申请同济大学工学博士学位论文

工程随机动力作用的正交展开理论及其应用研究

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研 究 生：刘章军

指导教师：李 杰 教授

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Orthogonal Expansion Method of Engineering Stochastic Dynamic Loads and its Application

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School/Department: School of Civil Engineering
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Major: Structural Engineering
Candidate: Zhang-Jun Liu
Supervisor: Prof. Jie Li

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摘 要

作用于工程结构的动力荷载不仅随时间变化(具有动态特性)，而且大多具有明显的随机性。经典的随机振动理论，一般用功率谱密度函数来描述这类随机动力作用。在本质上，功率谱密度函数是平稳随机过程的二阶数值特征，因此很难全面反映原始随机过程的丰富概率信息。事实上，建立在二阶数值特征意义上的随机振动分析仅能给出结构响应(无论是平稳还是非平稳)的数值特征解答，难以获得结构可靠度的精确解答。由此构成了结构可靠度理论发展中的一个瓶颈问题。有鉴于此，本文基于 Karhunen-Loeve 分解的基本原理，深入开展了工程随机动力作用的正交展开理论及其应用研究。

对于随机过程，Karhunen-Loeve(K-L)分解为人们提供了从独立随机变量集合的角度研究随机过程的可能性。其基本思想在于把随机过程描述为由互不相关的随机系数所调制的确定性函数的线性组合形式。在实际问题中，K-L 分解往往需要求解 Fredholm 积分方程，除少数情况外，获得其解析解答是相当困难的。为避免求解 Fredholm 积分方程的困难，本文首先建议了基于标准正交基的随机过程(随机场)展开法。研究证明：当展开项数趋于无穷大时，基于标准正交基的展开法等价于 K-L 分解法。而由于引入基于标准正交基的二重分解技巧，使得本文建议方法可以以较少的展开项数逼近原随机过程。在此基础上，通过对 Fourier 正交基和 Hartley 正交基的比较研究，本文进一步建议了采用 Hartley 正交基作为展开函数集实施对随机过程正交展开的基本方法。

以上述理论为基础，进行了基于 Hartley 正交基的地震动随机过程的正交展开研究。研究表明：直接对地震动加速度过程实施正交展开，很难达到以较少展开项数反映原随机过程的目的。为此，本文从地震动位移随机过程的正交展开出发，引入一类能量等效原理，获得了地震动加速度随机过程的正交展开公式。研究表明：沿着这一途径，可以将地震动随机过程展开为由少量独立随机变量所调制的确定性函数的线性组合形式。

以结构风作用为背景，本文进行了脉动风速随机过程的正交展开研究。通过引入虚拟脉动风位移过程的概念，应用能量等效原理，可以将反映脉动风特

性的随机过程表示为由 10 个左右的独立随机变量所表述的确定性函数的线性组合形式；在此基础上，针对工程中常用的线性指数型空间相关函数，利用随机场的 Karhunen-Loeve 分解，建立了一类随机脉动风场正交展开模型。利用数论选点方法，验证了随机脉动风场正交展开方法的可行性与有效性。

近年来，本研究梯队所发展的概率密度演化方法和等价极值事件思想，可以用来分析结构随机动力反应的概率密度分布及其随时间的演化过程，同时还能准确计算考虑复杂失效准则下的结构动力可靠度。应用本文提出的基于 Hartley 正交基的随机过程正交展开方法，结合这些方法，进行了结构非线性随机地震反应分析与动力可靠度研究。研究表明：本文建议方法为进行复杂结构非线性随机振动响应分析及动力可靠度计算打开了方便之门。

最后，简要讨论了下一步需要研究的问题。

关键词：随机动力作用，随机过程，正交展开，地震地面运动，随机脉动风场

ABSTRACT

The dynamic loads acting on engineering structures not only vary with time, but also have apparent stochastic characteristics. In classical random vibration theory, stochastic dynamic loads are generally depicted by the power spectral density function, which actually is the second-order statistical value of a stationary stochastic process. Therefore, the probabilistic information of the original stochastic process can not be roundly reflected. Whereas, the classical random vibration analysis can only give numerical characteristic solutions of structural response, not obtain the precise solution of structural reliability. This, consequently, leads to a bottleneck for the development of structural reliability theory. To solve this predicament, the orthogonal expansion method of engineering stochastic dynamic loads and its application are thoroughly studied in this paper based on the rationale of Karhunen-Loeve decomposition.

The Karhunen-Loeve (K-L) decomposition provides a feasible approach to study a stochastic process using a set of random variables. Its basic idea is to represent a stochastic process as a linear combination of deterministic functions modulated by uncorrelated random coefficients. Practically, the K-L decomposition needs to solve the Fredholm integral equation. However, the analytical solutions of the Fredholm integral equation are generally unavailable except for few cases, thus an expansion method based on normalized orthogonal bases is first proposed to decompose stochastic process. It has been proved that this method is equivalent to the Karhunen-Loeve decomposition when expanding terms $N\to\infty$. Further, after the comparative study of the Fourier orthogonal bases and Hartley bases, we choose the Hartley orthogonal bases to expand the stochastic process.

Utilizing the above method, the stochastic process for earthquake ground motion is carried out based on the Hartley orthogonal expansion bases. In order to capture the main probabilistic characteristics of seismic ground motion, we carry out the orthogonal expansion directly on the seismic displacement process. Further by using the principle of energy equivalence, the expanding expressions of seismic acceleration process is achieved with 10 random variables.

This orthogonal expansion method is also applied to the research on the simulation of random wind velocity fields. First the random wind velocity field is decomposed into the product of a stochastic process and a random field, which represent the temporal property and the spatial correlation of wind velocity fluctuations, respectively. The stochastic process for wind velocity fluctuations may be represented as a finite sum of deterministic time functions with corresponding uncorrelated random coefficients by the orthogonal expansion. Similarly, the random field can be expressed as a combination form with 5 random variables by the Karhunen-Loeve decomposition. Finally, a numerical example is given to demonstrate the accuracy and effectiveness of this procedure using the number theoretical method.

Since the recently developed probability density evolution method (PDEM) is capable of capturing instantaneous probability density function and its evolution of linear and/or nonlinear response of structures. So it is natural to combine the PDEM and the foregoing orthogonal expansion of seismic ground motion to study the nonlinear random earthquake response. Furthermore, the aseismatic reliability of structures is assessed using the idea of equivalent extreme-value, which can be used accurately to evaluate structural systems under compound failure criterion.

Finally, further researches are briefly discussed.

Key Words: stochastic dynamic loads; stochastic processes; orthogonal expansion; earthquake ground motion; stochastic wind field

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