DIMENSIONALITY-REDUCED PROBABILITY DENSITY EVOLUTION FOR COMPLEX STOCHASTIC DYNAMICAL SYSTEMS:

THEORY, COMPUTATIONAL METHODS AND ENGINEERING APPLICATIONS

Abstract:

Complex stochastic dynamical systems encountered in engineering often involve high dimensionality, strong nonlinearities, non-Markovian characteristics, and diverse types of stochastic excitations, making their probabilistic response analysis and reliability assessment particularly challenging. The dimension-reduced probability density evolution equation (DR-PDEE) provides a physics-driven framework for overcoming the curse of dimensionality while retaining the essential probabilistic information of the original high-dimensional system. Starting from the principle of preservation of probability, DR-PDEE establishes an exact low-dimensional governing equation for the transient probability density of stochastic responses. A key element of this framework is the intrinsic drift function, which enables the high-dimensional stochastic dynamics to be projected onto a reduced probabilistic description and closes the governing equation without requiring the original system to be Markovian. The theoretical framework has been progressively extended to a broad class of complex stochastic dynamical systems, including nonlinear and hysteretic systems, fractional-order and essentially non-Markov systems, systems under nonstationary, non-Gaussian, and non-white excitations, as well as systems with multiplicative and Poisson-type excitations. For path-discontinuous responses, a corresponding reduced partial integro-differential formulation has also been established, while the connection between DR-PDEE and the dimension-reduced Chapman-Kolmogorov equation provides an alternative integral representation of the same probabilistic evolution. The computational framework further enables applications to stochastic response analysis, dynamic reliability assessment, first-passage problems, and reliability-based design optimization. Representative engineering applications, including seismic reliability assessment of high-rise reinforced concrete shear-wall structures and stochastic response and reliability analysis of floating offshore wind turbines, will be presented. The theoretical developments and numerical examples demonstrate the potential of DR-PDEE as a unified computational framework for probabilistic analysis of complex high-dimensional stochastic dynamical systems and provide a physics-based foundation for further integration with data-driven and artificial-intelligence approaches.

Bio:

Dr. Meng-Ze Lyu (born in 1994) is a Research Fellow and DFG funded Principal Investigator at Institute for Risk & Reliability, Leibniz University Hannover. He received his B.Sc. (2015), M.Eng. (2017), and Ph.D. (2022) degrees from Tongji University. His research focuses on stochastic dynamics, reliability analysis and design optimization of complex engineering systems, including the development of dimension-reduced probability density evolution equations (DR-PDEE), time-variant extreme value distributions of Markov processes, decoupled multi-probability density evolution method (M-PDEM), and their applications in seismic, wind, and geotechnical safety and fragility assessment. Dr. Lyu has authored over 60 publications, including 50 peer-reviewed English journal papers, with 1000+ citations and an H-index of 19. He has delivered 2 keynotes and 9 invited talks, and organized 15 mini-symposia at international conferences. He serves as Secretary of TC R3 of IASSAR and National Chapter of ERSA in China, and an ECEB Member of *ASCE-ASME J Risk U A & B*. He also acts as a reviewer for more than 40 SCI journals and independently leads research projects funded by DFG and NSFC.