Spectral Representations of Stochastic Processes

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Abstract

Most of the first two chapters of Roger G. Ghanem and Pol D. Spanos. *Stochastic finite elements: a spectral approach* are covered and a method of calculating the eigenfunctions and eigenvalues of any integral covariance operator of a stationary process is detailed.

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1 The Spectral Approach to Stochastic Processes

1.1 The Gelfand-Vilenkin Spectral Representation

The majority of the results on the representation of random processes have been derived for the class of second order processes[1]; one of the most important of which is the `Gelfand-Vilenkin spectral representation` which states in its most general form

$$w\,(x,\theta) = \int g(x)\,d\,\mu(\theta) \tag{1}$$

where $w\,(x,\theta)$ is a stochastic process whose covariance function $C_{ww}(x_1,x_2)$ can be expressed as

$$C_{ww}(x_1,x_2) = \int g(x_1)\, g(x_2)\, d\,\mu_1(\theta)\, d\,\mu_2(\theta) \tag{2}$$

In equation (1), $g(x)$ is a deterministic function and $d\,\mu(\theta)$ is an orthogonal set function, also termed orthogonal stochastic measure, defined on the σ-field Ψ of random events. An important specialization of the spectral expansion occurs if the process $w\,(x,\theta)$ is wide stationary. In this case, equation (1) can be shown to reduce to the Wiener-Khintchine relation [3] and we have

$$w\,(x,\theta) = \int_{-\infty}^{\infty} e^{i\omega^T x}\, d\,\mu(\omega,\theta) \tag{3}$$

and

$$C_{ww}(x_1,x_2) = \int_{-\infty}^{\infty} e^{i(\omega_1 x_1 - \omega_2 x_2)^T} S(\omega)\, d\,\omega \tag{4}$$

where the symbol T denotes vector transposition, $S(\omega)$ is the usual `spectral density` of the stationary process, and ω is the `wave number vector`. In the equation for $C_{ww}(x_1,x_2)$:

- $e^{i(\omega_1 x_1 - \omega_2 x_2)^T}$ represents the complex exponential function used in Fourier transforms, indicating oscillations at frequencies ω_1 and ω_2 along dimensions x_1 and x_2, respectively.

- ω_1 and ω_2 are spatial frequency components corresponding to different axes/dimensions (e.g., x_1 and x_2). They indicate how the wave's frequency components vary along these dimensions.

- The term $S(\omega)$ represents the spectral density of the process at frequency ω, detailing how energy is distributed across different frequencies.

- The integral sums these contributions across all frequencies to calculate the covariance between two points x_1 and x_2 in the process, incorporating the spatial structure and dependence of the process.

The impact of these spectral representations on the theory of random processes is significant but limited to deterministic systems subjected to random excitations. This limitation arises because these representations require differentials of random functions, placing them in an infinite-dimensional space, which complicates the development of computational algorithms. Similarly,[2, Ch.1 Bibliogaphical notes, p.18] highlights a challenge in extending von Neumann's zero-sum two-person games to stochastic processes, hindered by the same issue of infinite-dimensionality.

1.2 The Karhunen-Loeve Expansion

The Karhunen-Loeve expansion is an extensively used spectral representation theorem, whereby a random process $w(x,\theta)$ can be expanded in terms of a denumerable set of orthogonal random variables in the form

$$w(x,\theta) = \sum_{i=1}^{\infty} \mu_i(\theta)\, g_i(x) \tag{5}$$

where $\{\mu_i(\theta)\}$ is a set of orthogonal random variables and $\{g_i(x)\}$ are deterministic functions, which can be related to the covariance kernel of $w(x,\theta)$. Note that since equation (?) constitutes a representation of the random process in terms of a denumerable set of random variables, it is a quantization of the random process. It is important to note that this equation can be viewed as a representation of the process $w(x,\theta)$ as a curve in the Hilbert space spanned by the set $\{g_i(x)\}$ expressed as a direct sum of orthogonal projections in this Hilbert space whereby the magnitudes of the projections on successive basis vectors are proportional to the corresponding eigenvalues of the covariance function associated with the process $w(x,\theta)$. Collectively, the representations discussed up to [1, 2.2] can be thought of as linear operators or filters acting on processes with independent increments.

1.2.1 Derivation

The Karhunen-Loeve expansion is abtheoretically elegant and computationally appealing way to deal with measures spaces. It works by expanding functions in Fourier-like series as

$$w(x,\theta) = \sum_{n=0}^{\infty} \sqrt{\lambda_n}\, \xi_n(\theta)\, f_n(x) \tag{6}$$

where $\{\xi_n(\theta)\}$ is a said to be a set of 'random' variables to be determined, λ_n is some constant, and $\{f_n(x)\}$ is an orthonormal set of deterministic basis functions. I find it a bit of a misnomer to refer to the sequence $\xi_n(\theta)$ as random variables because in many instances these formulas are applied to deterministic, defined exact functions that do not involve randomness and in fact the theorems related to the Karhunen-Loeve expansion do not depend on any concepts that are inherently stochastic.

1.2.2 Spectral Covariance Representations

Let $w(x,\theta)$ be a random process, function of the position vector x defined over the domain D, with θ belonging to the space of random events Ω. Let $\bar{w}(x)$ denote the expected value of $w(x,\theta)$ over all possible realizations of the process, and $C(x_1,x_2)$ denote its covariance function. By definition of the covariance function, it is bounded, symmetric and positive definite. Thus, it has the eigenfunction expansion [1, 2.3.1]

$$C(x_1,x_2) = \sum_{n=0}^{\infty} \lambda_n\, f_n(x_1)\, f_n(x_2) \tag{7}$$

where λ_n and $f_n(x)$ are the eigenvalue and the eigenfunction of the covariance kernel. And, specifically, that they are the solution to the integral equation

$$\int_D C(x_1, x_2)\, f_n(x_1)\, d\, x_1 = \lambda_n\, f_n(x_2) \tag{8}$$

Due to the symmetry and the positive definiteness of the covariance kernel, its eigenfunctions are orthogonal and form a complete set. They can be normalized according to the following criterion

$$\int_D f_n(x)\, f_m(x)\, d\, x = \delta_{nm} \tag{9}$$

where δ_{nm} is the Kronecker delta. Clearly, $w(x, \theta)$ can be written as

$$w\,(x, \theta) = \bar{w}(x) + \alpha(x, \theta) \tag{10}$$

where $\alpha(x, \theta)$ is a process with zero mean and covariance function $C(x_1, x_2)$. The process $\alpha(x, \theta)$ can be expanded in terms of the eigenfunctions $f_n(x)$ as

$$\alpha(x, \theta) = \sum_{n=0}^{\infty} \xi_n(\theta) \sqrt{\lambda_n}\, f_n(x) \tag{11}$$

Second order properties of the random variables ξ_n can be determined by multiplying both sides of equation (11) by $\alpha(x_2, \theta)$ and taking the expectation on both sides. Specifically, it is found that

$$\begin{aligned} C(x_1, x_2) &= \langle \alpha(x_1, \theta)\, \alpha(x_2, \theta) \rangle \\ &= \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} \langle \xi_n(\theta)\, \xi_m(\theta) \rangle \sqrt{\lambda_n\, \lambda_m}\, f_n(x_1)\, f_m(x_2) \end{aligned} \tag{12}$$

Then, multiplying both sides of equation (12) by $f_k(x_2)$, integrating over the domain D, and making use of the orthogonality of the eigenfunctions, yields

$$\begin{aligned} \int_D C(x_1, x_2)\, f_k(x_2)\, d\, x_2 &= \lambda_k\, f_k(x_1) \\ &= \sum_{n=0}^{\infty} \langle \xi_n(\theta)\, \xi_k(\theta) \rangle \sqrt{\lambda_n\, \lambda_k}\, f_n(x_1) \end{aligned} \tag{13}$$

Multiplying once more by $f_l(x_1)$ and integrating over D gives

$$\int_D \int_D f_l(x_1)\, f_k(x_1)\, d\, x_1 = \sum_{n=0}^{\infty} E\, \langle \xi_n(\theta)\, \xi_k(\theta) \rangle \sqrt{\lambda_n\, \lambda_k}\, \delta_{nl} \tag{14}$$

Then, using equation (9) leads to

$$\lambda_k \, \delta_{kl} = \sqrt{\lambda_k \, \lambda_l} \, \langle \xi_k(\theta) \, \xi_l(\theta) \rangle \tag{15}$$

Equation (15) can be rearranged to give

$$\langle \xi_k(\theta) \, \xi_l(\theta) \rangle = \delta_{kl} \tag{16}$$

Thus, the random process $w\,(x, \theta)$ can be written as

$$w\,(x, \theta) = \bar{w}(x) + \sum_{n=0}^{\infty} \xi_n(\theta) \sqrt{\lambda_n} \, f_n(x) \tag{17}$$

where

$$\langle \xi_n(\theta) \rangle = 0 \tag{18}$$

$$\langle \xi_n(\theta) \, \xi_m(\theta) \rangle = \delta_{nm} \tag{19}$$

and λ_n, $f_n(x)$ are solution to equation (8). Truncating the series in equation (17) at the Mth term, gives

$$w\,(x, \theta) = \bar{w}(x) + \sum_{n=0}^{M} \xi_n(\theta) \sqrt{\lambda_n} \, f_n(x) \tag{20}$$

An explicit expression for $\xi_n(\theta)$ can be obtained by multiplying equation (11) by $f_n(x)$ and integrating over the domain D. That is,

$$\xi_n(\theta) = \frac{\int_D \alpha(x, \theta) \, f_n(x) \, d\,x}{\sqrt{\lambda_n}} \tag{21}$$

1.2.3 Reproducing Kernel Hilbert Spaces (RKHS)

The essential thing that the Reproducing Kernel Hilbert Space (RKHS) paradigm provides, is that either of equations (11) or (20), are expressions for the congruence that maps the Hilbert space spanned by the functions $f_n(x)$ to the Hilbert space spanned by the random process, or equivalently, the set of random variables $\{\xi_n(\theta)\}$. It is this congruence along with the covariance function of the process that determines uniquely the random process $w\,(x, \theta)$ as can be seen by observing the similarity of equations (11) and (20) with equations (7) and (8), respectively. If a function can be represented in terms of linear operations on the family $\{C(\,\cdot, x_2)\}$, then f belongs to the RKHS corresponding to the kernel $C(x_1, x_2)$, and the congruence between the two Hilbert spaces can be realized by the same linear operations used to represent f in terms of $\{C(\,\cdot, x_2)\}$, $x_2 \in D$.

Another point of practical importance is that the expansion given by equation (19) can be used in a numerical simulation scheme to obtain numerical realizations of the random process. It is optimal in the Fourier sense, as it minimizes the mean square error resulting from truncation after a finite number of terms.It is well known from functional analysis that the steeper a bilinear form decays to zero as a function of one of its arguments, the more terms are needed in its spectral representation in order to reach a preset accuracy. Noting that the Fourier transform operator is a spectral representation, it may be concluded that the faster the autocorrelation function tends to zero, the broader is the corresponding spectral density, and the greater the number of requisite terms to represent the underlying random process by the Karhunen-Loeve expansion. Most theorems are limited to bounded-intervals and square-integrable kernels. This setup does not induce the ergodic assumption for the process since the domain is bounded; however, for many purposes the ergodic condition is not necessary but it may restored by extending the limits of integration in equation (35) to infinity.[1, 2.3.2]

1.3 Properties

1.3.1 Error Minimization

Lemma 1

***Error Minimization**: The generalized coordinate system defined by the eigenfunctions of the covariance kernel is optimal in the sense that the mean-square error resulting from a finite representation of the process $w(x,\theta)$ is minimized.*

Proof. Given a complete orthonormal set of functions $h_n(x)$, the process $w(x,\theta)$ can be approximated in a convergent series of the form

$$w(x,\theta) = \sum_{n=0}^{\infty} \lambda_n \, \xi_n(\theta) \, h_n(x) \tag{22}$$

Truncating equation (21) at the Mth term results in an error ϵ_M equal to

$$\epsilon_M = \sum_{n=M+1}^{\infty} \lambda_n \, \xi_n(\theta) \, h_n(x) \tag{23}$$

Multiplying equation (21) by $h_m(x)$ and integrating throughout gives

$$\xi_m(\theta) = \frac{\int_D w(x,\theta) \, h_m(x) \, d\,x}{\sqrt{\lambda_m}} \tag{24}$$

where use is made of the orthogonality property of the set $h_n(x)$. Substituting equation (23) for $\xi_m(\theta)$ back into equation (22), the mean-square error ϵ_M^2 can be written as

$$\epsilon_M^2 = \left[\sum_{m=M+1}^{\infty} \sum_{n=M+1}^{\infty} \int_D \int_D \langle \xi_m(\theta)\, \xi_n(\theta) \rangle\, h_m(x_1)\, h_n(x_2)\, d\,x_1\, d\,x_2 \right]^2 \tag{25}$$

Integrating equation (24) over D and using the orthonormality of the set $\{h_i(x)\}$ yields

$$\int_D \epsilon_M^2\, d\,x = \sum_{m=M+1}^{\infty} \int_D \int_D R_{ww}(x_1, x_2)\, h_m(x_1)\, h_m(x_2)\, d\,x_1\, d\,x_2 \tag{26}$$

The problem, then, is to minimize $\int_D \epsilon_M^2$ subject to the orthonormality of the functions $h_n(x)$. In other words, the solution minimizes the functional given by the equation

$$\mathcal{F}[h(x)] = \sum_{m=M+1}^{\infty} \int_D \int_D R_{ww}(x_1, x_2)\, h_m(x_1)\, h_m(x_2)\, d\,x_1\, d\,x_2 - \lambda_m \left[\int_D h_m(x)\, h_m(x)\, d\,x - 1 \right] \tag{27}$$

Differentiating equation (26) with respect to $h_i(x)$ and setting the result equal to zero, gives

$$\frac{\partial\, \mathcal{F}[h(x)]}{\partial\, h_i(x)} = \int_D \int_D R_{ww}(x_1, x_2)\, h_i(x_1)\, d\,x_1 - \lambda_i\, h_i(x_2)\, d\,x_2 = 0 \tag{28}$$

which is satisfied when

$$\int_D R_{ww}(x_1, x_2)\, h_i(x_2)\, d\,x_2 = \lambda_i\, h_i(x_1) \tag{29}$$ □

1.3.2 Uniqueness of the Expansion

Lemma 2

Uniqueness: *The random variables appearing in an expansion of the kind given by equation (10) are orthonormal if and only if the orthonormal functions $\{f_n(x)\}$ and the constants $\{\lambda_n\}$ are respectively the eigenfunctions and the eigenvalues of the covariance kernel as given by equation (8).*

Proof. The "if" part is an immediate consequence of equation (11). To show the "only if" part, equation (12) can be used with

$$\langle \xi_n(\theta)\, \xi_m(\theta) \rangle = \delta_{nm} \tag{30}$$

to obtain

$$C(x_1, x_2) = \sum_{n=0}^{\infty} \lambda_n \, f_n(x_1) \, f_n(x_2) \tag{31}$$

Multiplying both sides by $f_m(x_2)$ and integrating over D gives

$$\int_D C(x_1, x_2) \, f_m(x_2) \, d\, x_2 = \sum_{n=0}^{\infty} \lambda_n \, f_n(x_1) \, \delta_{nm} = \lambda_m \, f_m(x_1) \tag{32}$$ □

1.3.3 Expansion of Gaussian Processes

Let $w\,(x, \theta)$ be a Gaussian process with covariance function $C(x_1, x_2)$. Then $w\,(x, \theta)$ has the Karhunen-Loeve decomposition given by equation (17) with the random variables $\xi_i(\theta)$ forming a Gaussian vector. That is, any subset of $\{\xi_i(\theta)\}$ is jointly Gaussian. Since these random variables are uncorrelated, their Gaussian property implies their independence. Some important consequences derive from this property. Specifically,

$$\langle \xi_1(\theta), \ldots, \xi_{2n+1}(\theta) \rangle = 0 \tag{33}$$

and

$$\langle \xi_1(\theta), \ldots, \xi_{2n}(\theta) \rangle = \sum \prod \langle \xi_i(\theta) \, \xi_j(\theta) \rangle \tag{34}$$

where the summation extends over all the partitions of the set $\{\xi_i(\theta)\}_{i=1}^{2n}$ into sets of two elements, and the product is over all such sets in a given partition. Furthermore, it can be shown (Loeve, 1977) that for Gaussian processes, the Karhunen-Loeve expansion is almost surely convergent.

1.3.4 Minimum Representation Entropy

The minimum representation of entropy property is worth mentioning even though it only references and no details were given in [1].

1.4 Solution of the Integral Equation

The usefulness of the Karhunen-Loeve expansion hinges on the ability to solve the integral equation of the form

$$\int_D C(x_1, x_2) \, f(x_2) \, d\, x_2 = \lambda \, f(x_1) \tag{35}$$

where $C(x_1, x_2)$ is an autocovariance function. Equation (35) is a homogeneous Fredholm integral equation of the second kind. Being an autocovariance function, by definition the kernel $C(x_1, x_2)$ is bounded, symmetric, and positive definite. This fact simplifies the ensuing analysis considerably by virtue of the fact that positive definite kernels implies the existence of an RKHS for the kernel and its spectral density given by its Fourier transform is non-negative and non-decreasing over its domain of definition by Aronszajn's Theorem and Bochner's theorem respectively.

1.5 Numerical Solution

In this section, a Galerkin type procedure is described for the solution of the Fredholm equation (35). Let $h_i(x)$ be a complete set of functions in the Hilbert space H. Each eigenfunction of the kernel $C(x_1, x_2)$ may be represented as

$$f_k(x) = \sum_{i=1}^{N} d_i^{(k)} \, h_i(x) \tag{36}$$

with an error e_N resulting from truncating the summation after the Nth term. This error is equal to the difference between the left hand side and the right hand side of equation (35). Substituting equation (36) into equation (35) yields the following expression for the error

$$e_N = \sum_{i=1}^{N} d_i^{(k)} \left[\int_D \int_D C(x_1, x_2) \, h_i(x_2) \, d\,x_2 - \lambda_n \, h_i(x_1) \right] \tag{37}$$

Requiring the error to be orthogonal to the approximating space yields equations of the following form $\forall j = 1, \ldots, N$

$$(e_N, h_j(x)) = 0 \tag{38}$$

Equivalently,

$$\sum_{i=1}^{N} d_i^{(k)} \left[\int_D \int_D C(x_1, x_2) \, h_i(x_2) \, d\,x_2 \, h_j(x_1) \, d\,x_1 \right] - \lambda_n \int_D h_i(x) \, h_j(x) \, d\,x = 0 \tag{39}$$

Denoting

$$C_{ij} = \int_D \int_D C(x_1, x_2) \, h_i(x_2) \, h_j(x_1) \, d\,x_1 \, d\,x_2 \tag{40}$$

$$B_{ij} = \int_D h_i(x) \, h_j(x) \; d\,x \tag{41}$$

$$D_{ij} = d_i^{(j)} \tag{42}$$

$$\Lambda_{ij} = \delta_{ij} \, \lambda_j \tag{43}$$

equation (39) becomes

$$C\,D = \Lambda B\,D \tag{44}$$

where C, B and D are three N-dimensional matrices whose elements are given by equations (40)-(41). Equation (44) represents a generalized algebraic eigenvalue problem which may be solved for the matrix D and the eigenvalues λ_k. Backsubstituting into equation (36) yields the eigenfunctions of the covariance kernel. The preceding procedure can be implemented using piecewise polynomials as the basis for the expansion. With this choice of basis functions, the columns of the matrix $\mathbf{D}$ become the eigenvectors computed at the respective nodal points of the induced mesh, and the $i\,j^{th}$ element of the matrix $\mathbf{C}$ becomes the weighted correlation between the process at nodes i and j. Note that both matrices $\mathbf{C}$ and $\mathbf{B}$ are symmetric positive definite, a fact that substantially simplifies the numerical solution. The Galerkin scheme described above can be shown to be equivalent to a variational treatment of the problem. This property ensures that the computed eigenvalues are a lower bound of the correspondingly numbered exact eigenvalues. This implies that the convergence of each eigenvalue is monotonic in N. Further, note that the accuracy in estimating the eigenvalues is better than that achieved for the eigenfunctions (Delves and Mohamed, 1985).

1.6 Irrational Spectra and Ergodicity

At the time of writing of [1] there was no general method for the solution of the integral equation (35) corresponding to irrational spectra and furthermore most of the results are for finite bounded intervals. [1, 2.3.2] Most theorems are limited to bounded-intervals and therefore do not presume ergodicity which may restored by extending the limits of integration in equation (35) to infinity and modifying the portions of the corresponding lemmas and theorems that depend on boundedness of the interval or square-integrability of the kernel.[1, 2.3.2]

Bibliography

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