance

$$K_Z(t, s) = \sqrt{\dot{\theta}(t)\dot{\theta}(s)} \; K(\theta(t) - \theta(s)) \tag{175}$$

and the expected number of zeros in $[0, T]$ is

$$\mathbb{E}[N_{[0,T]}] = \sqrt{-2\pi \frac{\ddot{K}(0)}{K(0)}} \, [\theta(T) - \theta(0)] \tag{176}$$

Proof.

1. By the Kac-Rice formula:

$$\mathbb{E}[N_{[0,T]}] = \int_0^T \sqrt{\frac{2}{\pi}} \frac{\sqrt{-\lim_{s \to t} \frac{\partial^2}{\partial s \, \partial t} K_Z(s, t)}}{K_Z(t, t)} \, dt \tag{177}$$

2. Differentiate (175) with respect to s:

$$\frac{\partial}{\partial s} K_Z(s, t) = \frac{\ddot{\theta}(s)}{2\sqrt{\dot{\theta}(s)\dot{\theta}(t)}} \; K(\theta(t) - \theta(s)) - \dot{\theta}(s)\sqrt{\dot{\theta}(s)\dot{\theta}(t)} \; \dot{K}(\theta(t) - \theta(s)) \tag{178}$$

3. Differentiate (178) with respect to t and take $s \to t$. Since $\dot{K}(0) = 0$ by stationarity:

$$\lim_{s \to t} \frac{\partial^2}{\partial s \, \partial t} K_Z(s, t) = -\dot{\theta}(t)^2 \, \ddot{K}(0) \tag{179}$$

4. From (175) with $s = t$:

$$K_Z(t, t) = \dot{\theta}(t) \; K(0) \tag{180}$$

5. Substitute (179) and (180) into (177):

$$\mathbb{E}[N_{[0,T]}] = \int_0^T \sqrt{\frac{2}{\pi}} \frac{\sqrt{\dot{\theta}(t)^2 (-\ddot{K}(0))}}{\dot{\theta}(t) \, K(0)} \, dt \tag{181}$$

6. Since $\dot{\theta}(t) > 0$ and $\ddot{K}(0) < 0$:

$$\mathbb{E}[N_{[0,T]}] = \int_0^T \sqrt{\frac{2}{\pi}}\, \frac{\dot{\theta}(t)\sqrt{-\ddot{K}(0)}}{\dot{\theta}(t)\, K(0)}\, d\,t = \frac{\sqrt{-\ddot{K}(0)}}{\sqrt{2\,\pi\, K(0)}} \int_0^T \dot{\theta}(t)\ d\,t \tag{182}$$

7. Evaluate the integral:

$$\mathbb{E}[N_{[0,T]}] = \sqrt{-2\,\pi\, \frac{\ddot{K}(0)}{K(0)}}\, [\theta(T) - \theta(0)] \tag{183}$$ □

Theorem 22. ***[Deterministic zero-crossing at vanishing derivative]*** *Let X be a zero-mean stationary process with spectral measure F as in Definition 3 and finite variance $\sigma^2 = \mathbb{E}[X(t)^2] < \infty$. Let $\theta\colon \mathbb{R} \to \mathbb{R}$ be the time-change function from Theorem 10, which is absolutely continuous (has derivative $\dot{\theta}$ that exists almost everywhere and is Lebesgue integrable), strictly increasing (so $\theta(t_1) < \theta(t_2)$ whenever $t_1 < t_2$), and bijective (one-to-one and onto). The derivative $\dot{\theta}(t)$ is strictly positive almost everywhere, meaning $\dot{\theta}(t) > 0$ for all t except possibly on a set of Lebesgue measure zero. Define the transformed process*

$$Z(t) = (U_\theta X)(t) = \sqrt{\dot{\theta}(t)}\, X(\theta(t)) \tag{184}$$

as in equation (60). Consider a point $t_0 \in \mathbb{R}$ where the derivative vanishes: $\dot{\theta}(t_0) = 0$. Then ***every sample path of Z passes through zero at t_0****: for all $\omega \in \Omega$,*

$$Z(t_0, \omega) = 0 \tag{185}$$

This is a ***deterministic zero-crossing****: unlike the random zero-crossings of the stationary process X, which occur probabilistically according to Bulinskaya's statistics, the zero at t_0 occurs with certainty in every realization of Z. The randomness of X is completely suppressed at t_0 by the vanishing amplitude $\sqrt{\dot{\theta}(t_0)} = 0$.*

Proof.

1. Consider a point $t_0 \in \mathbb{R}$ where $\dot{\theta}(t_0) = 0$.
2. From the definition (184), the value of Z at t_0 for any sample path $\omega \in \Omega$ is

$$Z(t_0, \omega) = \sqrt{\dot{\theta}(t_0)} \cdot X(\theta(t_0), \omega) \tag{186}$$

3. Since $\dot{\theta}(t_0) = 0$ by hypothesis,

$$\sqrt{\dot{\theta}(t_0)} = \sqrt{0} = 0 \tag{187}$$

4. Substituting (187) into (186),

$$Z(t_0, \omega) = 0 \cdot X(\theta(t_0), \omega) = 0 \tag{188}$$

regardless of the value of $X(\theta(t_0), \omega)$.

5. Since $\omega \in \Omega$ was arbitrary, equation (188) holds for every sample path:

$$Z(t_0, \omega) = 0 \quad \forall \omega \in \Omega \tag{189}$$

6. Therefore t_0 is a deterministic zero-crossing: the process Z reaches zero at t_0 in every realization, not probabilistically.

7. As a direct consequence, the variance of Z at t_0 is zero:

$$\mathrm{Var}[Z(t_0)] = \mathbb{E}[(Z(t_0) - \mathbb{E}[Z(t_0)])^2] = \mathbb{E}[0^2] = 0 \tag{190}$$

8. By Corollary 13, the evolutionary spectrum at t_0 vanishes:

$$d\,F_{t_0}(\lambda) = \dot{\theta}(t_0)\,d\,F(\lambda) = 0 \cdot d\,F(\lambda) = 0 \tag{191}$$

   meaning there is no spectral energy at t_0.

9. The point t_0 belongs to the zero set $\{t \in \mathbb{R}: Z(t, \omega) = 0\}$ for every $\omega \in \Omega$. By Definition 4, this deterministic zero-crossing differs fundamentally from the random zero-crossings governed by the statistics of the stationary process X: it occurs because the amplitude factor $\sqrt{\dot{\theta}(t_0)}$ vanishes, completely eliminating the influence of the random process X at that instant. □

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