

9th COMPUTATIONAL STOCHASTIC MECHANICS CONFERENCE (CSM9)

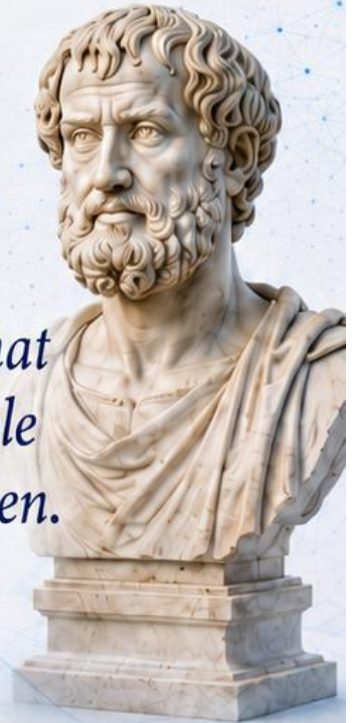
CORFU, GREECE
JUNE 21–25, 2026

“

*It is probable that
many improbable
things will happen.*

”

Ἀριστοτέλης
(Aristotle, Poetics,
quoting Agathon)



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INTERNATIONAL ASSOCIATION FOR
STRUCTURAL SAFETY AND RELIABILITY

9th Computational Stochastic Mechanics Conference (CSM9)

Corfu, Greece, June 21-25, 2026

under the aegis of

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Scientific Program

The 9th International Conference on Computational Stochastic Mechanics (CSM9) featured **88 presentations** representing contributions from researchers across **17 countries**, highlighting the broad international scope and interdisciplinary nature of the conference. The technical program reflected rich thematic diversity and the accepted contributions were organized into **9 thematic sessions**, designed to promote scientific exchange across foundational methodologies, computational developments, and engineering applications:

- Random Processes and Stochastic Operators
- Stochastic Dynamics
- Random Media and Material Properties
- Structural Reliability and Risk Analysis
- Surrogate Modeling and Machine Learning
- System Identification and Structural Health Monitoring
- Optimal Design and Decision-Making Under Uncertainty
- Earthquake Engineering: Methodologies and Applications
- Ocean, Offshore and Marine Systems



Photo of the CSM9 conference participants

Dynamic analysis of non-proportionally damped stochastic MDOF systems

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ABSTRACT

Dynamic analysis of linear multiple degrees of freedom (MDOF) systems with stochastic parameters has become increasingly relevant to lightweight composite designs in aerospace structures and ultra-large wind turbine blades, where material and geometric uncertainties significantly influence structural behavior. Although considerable research addresses undamped or proportionally damped stochastic systems [1,2], these represent idealized cases derived for mathematical convenience that often fail to capture physical damping behavior in complex structures. The assumption of proportional damping, though computationally attractive, is rarely satisfied in real engineering systems with heterogeneous materials, structural joints, or supplementary damping devices. Non-proportional damping introduces complex-valued eigenvalues and eigenvectors, creating three fundamental challenges: the ambiguity in applying probabilistic operations to complex quantities (whether to use real/imaginary parts or modulus/phase representations), an eight-fold increase in computational cost due to extended state-space formulation compared to configuration-space analysis, and significant complications in obtaining response statistics from complex eigensolutions. These difficulties have severely limited the practical application of stochastic analysis to realistic damped systems, creating a gap between theoretical developments and engineering practice.

This paper addresses these challenges by analytically proving, through the Rayleigh quotient, that parametric uncertainties affect eigenvalues and eigenvectors at fundamentally different orders of sensitivity. First-order perturbations in random mass, stiffness, and damping matrices produce first-order changes in eigenvalues but only second-order changes in eigenvectors. Exploiting this critical insight, we develop a hierarchical computational approach combining an extended perturbation framework that iteratively enriches complex eigenvalues with computationally efficient simplified analytical expansions for eigenvectors. The method assumes a diagonally dominant modal damping matrix, a condition satisfied by many practical engineering systems, and implements an efficient Monte Carlo simulation framework [3]. Two comprehensive example problems validate the proposed approach by comparing response statistics against benchmark full-scale exact Monte Carlo simulations, revealing substantial computational efficiency gains while maintaining excellent accuracy in capturing mean, variance, and probability distributions of dynamic responses. The method provides a practical and theoretically rigorous pathway for incorporating realistic non-proportional damping models in stochastic dynamic analysis of modern lightweight structures.

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Pendulum-based wave energy converter excited by stochastic sea states

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ABSTRACT

Pendulum-based wave energy converters (WECs) constitute a well-established and continuously evolving class of devices that exploit the relative motion between a floating hull and an internal oscillatory system to extract energy from ocean waves. Among these concepts, systems relying on rotational or parametrically excited pendulum dynamics have attracted particular interest due to their ability to achieve large-amplitude responses and sustained rotational motion under realistic, irregular (stochastic) sea states [1]. Extensive theoretical and numerical investigations have demonstrated that stochastic parametric excitation induced by wave-driven hull motions can trigger robust energy-harvesting regimes, especially when appropriate excitation filtering and nonlinear dynamic tuning are employed [2]. In the present concept, a pendulum is mechanically connected to the hull of a floating WEC and is excited primarily by the pitch motion of the structure, which has been shown to be particularly effective in activating parametric resonance mechanisms [3]. The pendulum rotor is mechanically coupled to a power take-off (PTO) system, enabling the conversion of mechanical rotation into electrical power. As the hull undergoes pitch motion due to incident waves, the pendulum experiences parametric excitation, leading to oscillatory or rotational responses depending on wave conditions and system parameters [4]. The nonlinear nature of the pendulum dynamics introduces rich dynamic behavior, including transition to continuous rotation, which is highly advantageous for broadband energy harvesting. In this paper, the wave-induced stochastic response is studied using state space models to account for the floater's radiation effects and for restoring Markov property in the excitation. The probabilistic dynamics are then studied in terms of the expected power output and the pendulum's rotational response.

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Hybrid Sampling for Efficient Failure Probability Estimation in Dynamical Systems with Rare Extremes

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ABSTRACT

The rarity of consequential dynamic events in engineering systems still challenges the assessment of safety and operational performance, as theoretically accurate methods (e.g. brute-force Monte Carlo simulations) become impractical due to the prohibitively long computational times required to generate statistically meaningful samples. To address this, the present work proposes an efficient sampling method based on conditioning, applicable to deterministic systems under additive random excitation. Specifically, a Slepian model formulated in Lindgren (1970) is employed to represent the input process given a peak of height u , assuming Gaussianity and ergodicity. The model comprises two independent component processes: the conditional mean and a residual process capturing the variability around it.

Leveraging independence, an initial approximation is obtained by considering only the deterministic part of the first component, aiming to calculate the probability that u exceeds the critical value at which system failure is marginally avoided, following Themelis and Spyrou (2007). Identifying the critical value is treated as a root-finding problem, tractable with a few targeted simulations via an essentially deterministic sampling procedure, while the probability distribution of u is known in closed form (Rice, 1945). Subsequently, improved approximations are achieved by strategically fixing u and calculating the probability of failures observed through small-scale random sampling experiments including the residual process. Although high-fidelity estimates would generally necessitate multiple such experiments, the initial approximation is expected to account for an increasing share of the total probability for rarer failures, as the failure-causing sample paths converge towards the deterministic part of the Slepian model (see also Boccotti, 2000), which allows for the computational effort to be alleviated. For further efficiency enhancement, a reduction of the stochastic dimensionality is explored.

The method is demonstrated on a softening Duffing-type oscillator, an archetypal model of ship roll dynamics, to evaluate the probability of capsizing. Its effectiveness is assessed and avenues for future development are outlined.

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Towards Quantification and Propagation of Uncertainty of a Data-Driven Force Model Applicable to Ship Maneuvering Prediction

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ABSTRACT

Maneuvering assessment is a critical aspect of both surface vessel design and operation. Given the fast-paced nature of modern design cycles, the ability to quickly predict maneuvering characteristics with reasonable accuracy is vital. High-fidelity models, while providing accurate results, are often too computationally expensive to meet the demands of tight design timelines [1]. Conversely, low-fidelity models offer faster solutions but typically sacrifice accuracy. A promising approach to address this challenge is the use of multi-fidelity modeling, which combines the strengths of various fidelity levels to optimize both speed and accuracy. However, an important consideration in this approach is the quantification of uncertainty in the model and its propagation across different fidelity levels.

This study employs a medium-fidelity method based on the Modular Modeling Group (MMG) [2, 3] framework, which is well-suited for ship design applications. The MMG method decomposes hydrodynamic forces, due to the hull, propellers, and rudders, into separate modules. Given that maneuvering forces are dominated by vortical flows, accurate modeling of viscous effects, like the numerical solution of the Navier-Stokes equations, is essential for reliable predictions. The resulting forces are then used in MMG, where hull forces are predicted by linear regression, and propeller and rudder forces are estimated through Gaussian Process Regression (GPR) [4].

The goal of this study is to quantify the uncertainties associated with each force component and propagate them through the MMG model to assess their impact on maneuvering characteristics, such as the tactical diameter. To do so, the MMG system is treated as a deterministic function of random variables (the forces), and a Monte Carlo simulation is used to propagate these uncertainties through to the final maneuvering characteristics.

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Extended PBEE to Account for Structure-Dependent Hazard and Structural Parameter Uncertainty

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ABSTRACT

Performance-Based Earthquake Engineering (PBEE) has been applied as a probabilistic framework in which hazard uncertainty, structural uncertainty, and limit-state exceedance probabilities are evaluated [1]. In standard PBEE practice, hazard characterization has been performed independently of structural properties, while structural uncertainty has been explicitly incorporated only during damage analysis and, less frequently, response analysis [2], [3]. However, for intensity measures that depend on structural parameters (e.g., the widely used pseudo-spectral acceleration defined at the natural period of the structure of interest [4]), the uncertainty in those parameters results in additional uncertainty in the hazard input used for structural analysis. This mechanism has not been explicitly represented in conventional PBEE formulations.

To incorporate this missing component, an extended PBEE framework is proposed, which is formally similar to the Performance-Based Wind Engineering [5] and Performance-Based Hurricane Engineering [6] frameworks. In this approach, the characterization of the hazard environment is conducted independently from the representation of structural parameters, and neither analysis relies on information from the other. These two components are then connected through an interaction analysis, in which structural realizations are paired with their corresponding hazard inputs based on the structural parameters that influence the intensity measure. Through this intermediate step, structural uncertainty is permitted to interact with the hazard input used for structural analysis while the independence of the original hazard description is preserved. A more complete propagation of uncertainty from the hazard field to structural demand is thus enabled.

To demonstrate the framework, non-linear single-degree-of-freedom systems based on a bilinear hysteretic constitutive model are evaluated under suites of ground motions. The role of response-modification factor (R-factor) is examined for multiple limit states corresponding to increasing levels of damage. Overall, the structure-dependent hazard formulation produces only small shifts in median spectral acceleration but consistently reduces dispersion, particularly for the Immediate Occupancy (IO) limit state [7], revealing trends that are not accessible under traditional PBEE.

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Optimal redundancy allocation in structural systems: a link between Bayesian utility theory and Info-Gaps

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ABSTRACT

Structural reliability theory addresses the calculation of failure probabilities which are conditional on an incomplete state of knowledge K . This incompleteness is exemplified by myriads of historical structural collapses due to unexpected loads, unknown or misunderstood failure modes and strength degradation, imperfect inspection and maintenance procedures, and human errors in general. As a consequence, Bayesian utility theory alone cannot address the problem of optimal redundancy allocation [1,2], which is a fundamental problem in reliability/robustness analysis. The latent failure probability concept [3] recognizes the open boundaries of structural systems and the effects of uncertainties not dealt with in reliability theory. This concept provides a useful link between Bayesian utility theory and Information-Gap theory [4], which maximizes robustness with respect to ignorance. The proposed formulation leads to Pareto fronts of compromise solutions of increasing structural redundancy, where trade-offs between maximizing expected utility and maximizing robustness w.r.t. epistemic uncertainty can be decided by the analyst.

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Reliability of power transmission steel poles under static and dynamic wind loading

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ABSTRACT

Steel transmission monopoles play an increasingly crucial role in power networks because they are becoming more common as the support structure of choice for carrying high-voltage power conductors from generation plants to local substations. Credible reliability models are essential for assessing risk to the electrical system, and steel transmission monopoles represent one of its key structural components. Their slender form makes them vulnerable to hurricane winds, especially when corrosion weakens the portion embedded in soil or close to the groundline. Despite the importance of these structures, existing reliability and fragility models in the literature have focused on distribution poles, which are much smaller structures and carry substantially lower conductor loads [1].

In this study, we present a systematic approach to calculate the reliability of these poles under strong winds and corrosion. Moreover, we compare the results that can be obtained with quasi-static and frequency-domain dynamic analyses. The static framework evaluates bending demand versus capacity under sustained wind loading on the pole and attached conductors, considering the reduction in the cross-section due to progressive corrosion and the potential of buckling of the cross-sectional walls. The dynamic framework considers corrosion and buckling as well, and it is based on the classical first-passage formulation to incorporate wind-induced vibrations of conductors, overhead ground wires, and the pole itself in the calculation of the bending failure [2-3]. Interestingly, the dynamic approach can account explicitly for the duration of high-intensity wind exposure, representing the most severe phase of the storm.

As an additional product of this study, we present parametric fragility models, which can be used for network-scale resilience assessment, catastrophe modeling, replacement prioritization, and the development of design standards for hurricane-prone regions.

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Stochastic Averaging of nonlinear soil-structure interaction systems through the Preisach formalism

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ABSTRACT

To date three main approaches are used for the analyses of nonlinear soil-structure-interactions (SSI) problems: i) linear analysis using soil properties consistent with the expected level of strains in the soil with the consequent use of an estimated reduced shear modulus and increased damping; ii) iterative linear analyses using soil properties (modulus and damping) adjusted to match assigned shear modulus reduction and damping curves; iii) nonlinear analysis in the time domain using a discrete model (e.g. finite elements or finite differences) with appropriate nonlinear constitutive equations for the soil. Simplified models in SSI study still remain attractive nowadays due to the limited computational effort and the physical interpretation of the quantities involved in the analyses. Despite the general consensus of the stochastic nature of the seismic action, however, research in the field of stochastic response of nonlinear SSI systems is quite limited. In this paper, the deterministic study proposed in [1] on the steady state response of nonlinear soil-structure interaction problems is extended to the stochastic case. In this regard, a version of the stochastic averaging [2] is applied to the nonlinear SSI system undergoing ground motion stochastic input. Preisach formalism is adopted to describe the hysteretic nature of the soil behaviour. The equivalent damping and stiffness terms are determined by a harmonic balance procedure [3],[4]. Then, a Markov approximation is introduced leading to a Fokker–Plank equation governing the evolution of the probability density function of the envelope. The stationary solution is finally used to estimate the power spectrum of the response of the nonlinear soil-structure interaction system. The reliability of the approximate solution is assessed by using numerical data from a relevant Monte Carlo simulation.

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State space Kriging model for uncertainty quantification of high-dimensional nonlinear stochastic dynamical systems

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ABSTRACT

In this contribution, we present a novel surrogate model, termed state space Kriging (S2K), for emulating high-dimensional nonlinear stochastic dynamical systems. S2K approximates stochastic dynamical systems in their state space form, whereby the high-dimensional stochastic excitation enters as a one-dimensional parameter. In this manner, the proposed surrogate model circumvents the “curse of dimensionality” that arises from the discretization of the stochastic excitation. For problems with partial observation of state variables, we combine S2K with time delay embedding to complement the spatial state variables with time-delayed state variables. We further employ model reduction to reduce computational complexity resulting from the high dimensionality of the state-space equation for systems with large degrees of freedom. Numerical examples show that the proposed S2K model yields stable and accurate predictions with only a few training time histories.

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Uncertainties and large deformations multiscale behavior for architected materials

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ABSTRACT

Architected materials, defined by smooth implicit geometries, can be efficiently manufactured using additive technologies; this is the case of triply periodic minimal surface (TPMS) lattices. Their periodic architecture allows for lightweight structures with high stiffness and energy absorption capabilities. While their mechanical properties under large deformations have been extensively studied, the influence of geometric scale on the mechanical behavior has received far less attention [1].

This work investigates the multiscale mechanical response of additively manufactured TPMS lattices subjected to large deformations. Several TPMS topologies are considered, and for each topology a series of samples is fabricated in which the number of unit cells is progressively increased. By varying the ratio between the overall sample size and the unit-cell dimension, it is possible to assess how the structural response evolves as the material goes from the scale of individual cells to that of an effective continuum.

Quasi-static compression tests are performed to characterize the nonlinear mechanical behavior and to identify the deformation and failure mechanisms that develop at different scales. The experimental results are complemented by numerical simulations, which are used primarily to support the interpretation of the observed responses and to correlate local deformation patterns with the overall mechanical performance. On the other hand, all materials, particularly printed materials or composite materials, exhibit varying degrees of inherent variability or randomness [2, 3]. The effects, at multiple scales, of uncertainties related to manufacturing tolerances or local defects are considered.

The study provides new insight into how geometric scale influences the large-deformation behavior of TPMS lattices and identifies the conditions under which scale-independent failure mechanism can be assumed. The outcomes contribute to improving the experimental understanding of multiscale effects in architected materials.

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Observations on Multi-Dimensional Reliability Sensitivity

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ABSTRACT

This note derives a simple upper bound reliability of a structural system in closed form for the case where the variables that define the system are Gaussian. Although other bounds are available [1, 2, 3], the thought process and implications for this approach provide interest. The mathematics is particularly applicable when there are a large number of failure modes with similar reliability levels. The system reliability is a function of the number of possible failure modes, and the hypersphere visualization is instructive, as is the hyper-ellipsoid reflecting correlations.

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Optimal allocation of redundancy and inspections with the latent failure probability

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ABSTRACT

The history of catastrophic structural collapses shows that they do not normally occur because a peak of a stochastic load process exceeds the strength of the structure. Yet, this is the basis of structural reliability theory. The latent failure probability concept is a way to consider the non-structural or non-technical factors which have produced structural collapses in the past. The concept is key for addressing structural redundancy, and for establishing a link between optimal redundancy and optimal frequency of inspections. In this paper we recall some fundamental results relating to optimal redundancy and optimal frequency of inspections and show how the latent failure probability concept can be employed to derive a methodology for fail-safe structural design. In the latter, partial safety factors are calibrated based on risk analysis, for the design of intact structural systems, and for their verification, for increasing levels of structural damage. The methodology targets particular classes of structural systems. Examples are shown for classical Daniel's systems and for cable-stayed bridges. The study provides important insights into how classical structural reliability theory can be extended to the fail-safe design of structural systems.

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Risk-Based Design of RC Flat Slabs against Fire-Induced Progressive Collapse: A Multi-Attribute Cost-Benefit Analysis

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ABSTRACT

The rational design of structures against low-probability, high-consequence events like fire is a critical challenge. Structural robustness is essential to prevent localized damage from escalating into disproportionate progressive collapse. However, traditional reinforcement techniques like the Alternative Load Path Method are often costly, unsustainable, and hazard-agnostic; a hazard-specific strategy, such as dedicated fire protection, can be more efficient [1]. This work proposes a novel Risk-Based Optimization framework to bridge this gap, holistically integrating these specific protection measures as design variables. The objective is to minimize the total expected cost by integrating a comprehensive, multi-attribute loss function (including economic, environmental, and fatality costs) [2] with the optimization of a composite design vector. This vector includes both structural design parameters and the Fire Safety Level (FSL) as an explicit, discrete design variable, allowing the optimization to directly balance the capital cost of fire protection (e.g., sprinklers, smoke control) against the life-cycle risk of fatalities. The methodology is demonstrated on a reinforced concrete flat slab building, a system used in high-risk applications (e.g., commercial, office, and parking garage) and highly vulnerable to pancake-type collapse [3]. A 3D structural analysis, essential for capturing the complex bi-directional load redistribution, poses an immense computational challenge due to a combinatorial explosion of system damage states. This was overcome using an efficient PC-Kriging surrogate modeling strategy. The framework successfully identifies the optimal structural design and FSL for threat-independent and threat-dependent (fire) scenarios. Results demonstrate the high sensitivity of the optimal design, especially on the FSL variable, to the annual hazard probability and quantify the cost-benefit trade-off of investing in different fire safety levels. This work provides a novel, rational methodology capable of transforming engineering practices by delivering robust, cost-efficient, and sustainable solutions. By holistically integrating structural and non-structural safety measures, it advances the design of safer and more resilient buildings.

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Response of a Tuned Liquid Column Device with dielectric elastomer membranes for wave energy harvesting on a tension leg platform

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ABSTRACT

This paper investigates the stochastic response of a wave energy harvesting system that utilizes the motion of a tension leg platform (TLP) subjected to wave-induced loads. The proposed harvester integrates a novel Tuned Liquid Column Device (TLCD) with dielectric elastomer (DE) membranes to achieve mechanical-to-electrical energy conversion [1]. The device harnesses the vertical oscillation of a liquid column in a U-shaped container excited by the surge motion of the TLP, and the resulting electromechanical deformation of the DE membranes to generate electrical power. The dynamics of the system is defined considering the coupled liquid motion in the U-shaped container with the pressure-induced deformation of the DE membranes. Further, a simple single-degree-of-freedom system is used to model the tension leg platform, and a Morison equation-based formulation is employed to take into account the wave-induced forces on the offshore structure [2, 3]. The statistics of the system are examined by an analytical procedure based on stochastic linearization methods. In this manner, repeated numerical integration of the highly nonlinear coupled differential equations of motion is circumvented, and a computationally efficient semi-analytical solution is obtained. Comparisons with pertinent Monte Carlo simulations data are used to assess reliability of the proposed approach. Finally, the energy harvesting performance of the device is investigated by coupling the device with an electrical circuit with an appropriate control strategy, and examining the influence of key system parameters on the overall power output.

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Complex-valued modeling and eigenanalysis of stochastic dynamical systems

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ABSTRACT

Complex-signal (analytic) representations of stochastic processes [1] have a long history in signal theory, introduced by Gabor [2] and extended by Ville [3] to formalize instantaneous phase and frequency. An analytic signal provides a complex-valued representation of a real process, with the imaginary component obtained via the Hilbert transform, producing a one-sided (positive-frequency) spectrum. This formulation separates amplitude and phase modulation, allowing narrow-band stochastic processes to be described in terms of slowly varying amplitudes and phases rather than rapidly oscillating real-valued signals [4]. Consequently, the analytic-signal framework is particularly advantageous for uncertainty quantification in nonlinear oscillators. In this work, the Hilbert transform is applied to construct analytic representations of nonlinear oscillator responses, naturally yielding reduced-order stochastic differential equations (SDEs) for the system amplitude. These SDEs are associated with, for example, the Fokker–Planck and backward Kolmogorov equations, which describe the evolution of probability densities and enable reliability assessment of complex dynamical systems [5]. These equations allow an eigenfunction-based spectral analysis, providing clear physical and spectral insight into the stochastic dynamics of nonlinear oscillators, facilitates semi-analytical estimation of response statistics, and ensures physically consistent probabilities while preserving boundary conditions. Accuracy and effectiveness are demonstrated through comparisons with Monte Carlo simulations. The proposed methodology offers a rigorous yet computationally efficient framework for modeling, analyzing, and predicting the stochastic behavior of nonlinear dynamical systems under uncertainty.

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Efficient eigenfunction expansion of the Fokker-Planck operator for nonlinear oscillators subject to white noise excitation

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ABSTRACT

Determining the time evolution of the probability density function (PDF) of nonlinear oscillators remains a central challenge in stochastic engineering dynamics. Addressing this problem requires methods that are both mathematically rigorous and computationally efficient. In this work, we present a novel spectral framework for estimating the time-dependent PDF of a nonlinear oscillator subject to white noise. Starting from the stochastic averaging [1] treatment of the single-degree-of-freedom (SDOF) hardening Duffing oscillator, we derive the corresponding stochastic differential equation (SDE) for the response amplitude and its Fokker–Planck equation (FPE) with multiplicative noise. We then transform the FPE into a self-adjoint form and apply a similarity transformation to obtain a Hermitian operator analogous to the Schrödinger equation [2]. Solving the associated eigenvalue problem yields a complete orthonormal basis and an ordered spectrum of eigenvalues and associated eigenfunctions, allowing a compact spectral representation of the time-dependent PDF. The formulation guarantees numerical stability, conservation of the probability mass, and accurate characterization of the time evolution of the system response. The Hermitian operator is constructed by domain discretization using finite differences with Robin boundary conditions, and its eigenmodes are efficiently computed using a symmetric solver [3]. Finally, comparisons with Monte Carlo simulations demonstrate excellent agreement in the transient phase and steady state, while achieving significant computational speedups. The proposed framework provides a robust and efficient methodology for solving Fokker–Planck equations with multiplicative noise for nonlinear oscillators under white noise excitation, thereby establishing a direct connection between stochastic dynamics and Hermitian operator theory.

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A Physics-Informed Machine Learning Ship Broaching Model

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ABSTRACT

The motion response of a surface vessel in following or stern quartering seas may include a sudden uncontrollable turn, known as broaching. The physical reason for broaching is an instability in yaw caused by a combination of the hull forces, thus the rudder action may not have an effect at all. Broaching-to is not a new problem; it has been known since the Age of Sail [1], so experienced operators are aware of it.

A commonly known precursor to the broaching phenomenon is surf-riding. During a surf-ride, a ship accelerates or decelerates to match the wave celerity such that the ship travels with the incident wave profile. In a realistic (i.e. random) sea, these periods of matching the speed of the wave profiles appear and disappear, making analysis complex. Given the common frequencies inherent to the sea and typical ship speeds, surf-rides are typically linked with periods of “high-run” [2]. It follows that the instantaneous speed of the ship as well as the speed of the wave profile at the ship’s center of gravity are important parameters that inform surf-riding and potentially broaching.

The proposed method introduces a machine learning framework that links time series realizations of ship speed and wave celerity to the instantaneous yaw of the ship. A Long-Short Term Memory (LSTM) [3] neural network is trained with various combinations of tri-chromatic wave time series and surge velocity time series simulated with the reduced-order SimpleCode [4] as input and with yaw time series generated by SimpleCode as targets. The results of the trained neural network are evaluated against SimpleCode in ability to estimate rare broaching / large yaw events.

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An adaptive similarity calibration method for parameter inversion and model updating

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ABSTRACT

Model calibration plays a pivotal role in refining computer models to faithfully represent the underlying physical processes^[1]. However, due to inherent theoretical imperfections and stochastic influences, biases between the model and reality are often inevitable^[2], especially in small samples scenarios. While it may seem tempting to blindly minimize discrepancies, such an approach risks pushing the calibrated parameters further away from the true physical values^[3]. To address this challenge, this paper introduces a novel correlation-based calibration method, which prioritizes achieving "maximum similarity" between the computer model and the physical process rather than merely pursuing "closest proximity". A key contribution of this method lies in its ability to distinguish between parameter uncertainty and simulation bias. The proposed method, which incorporates distance correlation-based parameter calibration, effectively retains the intrinsic discrepancies between the two domains, while simultaneously decoupling parameter uncertainty from model uncertainty. Where the Brownian distance correlation preserves the inherent discrepancy between the computer model and the physical process, and achieves the decoupling of parameter uncertainty and model uncertainty. Meanwhile, we utilize the Nested Stochastic Kriging model with response uncertainty parameters decoupled from other surrogate model parameters, which can significantly improve the accuracy of uncertainty quantification and modeling efficiency. Furthermore, we develop an innovative sequential sample infusion strategy tailored for small-sample contexts, which independently updates design variables and calibration parameters to enhance estimation accuracy. This method achieves high-precision calibration with low computational cost and provides comprehensive uncertainty quantification. The proposed method is verified by several numerical examples and one engineering example. The results show that our proposed method can obtain an accurate inversion of the model parameters, which also improves the prediction accuracy of the model.

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Uncertainty-aware damage identification in short-span bridges via physics-informed Gaussian copula variational autoencoder

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ABSTRACT

Vibration-based damage identification in civil infrastructure is a challenging, ill-posed inverse problem due to multiple sources of uncertainty, including measurement noise, sparse sensor arrays, and limited data sensitivity to structural changes. While deep learning is a powerful tool for system identification, standard deterministic approaches fail to provide reliable uncertainty quantification and often yield physically inconsistent results.

This work proposes a novel methodology for uncertainty-aware damage identification: a physics-informed Gaussian copula variational autoencoder (PI-GCVAE). Our methodology introduces two main contributions to the field of Structural Health Monitoring (SHM). First, we eliminate the need for a data-driven surrogate decoder by embedding a differentiable numerical eigenvalue solver directly into the VAE architecture [1]. This ensures that every sample drawn from the latent space strictly satisfies the underlying governing equations of structural dynamics, reducing the trainable parameter space and improving generalization. Second, we replace the conventional VAE assumption of independent latent variables with a Gaussian copula [2]. The marginals are originally modeled as single Gaussians, but can accommodate more complex distributions, such as mixtures, to capture potential multimodality. This allows the model to capture complex, physics-dependent spatial cross-correlations between adjacent structural elements, which are critical for identifying localized damage patterns.

We validate our approach using a synthetic dataset of a simply supported bridge subjected to various damage scenarios and corrupted with stochastic Gaussian noise (2.5% on frequencies, 5% on mode shapes). Results demonstrate that the PI-GCVAE accurately recovers the true posterior distribution, achieving a 77.2% coverage probability and providing robust uncertainty bounds. By disentangling

marginal uncertainty from spatial dependence, the proposed framework provides a physically consistent, scalable tool for early-stage damage diagnosis in operating bridges.

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Sub-Nyquist frequency-agnostic power spectrum estimation using optimal multi-coset sampling in the mean-square sense

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ABSTRACT

Over the past decade, various sub-Nyquist sampling schemes emerged for reducing the number of structural response acceleration measurements (i.e., data points in time) for structural system identification, thus relaxing power supply and data storage demands in wireless sensors used for structural health monitoring [1]. Whilst random sub-Nyquist sampling schemes, grouped under the umbrella of compressive sensing (CS), focus on the deterministic recovery of the underlying Nyquist-sampled signals, deterministic sub-Nyquist sampling schemes support efficient power spectrum density (PSD) estimation, assuming that the sampled signals are realizations of ergodic stochastic processes [2,3]. In this context, this study provides novel theoretical proofs for constructing optimal deterministic sub-Nyquist multi-coset sampling patterns for PSD estimation by minimizing a weighted mean-square error, assuming an ergodic frequency-agnostic (i.e. white noise) input process to the sampler. Different multi-coset sampling patterns with average sampling rate up to 90% lower than the Nyquist rate are derived by solving numerically the derived optimal sampling problem using brute-force exhaustive search. Then, the accuracy of the PSD estimation achieved by the derived sampling patterns is gauged by considering white noise-corrupted simulated signals compatible with a bimodal PSD corresponding to the acceleration response of a lightly damped steel simply supported beam excited by band-limited white noise. Numerical results show less than 10% root-mean-square error of PSD estimates in the vicinity of the local maximum PSD values (i.e., the natural frequencies of the considered beam) for sufficiently long observation windows, independently of the signal-to-noise ratio. It is concluded that the herein adopted frequency-agnostic assumption for deriving sampling patterns bypasses the limitation of standard CS sampling, whose ability for signal reconstruction (and thus PSD estimation) relies on some level of signal sparsity in some domain, commonly the frequency domain.

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Conformalized Polynomial Chaos Regression via Jackknife and Jackknife+

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ABSTRACT

We integrate conformal prediction methods based on the jackknife approach and its jackknife+ extension [1] into data-driven polynomial chaos regression models [2]. The resulting conformalized polynomial chaos expansion models [3] are equipped with predictive uncertainty intervals, thus being uncertainty-aware regression models instead of simple point predictors. The predictive uncertainty intervals are estimated very efficiently by leveraging the regression model's linear form to establish analytical, closed-form expressions for computing the leave-one-out residuals and model predictions required by the jackknife-based conformal prediction methods. This eliminates the need for repeated model re-sampling in standard jackknife-based cross-validation techniques. The method is first validated on standard benchmark models and then applied to a stochastic elasto-viscoplastic problem governed by the shear transformation zone (STZ) theory of amorphous plasticity. The response considered includes the spatial mean of the equivalent plastic strain over the domain, representative of plastic activity and localization patterns. The numerical results show that the uncertainty-aware polynomial chaos regression models reach the required target coverage levels. Additionally, different configurations of conformalized polynomial chaos regression models are examined and compared, depending on polynomial degree, training data volume, jackknife approach, and type of non-conformity score.

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A surrogate modelling approach for stochastic parameter identification

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ABSTRACT

Reliable predictions of structural performance require accurate computational models of the underlying physical processes. The calibration and validation of these models are critical steps in the design and analysis of engineering structures. Numerous methodologies have been developed to accomplish these steps, including the assessment of inherent uncertainties in the model and its parameters. The Bayesian approach is one of the most promising due to its ability to quantitatively account for uncertainties in both the model and noisy data, as well as its ability to address ill-posed problems, which are frequently encountered in practice. However, applying the Bayesian approach to real engineering structures, particularly those involving complex numerical models, often incurs significant computational costs. Recent advancements in various engineering and scientific disciplines highlight a growing interest in using machine learning methods to accelerate such analyses. The present study contributes to this field by assessing the potential of machine learning for stochastic parameter identification of dynamical systems. Specifically, this study employs an efficient simulation-based parameter identification method known as Subset Simulation. Subset Simulation was originally developed for reliability analysis [1] but has recently been adapted for stochastic parameter identification due to its ability to efficiently sample high-dimensional parameter spaces [2]. To reduce computational time associated with repeated evaluations of the computational model, a surrogate model will be incorporated and updated iteratively during the identification process. Unlike the widely used approach of establishing a global surrogate model, this work proposes a local, adaptive surrogate model [4]. This model uses information from the Subset Simulation approach, making it suitable for scenarios involving peaked or multi-modal posterior distributions, which are common in practice. Numerical examples will be presented to illustrate the fundamental principles of the proposed method and demonstrate its potential for application to real engineering structures.

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Materials Structure-Property Mapping with Heteroscedastic Gaussian Process Regression and Active Learning

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ABSTRACT

Understanding and exploiting structure-property relationships in materials is essential for designing materials with superior performance characteristics. Engineering materials' mechanical properties are strongly influenced by microstructural features including morphology, interface properties, and spatial distributions. However, mapping these relationships presents significant challenges; structure-property relationships are often highly complex and non-linear, making them difficult to predict and optimize. Additionally, microstructural variability introduces input-dependent noise, as statistically equivalent microstructures can exhibit varying responses that standard modeling approaches do not capture. Therefore, an efficient sampling strategy that accounts for both epistemic and aleatoric uncertainty is needed to navigate the design space while simultaneously improving our understanding of the underlying material behavior.

We present a Heteroscedastic Gaussian Process Regression (HGPR) framework integrated with batch active learning (AL) to efficiently map microstructure-property relationships in materials [1,2]. Unlike traditional GPR approaches, our heteroscedastic model explicitly accounts for input-dependent noise variations across the design space, capturing the aleatoric uncertainty arising from microstructural variations. Our batch active learning algorithm leverages both epistemic and aleatoric uncertainty estimates to strategically select multiple informative microstructural configurations simultaneously for subsequent physics-based simulations. This batch selection approach enables parallel simulation runs, ensures sample diversity across the possible configurations, and improves performance of the surrogate model.

This framework systematically quantifies how microstructural features such as void size, shape, and spatial distributions influence material properties, revealing fundamental structure-property relationships that guide materials design. Compared to grid search or random sampling, our informed batch sampling strategy achieves maximum information gain with a minimum number of physics-based simulations, resulting in improved GPR model performance and enabling efficient design space exploration. This approach identifies microstructures with tailored performance while providing mechanistic insights into deformation and failure mechanisms. By effectively integrating heteroscedastic uncertainty quantification with physics-based simulations, we can navigate high-dimensional design spaces for accelerated materials discovery.

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Estimates of extremes of random processes

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ABSTRACT

A method is developed for estimating the distributions of extremes of nonstationary, non-Gaussian real-valued stochastic processes over bounded time intervals, e.g., the distribution of the extreme $\sup_{0 \leq t \leq \tau} |X(t)|$ of a real-valued process X in a time interval $[0, \tau]$. These distributions are rarely available analytically so that they have to be constructed numerically. Numerical methods cannot be applied directly since they can handle only finite sets of random variables and continuous time processes are uncountable families of random variables indexed by time.

To overcome this limitation, we construct finite dimensional (FD) models X_d of X , i.e., deterministic functions of time and d random variables $Z = (Z_1, \dots, Z_d)$, and establish conditions under which the distribution of $\sup_{0 \leq t \leq \tau} |X_d(t)|$ converges to that of $\sup_{0 \leq t \leq \tau} |X(t)|$ as $d \rightarrow \infty$. Then, extremes of X can be approximated by extremes of X_d for a sufficiently large stochastic dimensions d .

The implementation of the method requires the distribution of $\sup_{0 \leq t \leq \tau} |X_d(t)|$, which is a surrogate for the distribution of $\sup_{0 \leq t \leq \tau} |X(t)|$ under some conditions provided that d is sufficiently large. This distribution can be estimated from paths of X_d which can be calculated from samples of the random vector Z . The generation of samples of Z requires the joint distribution of this vector which is unknown. We construct translated polynomial chaos (PCT) models Z^{PCT} for Z for increasing truncation levels and establish conditions under which the FD models X_d with random coefficients Z^{PCT} in place of Z , denoted by X_d^{PCT} , are such that the distribution of $\sup_{0 \leq t \leq \tau} |X_d^{\text{PCT}}(t)|$ converges to that of $\sup_{0 \leq t \leq \tau} |X(t)|$ as the stochastic dimension and the truncation level increase indefinitely. Then, the distribution of $\sup_{0 \leq t \leq \tau} |X_d^{\text{PCT}}(t)|$ can be used as a surrogate for that of $\sup_{0 \leq t \leq \tau} |X(t)|$ provided that the stochastic dimension and the truncation level are sufficiently large. Numerical illustrations are presented to demonstrate the implementation and the accuracy of the method.

Performance of Classical and Non-traditional Tuned Mass Dampers under narrowband and wideband excitation

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ABSTRACT

We investigate the optimal configuration of both classical and unconventional tuned mass dampers (TMDs) subjected to narrowband random input, with the goal of reducing the primary structure's kinetic energy. By means of an exact steady-state moment solution for the standard two-degree-of-freedom TMD under narrowband excitation, we formulate and assess the primary mass mean-square velocity, as the performance index. Due to complexity of the analytical solution, we study this solution numerically, revealing the effect of the system's parameters like mass and frequency ratio, noise intensity, on the kinetic energy of the primary mass. Three distinct optimisation routines—reinforcement learning (RL) [1], particle swarm optimisation (PSO) [2], and Kriging-based surrogate optimisation (SO+KRG) [3]—are first verified against the exact analytical solution and then employed to refine non-traditional TMD arrangements. To generate them, an incidence-matrix algorithm is employed to automatically create and prune non-traditional spring-damper layouts, allowing various connection patterns between the primary and secondary masses. Since the analytical approach deemed to be unfeasible in these cases, the validated optimization algorithms are implemented. Among these, RL exhibits superior efficiency and records the lowest deviation from the analytical D22 optimum in both deterministic and stochastic trials. Screening 29 candidate configurations composed of combinations of two springs and two dashpots yield several topologies that surpass the conventional TMD under both deterministic and random excitation [4]. The findings deliver verified design tools and practical tuning recommendations for real-world narrowband or mixed excitation scenarios, while pointing to advantageous non-standard configurations.

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An novel Stochastic isogeometric analysis method of complex thin-walled structures based on nested geometric model

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ABSTRACT

Uncertainties in material properties and geometric dimensions are inherent in the fabrication of thin-walled structures, which significantly influence the load-bearing capacity and reliability. To ensure structural safety, these factors need to be incorporated into the structural stochastic analysis. Specifically, due to the small amplitude of geometric dimensions, precise geometric modeling and analysis are necessary^[1]. Leveraging the advantage of isogeometric analysis (IGA) in eliminating geometric discretization errors in modeling^[2], this study proposes a perturbation stochastic isogeometric analysis (PSIGA) method based on a nested geometric model to predict the stochastic responses of thin-walled structures under material properties and geometric dimensions. In modeling process, the nested geometric model is adopted to ensure model accuracy and watertightness, securing numerical analysis precision. In uncertainty representation process, a random field modeling method is developed. Uncertainties of structures are represented as random fields via the Karhunen–Loève (K-L) expansion, which are then assembled into the stochastic static and buckling equations and incorporated into the stochastic isogeometric analysis framework^[3]. In analysis process, a first-order perturbation method is employed to solve these stochastic equations and derive the statistical characteristics of stiffened panel responses. Moreover, a sensitivity analysis is conducted to quantify the relative influences of individual uncertainties on the structural behavior. The calculation accuracy of the proposed PSIGA method under multiple uncertainties are demonstrated through several examples, with the Monte Carlo simulation (MCS) results serving as the benchmark. The outcomes demonstrate that the proposed PSIGA method efficiently and accurately captures the stochastic behavior of stiffened panels, providing a robust tool for engineering structural safety evaluations.

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Quantum amplitude estimation - based reliability analysis for structures

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ABSTRACT

Reliability analysis of complex engineering structures is demanding for computational resources. In fact, efficient computational methods without losing of accuracy are widely studied and great progresses have been made for classical computing systems. To this date, the development of quantum computing has provided new perspective for improving computational efficiency of reliability analysis. In theory, the quantum system is ideal for representing stochastic structural systems, since the probability amplitude of superposition of particle in quantum mechanics is a powerful tool for stochastic modelling. It is studied that the Grover's algorithm in quantum computing system has higher efficiency for estimating the probability amplitude than Monte Carlo method. The computation cost of the Grover's algorithm is at the magnitude of square root of the cost of Monte Carlo method. The estimation of probability amplitude using Grover's algorithm is named as quantum amplitude estimation. In this study, the formulation of structural reliability problem in quantum computing system along with the solution of the problem using quantum amplitude estimation is provided. The efficiency of the proposed method is verified by numerical examples with comparison to Monte Carlo method.

Exponential polynomial closure method for dynamical systems under Poisson impulse process excitation

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ABSTRACT

The dynamical system subjected to a Poisson impulse process excitation is considered. For such a problem the equation governing the probability density of the response state vector is assumed by some authors as the generalized Fokker-Planck-Kolmogorov partial differential equation including the partial derivatives up to and including the fourth order. Here the probability density of the response state vector is assumed to be governed by an exact integro-differential (called Kolmogorov-Feller), e.g. [1]. Unfortunately no exact solution to this equation is known. An approximate exponential polynomial closure method is developed for this problem. This method was applied e.g. for non-linear systems under Gaussian white noise excitations [2]. The approximate form of the response probability density function is assumed as the exponential function of the polynomial of state variables with time-varying coefficients. The approximate probability density function is inserted into the governing integro-differential which results in the residual function. It is required that the residual be orthogonal with suitably chosen trial function. The result is the set of ordinary differential equations governing the coefficients of the underlying polynomial. As an example a linear oscillator is considered. The approximate analytical results are verified against numerical Monte Carlo simulations.

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Physics-based ballasted railway track aging assessment using Gaussian process surrogate models

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ABSTRACT

Ballasted railway tracks have been designed, built, and maintained in continuously evolving operational conditions for more than a century in many countries worldwide. Nowadays, they are still chosen as the relevant option for developing new transportation capacities, nationally and internationally, especially with the operation of high-speed trains.

Physics-based computational simulations of ballasted railway tracks are useful for optimizing maintenance strategies using forward estimations of its aging. They are also relevant for assessing the actual physical state of the tracks from monitoring data. These applications are key for infrastructure managers; they can however often not be completely achieved using physics-based computational simulations alone due to the high computational effort required. Critical aging consequences such as rail failures and ballast settlements are localized while dependent on more global effects like changes in the track bed stiffness over the railway. Besides, dynamic behaviors such as dancing sleepers in low-ballast zones may occur. Finally, 3D mechanisms can be activated in the presence of differential settlements or in curves. Consequently, the numerical simulation of ballasted railway tracks must be performed over a large 3D physical domain and in dynamics, thus requiring large computational resources. This is even more demanding for high-speed lines where the representation of dozens of meters of track is needed to properly grasp their dynamic response.

The objective of this contribution is to present and discuss the capabilities of Gaussian process surrogate models for achieving the two following tasks: calibrating physical finite elements models of ballasted railway tracks and exploring aging scenarios in various operating conditions. Calibration is performed based on displacements and accelerations histories recorded on a high-speed line in France and on a global sensitivity analysis using Gaussian process surrogate models [1]. Aging scenarios are explored introducing various ballast settlements patterns as well as changes in the track bed stiffness over the railway; Gaussian process surrogate models of engineering quantities related to fatigue are used to assess the impact of the aging scenarios on key track components.

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Contaminant source characterization in water distribution networks: A reliability-based approach

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ABSTRACT

Water distribution networks play a crucial role in ensuring public health and supporting diverse economic activities. However, these systems are constantly exposed to uncontrolled external events, such as the intrusion of contaminants. Under this condition, a critical task relates to contaminant source characterization, where the goal is to identify the injection point and time evolution of the unwanted substance based on measurement data [1]. To address this task, a Bayesian model updating approach for contaminant source identification is proposed in this work. A model class selection problem is formulated to identify the contaminant source location. In this setting, each feasible injection point defines a model class whose parameters determine the contaminant injection over time. The associated posterior probabilities quantify the relative plausibility of the possible locations based on prior engineering knowledge and available data, which in turn allows identifying the most plausible injection scenario. Specifically, it is assumed that contaminant concentration measurements over time are available at certain network points. The posterior probabilities are evaluated in the framework of Bayesian model updating with structural reliability methods (BUS), where an auxiliary failure event allows estimating the required quantities. An approach that integrates subset simulation with a Hamiltonian Monte Carlo technique is implemented to solve the associated reliability problem [2], while the required contaminant propagation analyses are performed with the well-known software EPANET. An application example is studied to illustrate the capabilities of the proposed approach.

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Efficient Reliability Updating of Dynamical Systems via Variational Inference and Importance Sampling

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ABSTRACT

This study investigates reliability updating for dynamical systems under uncertainty by proposing a variational inference (VI)-based hierarchical Bayesian approach [1–3]. Within the proposed framework, uncertainties in model parameters are systematically incorporated through a hierarchical Bayesian formulation, enabling consistent posterior updating and reliability assessment. The method proceeds in two stages. First, VI is employed to approximate the posterior distribution of model parameters, leading to an analytic expression of the parameter posterior and enabling efficient Bayesian updating without resorting to expensive sampling-based inference. Second, a variational distribution is constructed to approximate the optimal importance sampling density for failure probability estimation, and stochastic gradient descent is used to optimize the corresponding variational parameters. Notably, the samples generated during the optimization of the variational importance density are reused to estimate the failure probability, thereby avoiding repeated sampling and repeated dynamical analyses and substantially improving computational efficiency. The proposed approach establishes a unified framework that couples posterior parameter inference with reliability evaluation for dynamical systems. One numerical simulation and one experimental dynamical example are used to validate the proposed method, demonstrating its effectiveness and robustness in terms of both accuracy and computational efficiency.

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Response power spectral density determination of nonlinear oscillators via the Wiener path integral technique

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The determination of stationary response power spectral density (PSD) functions of nonlinear oscillators subjected to stochastic excitation remains a significant challenge in stochastic structural dynamics. In this regard, various approximate methodologies have been developed over the years, including Volterra–Wiener functional expansions, statistical quadratization/cubicization approaches, as well as stochastic averaging techniques combined with concepts such as conditional response power spectral density determination (e.g., [1-2]). Although these methodologies have exhibited varying degrees of success, they commonly involve either significant computational cost, particularly as higher-order nonlinear contributions are retained, or additional approximations that may reduce the exhibited degree of accuracy.

To address these challenges, a Wiener path integral (WPI)-based methodology [3] is developed herein for determining efficiently and accurately stationary response PSD functions of nonlinear oscillators under stochastic excitation. Specifically, relying on the Wiener–Khinchine theorem, the response PSD is represented through the Fourier transform of the stationary autocorrelation function. Further, the autocorrelation function is expressed directly in terms of the nonlinear oscillator response transition probability density function (PDF). The requisite transition PDF is determined within the WPI framework by solving only a relatively small number of deterministic boundary value problems corresponding to most probable response trajectories, while an extrapolation treatment leveraging information embedded in the time histories of these trajectories enables the evaluation of additional transition PDF points at essentially zero additional computational cost [4]. In this regard, the computational burden becomes associated only with the numerical treatment of $O(10^1)$ boundary value problems. Representative numerical examples involving strongly nonlinear oscillators are considered for assessing the performance of the developed methodology. Comparisons with pertinent Monte Carlo simulation data demonstrate excellent agreement, thereby illustrating that the proposed treatment combines high accuracy with low computational cost.

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A Functional Integral Formulation for Stochastic Engineering Mechanics

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ABSTRACT

A versatile and computationally efficient functional-integral-based methodology is developed for the stochastic response determination of nonlinear engineering mechanics systems, in which uncertainty may arise either as additive excitation or through stochastic operators embedded within the governing equations. The formulation relies on the concept of the probability density functional (e.g., [1]), representing the infinite-dimensional analogue of the conventional probability density function (PDF), thereby enabling a continuum-level probabilistic description of stochastic fields without a priori discretization. Further, relying on this representation of stochastic fields, a general probabilistic–variational framework is developed, wherein the governing equations are enforced as functional constraints within a functional integral representation of the response PDF. Furthermore, the functional integral is approximated via a variational principle, based on the extremization of an appropriately defined stochastic action functional, yielding the most probable admissible field configuration. The methodology exhibits several significant advantages: a) the complexity of the original stochastic problem is substantially reduced, as it is recast as a standard deterministic boundary value problem for the most probable field configuration; b) the formulation enables the direct determination of the full response PDF, rather than being restricted to low-order statistical moments; c) both additive stochastic excitation and stochastic operators of general form (including nonlinear and nonlocal) can be treated in a unified and direct manner, while the classical Wiener path integral formulation [2] is recovered as a special case when an explicit input–response transformation is available; and d) the framework provides natural localization capabilities, enabling the direct evaluation of marginal PDFs for response quantities of interest at prescribed spatial locations. The accuracy of the methodology is assessed through both a linear benchmark problem, for which exact solutions are recovered, and a geometrically nonlinear, statically indeterminate stochastic beam problem, where comparisons with Monte Carlo simulations demonstrate satisfactory agreement. Overall, the proposed functional integral formulation provides a fundamentally new pathway for addressing stochastic engineering mechanics problems and a foundation for future developments in stochastic finite element approaches.

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Mapping Algorithms for Material Random Fields in Stochastic Finite Element Analysis of Strain-Softening Continua

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ABSTRACT

This study investigates the algorithms for mapping random fields of material properties onto finite element (FE) meshes and examines their implications for stochastic FE analysis of damage and fracture in strain-softening continua. A continuum damage constitutive modeling framework is adopted, in which the constitutive law of each finite element is regularized to ensure correct energy dissipation regardless of mesh size. Three mapping methods for random fields are considered: (1) local mapping, where the constitutive property of an element is directly sampled from the random field at a specific point (e.g., element centroid or integration point); (2) local averaging, where the property is obtained by averaging the random field over the element domain; and (3) mechanism-based mapping, where the projection of the random field onto the FE mesh is governed by the prevailing damage mechanism within each element. These methods are implemented in stochastic FE simulations of recent bending beam and cavity expansion tests on Dunnville sandstone, which exhibit distinct failure patterns. Comparison between experimental and simulated results highlights the critical role of linking the mapping algorithm to the evolving constitutive behavior of individual finite elements to ensure model robustness. The analysis further elucidates the influence of multiple characteristic length scales—including FE mesh size, correlation length, and fracture process zone width—on the mapping behavior. The study also provides new insights into the experimental calibration and validation of stochastic FE models.

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Moment equations-driven discovery of stochastic systems with coloured noise

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ABSTRACT

This study presents a stochastic system identification framework based on one/two-time moment equations for discovering the governing nonlinear stochastic differential equations (SDEs) directly from data. The framework is complemented by a Selective Segmented Sampling data-acquisition strategy that enables reliable estimation of the required statistical moments/correlation functions, even from limited experimental measurements.

Reduced-order modeling of nonlinear dynamical systems from first principles remains a central challenge across science and engineering [1]. Recent advances in data-driven discovery and machine learning [2] have enabled direct identification of governing equations from data. However, most existing approaches are restricted to deterministic systems [3], providing no means to discover the underlying stochastic dynamics other than additive measurement noise.

Inspired by sparse regression [4], the proposed method seeks to identify stochastic systems under white/coloured noise excitations from observed data. The drift and diffusion functions are represented by a linear combination of candidate nonlinear functions with sparse matrices of coefficients. By deriving deterministic one-time [5] and two-time moment equations [6] from the SDEs, the identification problem reduces to a sparse nonlinear regression, in which the sparse coefficients are identified by minimizing the discrepancy between predicted and observed time derivatives of the moments and correlation functions.

The proposed framework is validated on several representative examples of increasing complexity, including stochastic Duffing oscillators, the van der Pol oscillator under additive coloured noise, and the stochastic Mathieu equation. The results demonstrate excellent accuracy and robustness in recovering both deterministic and stochastic components of nonlinear dynamics, highlighting the method's potential for data-driven discovery of stochastic systems in practical engineering applications.

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A Novel Data-Model Dual-Driven Implicit Remaining Useful Life Prediction Method for Reusable Thin-Walled Structures

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ABSTRACT

Accurately predicting the remaining useful life (RUL)[1] of thin-walled load-bearing structures is essential for improving reusable spacecraft safety and reliability. However, structural health monitoring is often incomplete and indirect, limiting the accuracy of existing data-driven lifespan prediction methods. For small sample data, data-driven RUL prediction methods exhibit poor generalization capabilities and insufficient quantification of temporal uncertainty. To address this challenge, this paper proposes a data-model dual-driven implicit RUL prediction method (DMDI). This method first introduces a correlation-based [2] feature mapping strategy. By employing computational modeling, it uncovers nonlinear mapping relationships between monitoring data and implicit degradation indicators, thereby extending their applicability to real-world monitoring data. To address the inherent non-stationary, time-varying uncertainties in degradation processes, DMDI proposes a triple-uncertainty adaptive Wiener [3] feature extraction method. This approach effectively characterizes uncertainties stemming from random effects, temporal variability, and measurement errors. Subsequently, model calibration via a degradation function enables the propagation of degradation responses from monitoring outputs to intrinsic parameters, thereby revealing the model's underlying degradation mechanisms. Finally, by integrating model uncertainty and employing a variable-fidelity Gaussian process model, the DMDI method achieves high-precision remaining service life prediction with exceptional generalization capability. The accuracy of remaining service life prediction is validated using a reusable thin-walled structure case study. Compared to Wiener processes and LSTM methods, DMDI combines data-extracted features with high-fidelity models to propagate degradation from response to intrinsic parameters, thereby uncovering underlying degradation mechanisms. By simultaneously accounting for quadruple uncertainties (random effects, temporal uncertainty, measurement uncertainty, and model uncertainty), this method delivers more precise RUL predictions.

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Nonstationary Response Statistics of Linear and Nonlinear System with Fractional-Derivatives: A Stochastic Averaging-Based Analysis

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ABSTRACT

This work presents an investigation into the stochastic response analysis of linear and nonlinear dynamical systems endowed with fractional derivative elements under nonstationary and nonwhite excitations. The study is motivated by the challenge that exact analytical solutions for such systems are rare, even in linear settings, especially when the excitation features non-separable evolutionary power spectral density (EPSD). To address this, the stochastic averaging technique is employed as the core analysis tool.

For linear systems, the fractional derivative approximation yields an equivalent integer-order representation characterized by an equivalent natural frequency and damping ratio, which can be obtained by solving a simple one-dimensional algebraic equation. Building upon this, two efficient approximate analytical solutions for the time-varying response statistics are developed. The first follows the classical stochastic averaging procedure, the second solves directly the equivalent integer-order system subject to the same excitation, providing consistently higher accuracy than the first solution across a broad range of system parameters and excitation types.

For nonlinear systems, stochastic averaging leads to an integer-order stochastic differential equation governing the evolution of the response amplitude, from which the corresponding averaged Fokker-Planck-Kolmogorov (FPK) equation can be given. To solve this equation efficiently, a Galerkin scheme is introduced using basis functions constructed from eigenfunctions of the associated linear system. Specific modifications are proposed to adapt the Galerkin scheme to cases involving nonstationary and nonwhite excitations with inseparable EPSD. As a complementary benchmark, numerical path integration is also employed to solve the FPK equation for validation.

Several representative examples, including linear oscillators, the Van der Pol system, and the Duffing system, confirm the reliability and accuracy of the proposed methods when benchmarked against Monte Carlo simulation results or exact analytical solutions. The results demonstrate that the combined framework enables efficient and accurate prediction of nonstationary response statistics for a broad class of fractional-derivative dynamical systems.

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Monte Carlo simulation of non-Gaussian rainfall fields based on frequency-wavenumber spectral analysis

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A Monte Carlo simulation framework is developed for generating ensembles of synthetic rainfall fields that fully reflect the spatio-temporal probabilistic characteristics of a recorded extreme rainfall event. The framework relies on first establishing the empirical frequency-wavenumber (F-K) spectrum of the event through the appropriate three-dimensional Fourier transform applied to the observed rainfall field data, along with its empirical marginal probability distribution. Sample functions of the rainfall field are then generated using the Spectral Representation Method (Deodatis & Shields, 2025), which synthesizes Gaussian realizations via randomized phase angles that reflect the prescribed three-dimensional F-K spectrum. Since rainfall is inherently non-Gaussian, each Gaussian realization is subsequently transformed into a non-Gaussian one through Grigoriu's Translation Process Theory (Grigoriu, 1984, 1995). The F-K spectrum also enables the extraction of dominant propagation characteristics of the rainfall field through its transformation into the corresponding “slowness” function, a framework originally developed in seismology to analyze propagating earthquake waves (Aki & Richards, 1980). The methodology is applied to a recorded extreme rainfall event that occurred in the Gard region of southern France in 2002. The analyzed rainfall field covers a $50 \text{ km} \times 50 \text{ km}$ area and spans an 11-hour period, with a spatial resolution of $1 \text{ km} \times 1 \text{ km}$ and a temporal resolution of 5 minutes. One thousand non-Gaussian synthetic realizations are generated and validated against the recorded event. The ensemble-averaged synthetic F-K spectrum closely matches its empirical target, while the corresponding ensemble-averaged slowness function agrees with the empirical one within a mean relative difference of only 0.17%. Individual realizations exhibit spatio-temporal variability and propagation patterns consistent with the observed event. These generated sample rainfall fields can serve as a basis for probabilistic flood risk analysis of dense urban areas, where flood development and evolution depend critically on high-resolution, space-time rainfall modeling.

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Unified framework for dimension-reduced differential and integral equations in stochastic dynamics: DR-PDEE and DRCK formulations

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ABSTRACT

High-dimensional stochastic dynamical systems pose fundamental challenges in probabilistic analysis and reliability assessment due to the curse of dimensionality. Recent developments have established two theoretically rigorous yet seemingly distinct dimension-reduction formulations: the dimension-reduced probability density evolution equation (DR-PDEE) in differential form [1] and the dimension-reduced Chapman-Kolmogorov (DRCK) equation in integral form [2]. Despite their different mathematical representations – partial differential vs. integral equations – both describe the transient evolution of the probability density function (PDF) of any quantity of interest in a reduced-dimensional space. This study presents a unified theoretical framework that rigorously demonstrates the mathematical equivalence between DR-PDEE and DRCK under consistent assumptions on system continuity and Markovianity. Specifically, it is shown that the intrinsic transition probability density (TPD) in the DRCK formulation acts as the integral kernel corresponding to the drift and diffusion terms in the DR-PDEE, thus establishing their one-to-one correspondence. The unified formulation provides both analytical transparency and computational flexibility – the DR-PDEE is well suited for local differential approximations, while the DRCK form facilitates efficient path-integral-based numerical schemes. Numerical demonstrations on nonlinear stochastic systems under Gaussian and Poisson excitations confirm that the two formulations yield identical transient PDFs with consistent computational efficiency. This unified perspective not only bridges the gap between integral and differential stochastic representations but also offers a versatile foundation for future data-driven and hybrid stochastic modeling of complex engineering systems [3].

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Performance-based risk optimization of transmission line systems subject to non-synoptic winds using stochastic emulators

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ABSTRACT

The reliable and cost-effective design of electric power transmission systems remains a critical challenge, particularly due to their vulnerability to extreme non-synoptic wind events (e.g., downbursts or tornadoes). This work addresses the risk-informed performance-based optimization of transmission line (TL) structures, explicitly considering these extreme wind hazards. The optimization formulation is founded upon the Performance-Based Wind Engineering (PBWE) framework, which systematically integrates hazard, structural, and damage/loss analyses. The primary objective is to minimize the Total Expected Cost (C_{TE}), defined as the sum of the initial construction cost and the expected failure costs associated with wind-induced damage. Within the PBWE methodology, a crucial step is the estimation of conditional failure probabilities, expressed through fragility functions. These functions are computationally demanding to derive, requiring extensive structural simulations. To overcome this computational bottleneck and accurately characterize the required conditional probabilities, this study heavily leverages advanced Stochastic Emulators [1, 2, 3]. These surrogate models serve to efficiently construct structural fragility functions, offering significant computational cost reduction while adequately capturing the stochastic characteristics of the system response. The design variable considered for optimization is the tower-to-tower span length. Preliminary results demonstrate that the optimal solution achieves a necessary balance between the initial construction costs and the expected failure costs induced by non-synoptic wind actions. Specifically, increased span lengths generally reduce the probability of a localized wind event hitting a single tower. However, larger spans also necessitate the use of taller and more robust towers to satisfy prescribed strength and serviceability requirements, highlighting a complex trade-off that performance-based risk optimization successfully resolves.

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The Inherent Resilience of Cities to Natural Hazards: Records, Evidence and Predictions

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ABSTRACT

In view that cities will continue to house the majority of the world's population at an increasing rate in association with the face of climate change, in this paper we quantify urban resilience to natural hazards by examining the response history of the mean-square displacement of the citizens of large cities prior and upon natural hazards strike. The recorded mean-square displacements of large numbers of cell-phone users from the cities of *Houston*, *Miami* and *Jacksonville* when struck by hurricanes *Harvey 2017*, *Irma 2017* and *Dorian 2019* together with the recorded mean-square displacements of the citizens of *Dallas* and *Houston* from traffic-flow data when experienced the 2021 North American winter storm, revert immediately to their pre-event steady-state response, suggesting that large cities when struck by natural hazards are inherently and invariably resilient within the context of "*engineering resilience*". During the talk we explain how the mean-square displacement from a random (stochastic) process is intimately related to deterministic, emergent time-response functions. This overarching relation which emerges from the theory of Brownian motion in association with the recorded data presented in this study also leads to a mechanical model for cities, recently developed by the first author, which is rooted in Langevin dynamics. Our mechanical model predicts precisely what the recorded data uncover—that following a natural hazard, large American cities revert immediately to their initial steady-state regime and resume their normal, pre-event activities.

Physics-Informed Machine Learning Architectures for Predicting Aeroelastic Response of Laminated Composite Beams

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ABSTRACT

Accurate and efficient prediction of the aeroelastic response of laminated composite beams subjected to spatially and temporally varying aerodynamic loads remains a central challenge in aeroelastic analysis and design. This challenge arises from the combined effects of transverse shear deformation, material anisotropy due to lamination, and strong parameter sensitivity, which are not adequately captured by classical beam theories. In this work, we present a physics-informed machine learning framework for aeroelastic beam analysis based on first-order shear deformation theory, in which transverse displacement and cross-section rotation are treated as independent fields. This formulation naturally accommodates laminated composite constructions and provides the fidelity required for moderately thick beams commonly encountered in aeroelastic applications.

A key innovation of the proposed approach is the systematic nondimensionalization of the governing equations, which reveals that the aeroelastic response is governed by a small number of physically meaningful parameters and leads to a coupled second-order system with smooth, Laplacian-like behavior and stable structural response under variable aerodynamic loading. This structure plays a crucial role in facilitating the training of physics-informed neural networks by improving numerical conditioning, accelerating convergence, and enhancing predictive accuracy across different laminate configurations, load amplitudes, and flow conditions.

The resulting physics-informed learning framework enables robust, generalizable, and computationally efficient prediction of aeroelastic beam responses, offering a viable alternative to high-fidelity simulations for applications such as flutter analysis, parametric studies, and design optimization of advanced composite aeroelastic structures.

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Efficient response and power output estimation of massive WEC arrays exposed to random waves

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ABSTRACT

Research conducted during the last two decades in the wave energy sector led to the conclusion that single point absorbers and oscillating water columns (OWC) have commercial potential due to their energy-wise efficiencies [1]. Consequently, current research focuses on the implementation of these technologies in arrays. That is, collections of hundreds of devices operating in identical environmental conditions at a distance comparable with typical water wave lengths.

A fundamental characteristic of WEC arrays is that, due to the relatively short distance between the devices, the WECs interact with each other through radiation effects described mathematically by the Cummins' equation. In this context, radiation effects are captured via convolution integrals depending on the past values of the response, which make Monte Carlo studies computationally prohibitive.

The objective of this article is to show that expeditious Monte Carlo simulations of massive WEC arrays can be conducted by representing the kernels of the convolution integrals via the Prony method. It allows approximating them up to a desired level of accuracy, while removing the need to storing the past response values of the response, and without the need to utilize additional differential equations. The reliability of this approach is assessed by time domain data pertaining to U-OWC arrays exposed to random waves [2,3].

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Isogeometric-Sensitivity-Informed Polynomial Chaos Expansion

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ABSTRACT

Surrogate models, such as the Polynomial Chaos Expansion (PCE) method, provide a more efficient means of quantifying uncertainty in complex systems than direct numerical simulations. These models enhance predictive accuracy and reduce the need for extensive training data by incorporating problem-specific physical insights, thereby enabling more efficient estimation of system responses. Nevertheless, when uncertainties arise from geometric variations, traditional finite element analysis (FEA) methods can be computationally expensive when generating training data, which can lead to inaccurate representation of the geometry. To address these issues, this study employs isogeometric analysis (IGA) [1] to extract detailed physical insights for systems affected by geometric uncertainty. The sensitivities derived from the IGA model are integrated into a physics-informed PCE framework [2], embedding constraints such as boundary conditions and system behavior directly into the surrogate model. Sensitivities are computed using a variational approach, enabling the simultaneous evaluation of system response and sensitivities. The proposed methodology is validated through a numerical study on a three-dimensional linear elasticity problem with geometrically uncertain parameters. The results show that the integration of IGA-derived sensitivities into the PCE formulation enables accurate prediction of complex response quantities, including stress triaxiality, without compromising computational efficiency.

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Line Element-less Method for Plates with Random Material Properties

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ABSTRACT

Within the broader framework of continuum and structural modeling, the Line Element-less Method (LEM) has recently gained significant attention as a versatile and computationally efficient tool for the analysis of a wide range of structural problems. Previous studies have demonstrated its accuracy and flexibility in addressing torsion in beams [1–2] and bending in plates [3–4], effectively handling arbitrary geometries, diverse loading scenarios, and complex boundary conditions without the need for a traditional mesh. In this study, the method is further generalized to provide a comprehensive formulation for Kirchhoff plates, extending its applicability to cases involving internal constraints and partially distributed loads acting over limited portions of the domain, enabling accurate modeling of realistic engineering scenarios where loads are not necessarily uniform or acting over the entire plate surface. In addition to geometric and loading complexities, the proposed approach incorporates material uncertainty by modeling the flexural rigidity as a random variable. Such an approach allows one to capture intrinsic variability related to material properties, fabrication processes, or thickness tolerances, which can play a critical role in the reliability assessment of plate structures. To quantify these effects, a perturbation-based method is employed to evaluate the probabilistic response: the zeroth-order solution corresponds to the standard LEM solution, while the first-order correction accounts for variability in the flexural rigidity. In this way, the statistics of the displacement field are computed with limited computational effort, providing valuable insight into structural reliability under uncertain material properties. To validate the proposed methodology, several numerical examples are presented. The results show that, for plates under different combinations of loading and boundary conditions, deterministic LEM solutions closely match classical plate theory, while the probabilistic extension quantifies the effect of material variability on the structural response and highlights deviations from the deterministic predictions.

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A quantum computing approach for solving Fokker-Planck equations governing the stochastic response of nonlinear structural systems

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The response transition probability density function (PDF) of a wide range of stochastically excited structural systems is governed by the Fokker–Planck (FP) partial differential equation [1]. In this regard, various numerical strategies have been developed for its solution, including finite elements, eigenfunction–eigenvalue expansions, and related operator-based discretizations. Despite their respective advantages, these methods share a central limitation: computational cost escalates rapidly with the number of degrees of freedom, rendering the solution of high-dimensional FP equations a daunting task without resorting to approximate, reduced-order schemes. This motivates approaches that can represent and evolve system response PDFs with improved scaling while retaining accuracy and physical consistency.

In this work, a quantum computing methodology based on variational principles is adapted to recast the FP equation into a functional optimization problem that can be treated by state-of-the-art variational quantum algorithms. The central challenge is that mapping a discretized FP operator into a hardware-compatible variational objective is nontrivial. However, if successfully implemented, it can shift the burden from explicit high-dimensional tensor operations to parameter optimization over a compact quantum representation, thereby offering a pathway to leverage near-term quantum resources. To this end, a VarQITE-based formulation [2] grounded in McLachlan’s variational principle is employed and applied to a representative nonlinear structural dynamical system under white-noise excitation. Key components include a structured discretization of the FP operator and an expressive, yet resource-aware, circuit ansatz designed to capture the evolving density on the chosen state space. Numerical examples are considered to assess accuracy and practical feasibility on current quantum hardware.

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Fractional viscoelastic parasitic damping of inerters in the optimal design of enhanced isolation systems

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ABSTRACT

Over the last decade, the use of the inerter for vibration control has become increasingly widespread, and a growing number of scientific contributions on the subject can be found in the literature [1]. The ideal inerter is a mechanical device capable of generating a force proportional to the relative acceleration between its two terminals, thereby introducing an inertial effect without requiring a significant increase in mass. Because of this unique property, the inerter has attracted considerable interest in various engineering fields, particularly in structural and seismic engineering.

Applications in earthquake engineering have shown that the integration of an inerter into traditional base-isolation systems can lead to significant improvements in seismic performance, achieving an effective decoupling between the structure and the ground motion and contextually reducing structural displacements, thus resolving one of the typical drawbacks of base isolation [2].

Practical implementations of the inerter have revealed the presence of additional parasitic dissipation that must be considered in the analysis to adequately represent its actual behavior.

However, it has been shown that accounting for the effect of parasitic damping can enhance the performance of the advanced isolation system [3]; it is therefore essential to properly represent its effect using suitable mathematical models.

Recently, it has been demonstrated that the dissipative behavior of the inerter can be represented by a fractional viscoelastic model whose parameters can be easily identified from experimental data obtained through frequency-sweep tests.

In the present work, we aim to investigate the effects of the parameters of the fractional model for parasitic damping on the determination of the optimal parameters of the advanced isolation system by minimizing the variance of the structural displacement. This aspect will be studied using different PSD functions to account for the different power contents at various frequencies of the seismic excitation.

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Intervention planning for stochastic engineering systems through adaptive resource allocation-based reinforcement learning

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ABSTRACT

Intervention planning for stochastically degrading engineering systems is critical for ensuring reliable performance and safety. Due to scale, constraints, and uncertainties, devising inspection and maintenance strategies that minimize use of resources while preserving global system integrity is computationally challenging. This task is a stochastic optimal control problem that can be mathematically formulated as a (partially observable) Markov decision process and solved through deep reinforcement learning (DRL). Multi-Agent DRL (MADRL) allows us to alleviate several planning complexities arising in multi-component engineering systems with large-scale state and action spaces, outperforming heuristic maintenance strategies. Multi-agent approaches hinge on a flat decentralized approximation of the joint policy, where each agent is in control of a different component. In principle, this approximation can only provide a lower bound on the global optimum, as efficient cooperation among agents diminishes when their population and the global system redundancies grow. In this work, we propose a DRL framework based on hierarchical decomposition instead of flat decentralization, formulating the maintenance task as an adaptive resource allocation problem that can either leverage the fixed topology of the system or learn to dynamically cluster it in order to hierarchically compute resource flows. In the former case, this approach allocates resources, such as budget, in a structured manner, following a predefined static hierarchical decomposition that moves from system- to subsystem- to component-scales. In the latter case, we generalize to account for subsystems that are dynamic and learnable. Thus, assumptions regarding static decomposition are relaxed, allowing complex engineering systems to be tackled without loss of generality. We introduce a novel adaptive-hierarchy resource allocator DRL architecture, in which the system is decomposed into learnable subsystems, adaptively reshaped at every decision step. An agent is trained to optimally group the components of a system in multiple subsystem-clusters, while allocating budget so that local subsystem risks are minimized and global system risks do not exceed acceptable levels. The component states and subsystem budgets are hierarchically embedded in a fixed and explicitly interpretable latent vector space, in which vector similarity is leveraged to optimally assign components to subsystems. The efficacy and scalability of the proposed algorithmic framework is demonstrated in an engineering system with multiple-components subject to stochastic deterioration. Results show that the new approach outperforms both conventional heuristics and MADRL counterparts while improving policy interpretability.

Fractional-order contact effects in the reliability assessment of nonlinear blocks rocking under evolutionary ground motion excitation

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ABSTRACT

This work presents a semi-analytical framework to quantify the survival (no-toppling) probability of a rigid block rocking on a nonlinear foundation when dissipation arises from fractional-order contact effects. The restoring action is modeled by a linear Winkler-type foundation, while energy loss is captured by a history-dependent, fractional-order nonlinear component that generalizes classical damping contact laws. Seismic excitation is represented by evolutionary, code-consistent stochastic ground motions with time-varying intensity and frequency content [1].

A stochastic averaging procedure tailored to the nonlocal character of fractional dissipation yields reduced amplitude–phase dynamics that explicitly accommodate the unbounded escape branch associated with toppling [2]. A special form of nonstationary probability density function (PDF) of the rocking amplitude is proposed, enabling efficient evaluation of time-dependent survival probability without resorting to large-scale Monte Carlo simulation [3].

Relevant studies on blocks of varying slenderness and mass, and on foundations spanning stiffness and damping levels, demonstrate how the fractional order and contact nonlinearity jointly modulate effective damping, energy restitution, and toppling rates under evolutionary excitation. Across cases, the proposed method reproduces Monte Carlo estimates of survival probability with fidelity at markedly reduced computational cost. These results underscore the value of fractional-order contact modeling, paired with potent stochastic dynamics techniques, for probabilistic seismic assessment of rocking systems with realistic soil–structure interaction and memory-dependent dissipation.

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Reliability and resilience assessment via spectral properties of continuous-time Markov chains

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ABSTRACT

Performance-Based Earthquake Engineering (PBEE) is being increasingly deployed not only to determine how likely a system is to fail, but also how long it is expected to remain functional and how efficiently it can recover after a seismic event [1]. To address this shift in perspective, we introduce a continuous-time Markov chain (CTMC) framework that embeds both seismic damage accumulation and recovery within a unified stochastic model, extending classical Poisson-based PBEE formulations [2]-[3]-[4].

The dynamic evolution of the performance of a structure is governed by a transition rate matrix whose spectral properties provide direct access to long-term reliability and resilience metrics. In particular, the dominant eigenvalue of the transition rate matrix conditioned on survival defines the characteristic degradation timescale, while the corresponding eigenvector yields a quasi-stationary distribution describing the typical operational state of the system prior to collapse [5]. These spectral quantities enable closed-form and computationally efficient evaluation of survival probabilities, expected time to failure, and resilience indices over finite engineering horizons, avoiding the need for extensive Monte Carlo simulations.

We present a simple example to clarify the physical interpretation of these spectral descriptors and to illustrate how recovery processes can reshape the resilience of systems through their impact on the generator spectrum.

Thus, the proposed CTMC-based PBEE extension provides an interpretable and efficient tool for seismic reliability and resilience assessment, supporting performance-informed design strategies that explicitly account for recovery and long-term functionality.

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A Response-Excitation Approach to Non-Markovian Dynamics

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ABSTRACT

Dynamical systems under colored Gaussian excitations give rise to non-Markovian responses characterized by an infinite hierarchy of probability density functions (pdfs). Traditionally, the first step toward probabilistic characterization of such problems is the derivation of one-time response-only pdf-evolution equations (pdf-EEs). However, under multiplicative excitation, response-only pdf-EEs face severe closure difficulties—even for the simplest scalar random differential equation (RDE)—due to the inherent response–excitation (RE) coupling. To address this issue, we are adopting a RE framework evolving joint RE pdf. We formulate an exact RE Stochastic Liouville Equation (SLE) and, following the functional-calculus approach [1–3], we utilize an extended Novikov–Furutsu theorem to transform the RE-SLE into a master equation. In contradistinction with the usual approaches which are restricted to Ornstein-Uhlenbeck excitations [4, 5], our approach applies to any Gaussian excitation. Our equation involves averages of variational (Volterra) derivatives of the RDE solution with respect to the excitation; these terms are temporally nonlocal, rendering the equation non-closed. We show that several closure schemes can be applied, yielding closed RE pdf-EEs. In contrast to the response-only approach, closure is achieved without neglecting or weakening the RE coupling; it follows solely from current-time approximations that enable ensemble averaging, resulting in approximate, closed RE pdf-EEs with non-local in time diffusion coefficients. Note that, marginalizing the joint RE equation with respect to the excitation recovers the exact response-only SLE, ensuring consistency with the marginal probabilistic dynamics. Also, marginal consistency with respect to the excitation (given) holds true. Furthermore, a mean-value decomposition closure scheme can be applied in an analogous manner to [2, 6] (which treat the scalar and multidimensional additive cases), yielding a closed nonlinear pdf-EE. The resulting equations are numerically tractable, admitting straightforward time–space discretization. First numerical solutions of the new pdf-EE and comparisons with Monte Carlo simulations validate the present approach. Extension to the multidimensional setting is feasible.

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Unified Analytical Framework for Evolutionary Probability Density Based on Complex Fractional Moments

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ABSTRACT

Due to inevitable manufacturing imperfections and environmental uncertainties, the responses of structural engineering systems need to be characterized in probabilistic terms. Among various probabilistic descriptions, the evolutionary probability density function (PDF) plays a crucial role, as it contains complete probabilistic information about system behavior, and is essential for predicting responses as well as optimizing structural designs. However, obtaining the evolutionary PDF of nonlinear stochastic dynamical systems accurately and efficiently remains a challenge problem. The complex fractional moments [1], constructed from the Mellin transform in a probabilistic sense, can equivalently characterize the probabilistic features of random variables. Based on which, a unified probabilistic evolution analysis framework is developed for stochastic Hamiltonian systems, stochastic fractional systems, and so on [2-3]. Furthermore, by introducing the Laplace transform, the complex fractional moment is extended to the Shifted Characteristic Function (SCF), and subsequently generalized to a multi-dimensional SCF framework. This advancement enables high-dimensional probabilistic evolution analysis and establishes a rigorous theoretical basis for quantifying first-passage reliability in structural systems, which has been successfully validated through representative applications in stochastic structural dynamics.

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A Wiener path integral technique for stochastic response determination of nonlinear systems under Poisson white noise excitation

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The Wiener path integral (WPI) technique for determining the stochastic response of diverse nonlinear dynamical systems relates to treating the system response joint transition probability density function (PDF) as a functional integral over the space of all possible paths connecting the initial and the final states of the response vector [1]. Further, the functional integral is evaluated, ordinarily, by resorting to an approximate approach that considers the contribution only of the most probable path. This corresponds to an extremum of the functional integrand and is determined by solving a functional minimization problem that takes the form of a deterministic boundary value problem. However, the validity of the WPI formalism is restricted, to-date, to excitations modeled as Gaussian white noise processes. Note that a wide range of non-Gaussian and/or non-white processes can be accounted for, within the same framework, by augmenting the state-variable vector and by utilizing additional auxiliary filter equations [2]. Herein, the WPI technique is extended to treat, in a direct manner, cases of stochastic excitations modeled as Poisson white noise processes. This is done by employing an appropriate expression for the short-time transition PDF [3], and by deriving a novel representation of the system response PDF as a functional integral over the space of possible paths. The reliability of the technique is demonstrated by comparisons with pertinent Monte Carlo simulation data.

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Bayesian Learning using Physics-Constrained Priors

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ABSTRACT

The problem of state and parameter estimation in structural dynamics has been approached by Bayesian batch and sequential learning methods. For Bayesian batch learning methods, the posterior distribution of the model parameters is built from the likelihood, integrating model-based predictions and sparse response time history measurements, for a selected time interval and using subjective priors of the model parameters. For Bayesian sequential methods, the posterior distribution of state variables and model parameters is built sequentially by processing sequentially the data at each time instance using the state space and observation equations. Following recent developments in Bayesian ODIL [1], a new Bayesian learning methodology is presented for state and parameter estimation for which the state and parameters are inferred simultaneously using physics-constrained priors for the state variables and subjective priors for the model parameters. The method is applied to problems in structural dynamics to demonstrate its applicability and effectiveness in predicting the uncertainty in the state and model parameters in light of the data (sparse response time history measurements) and in the presence of model and measurement errors. The proposed approach generalizes conventional Bayesian batch learning developments. Applications to demonstrate the capabilities of the method, its effectiveness and computational efficiency to estimate the posterior distribution of state variables and model parameters in light of time history data are presented for cases of linear and non-linear structural dynamics using acceleration and/or strain response time history measurements. It is demonstrated that the proposed Bayesian method outperforms in terms of computational efficiency and accuracy existing ones, as well as outperforms algorithms based on physics-informed neural networks used to estimate state variables and model parameters.

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STOCHASTIC MANIFOLD-AWARE NEURAL PRECONDITIONING FOR PARAMETRIC ELLIPTIC PDES

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ABSTRACT

We propose a novel method for accelerating the Conjugate-Gradient iterative solution of parametric elliptic PDEs by utilizing a neural architecture as a non-linear preconditioner. Unlike traditional algebraic approaches, our model is trained directly on a manifold formed by stochastically generated solutions of the PDE, ensuring the network captures the representative features of the underlying physical system. The training process is explicitly grounded in the Krylov subspace, where the network is optimized to map solver residuals to error corrections using data trajectories collected from the iterative process itself. By learning this mapping over the stochastic solution manifold, the neural architecture provides a robust approximate inverse that significantly expedites the solver convergence for complex parametric variations.

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FORM-based global sensitivity analysis for time-variant reliability

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ABSTRACT

In reliability-based decision-making, sensitivity analysis plays a central role in guiding choices about refining or simplifying probabilistic models. This work examines global reliability sensitivity measures for time-variant reliability analysis that accounts for both stochastic loads and uncertain system parameters. We present two approaches for time-variant reliability sensitivity analysis: one based on approximating the first passage probability with the probability of a series of time interval failure events and another that expresses the failure event through an auxiliary limit state in terms of the conditional failure probability given the system parameters. For both approaches, reliability sensitivity indices can be estimated through leveraging FORM approximations for time-invariant global reliability sensitivities proposed in [1, 2]. The behavior and accuracy of these approximations are illustrated through numerical examples involving deteriorating structural systems.

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Introducing the Value of Adaptation and Value of Adaptive Design for Optimal Infrastructure Management

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ABSTRACT

Preserving the safety, functionality, and performance of civil infrastructure against the compounded threats of environmental deterioration and natural hazard events necessitates decision-making frameworks that extend beyond reactive repair strategies. While existing Performance-Based Engineering approaches have incorporated probabilistic loss estimation within life-cycle analysis, they often view structural systems as static and/or neglect opportunities for proactive structural improvement and adaptation. In this work, we present a probabilistic optimization framework that transforms this risk assessment paradigm into an extended approach by integrating hazard uncertainties, nonstationary deterioration, damage accumulation, state-dependent fragility assessments, and implementing dynamic maintenance and retrofit strategies. The life-cycle cost optimization problem is formulated as a Markov Decision Process (MDP), utilizing transition matrices derived via developed Dynamic Bayesian Networks (DBN), reflecting time-variant deterioration effects and hazard risks. The decision space is expanded in this work beyond standard maintenance to explicitly include retrofitting actions, allowing the system to fundamentally alter its performance trajectory rather than merely restoring it. To rigorously quantify the economic and structural benefits of these interventions, we introduce two novel metrics: the *Value of Adaptation* (VoA) and the *Value of Adaptive Design* (VoAD). VoA serves as an intrinsic, state-specific metric quantifying the immediate strategic advantage of retrofitting at each planning horizon step. Analogously, VoAD quantifies the global life-cycle value of incorporating adaptation capabilities directly into the structural design, effectively comparing a flexible design option capable of future retrofitting actions against a rigid baseline restricted to standard maintenance. Demonstrated on a representative structural system, the framework reveals that derived flexible, dynamic policies significantly outperform traditional strategies, providing decision-makers with a rigorous quantitative tool to plan and justify capital investments in structural adaptation and maintenance.

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Identification and evolutionary power spectral density modeling of typical pulse-like stochastic ground motions

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ABSTRACT

Near-fault pulse-like ground motions (PLGMs) exhibit strong non-stationarity and randomness. Classical identification methods yield inconsistent categorization results, while conventional modeling approaches decompose PLGMs into a deterministic pulse component and a stochastic residual characterized by power spectral density (PSD), resulting in an inconsistent representation of their stochastic nature. To overcome this limitation, this study proposes a unified framework for PLGMs' identification and evolutionary power spectral density modeling, consisting of (i) identification and construction of a typical PLGM database and (ii) development of an evolutionary power spectral density (EPSD) modeling method tailored to such motions. First, a representative PLGM database is constructed using a comprehensive categorization method that integrates multiple benchmark identification approaches and classifies ground motions into four levels according to pulse intensity. In this study, only Category A records, representing the most pronounced pulse-like characteristics, are selected to form the typical PLGM dataset, ensuring a clear and robust representation of essential pulse effects for subsequent modeling. Based on the constructed dataset, an EPSD modeling framework for PLGMs is subsequently developed. The core idea is to treat individual PLGMs as primary representation targets, thereby preserving pulse characteristics without being obscured by ensemble averaging effects. The overall EPSD is formulated by accounting for both pulse-related effects and site effects, which are characterized separately in the velocity and acceleration spectral domains. In this way, the proposed framework captures the strong non-stationarity and low-frequency concentration of PLGMs while naturally retaining the stochastic nature of both pulse and non-pulse components in a unified representation. The numerical examples demonstrate the model's capability to capture the pulse-like characteristics of ground motions and its effectiveness in structural random vibration analysis.

EFFECT OF MATERIAL AND GEOMETRIC UNCERTAINTIES ON THE MECHANICAL PROPERTIES OF SINGLE LAYER GRAPHENE SHEETS

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ABSTRACT

Graphene, a two-dimensional carbon lattice, is widely recognized for its exceptional mechanical properties, making it a promising material for applications in electronics, biomedicine, and composites. However, experimental testing at the nanoscale is challenging, leading to a reliance on computational models. This study explores the effect of material and geometric uncertainties on the mechanical properties of Single Layer Graphene Sheets (SLGS), with a particular focus on the modeling of atomic bond variability and structural defects. A stick-and-spring model is used, with interatomic interactions described by a modified Morse potential, which accounts for the non-linear nature of the atomic forces [1]. The bond stiffness is modeled as a random field, introducing spatial variability to the atomic interactions, which is represented using a probabilistic approach. This framework allows to assess how the random variation in bond strength due to material uncertainties affects the mechanical properties of single layer graphene sheets. Additionally, defects such as Stone-Wales and single and double vacancies are incorporated into the model as perturbations in the lattice, modeled using a Monte Carlo simulation to generate the statistical distribution of defect configurations [2,3]. The mechanical response is analyzed by solving the governing equations for the system to compute the elastic constants of SLGS under different loading conditions. The random field approach allows for the propagation of uncertainties in the material properties, which is captured through statistical measures. The study quantifies the influence of defect-induced and material-induced uncertainties on the mechanical behavior of SLGS, providing a robust mathematical framework for analyzing the effects of these uncertainties in nanomaterial design.

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On Longuet-Higgins Model of Random Waves

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ABSTRACT

The Longuet-Higgins (LH) model developed by Longuet-Higgins [1,2] is widely used in naval architecture (e.g. [3]), oceanography, marine engineering, and other fields to describe ocean wave height over a spatial domain and across time. When it involves random phases, the LH model emulates random (irregular) waves. Despite its popularity and prevalence, several peculiar issues have recently been identified for the LH model for random waves. Spatial-temporal random models are often approximated by Auto-Regressive Moving Averages (ARMA), but the LH model can be shown not to admit such ARMA representations and consequently, to have surprising implications about its predictability [4]. There are also curious findings about the LH model concerning the uncertainty of the averages of its higher-order moments, whereby classical methods to quantify uncertainty may not work in practice [5]. The same observations extend to processes driven linearly by the LH model (e.g., those of ship motions or loads). The talk will review those issues, complementing them with more extensive numerical simulations and possibly exploring their relevance to actual wave height data collected from a ship model basin.

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Dynamic analysis of a Venice Lagoon tidal defense gate under stochastic sea states: a simplified modeling approach

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ABSTRACT

A simplified dynamic analysis is proposed to investigate the behavior of the MoSE system—the mobile barrier complex designed to close the tidal inlets of the Venice Lagoon and protect the city from recurrent high tides. The system comprises multiple steel caissons (gates) hinged to the seabed, which are raised by injecting compressed air to expel water and make buoyancy the dominant factor in the system dynamics. In the study, each gate is modeled as a nonlinear single-degree-of-freedom oscillator operating under various hydrodynamic and pumping conditions. The analysis deliberately neglects resonance effects arising from the interaction among multiple gates, which have been extensively studied in previous works [1, 2].

The main objective is to characterize the oscillatory behavior of individual gates as a function of the sea state and the air pumping rate, enabling the estimation of realistic submergence (sinking) times and the associated reaction forces on the elastomeric fenders. To achieve this, autoregressive (AR) and autoregressive-moving-average (ARMA) digital filters are employed to generate

synthetic sea-surface elevation time histories compatible with real wave energy spectra derived from prevailing wind conditions. This ensures a physically consistent representation of wave kinematics and the resulting dynamic loads acting on the gate.

The governing equation of motion for the gate in water complies with the original design criteria [3]. Hydrodynamic forces are modeled by introducing a drag term, and an inertial component accounting for the displaced fluid volume below the gate, as well as an added mass contribution associated with the water moving in phase with the gate.

The reliability of the proposed modeling approach is assessed using Monte Carlo simulations, comparing the predicted gate motion with available experimental data for selected events. The model exhibits predictive capability across various air-pumping scenarios, and sea-lagoon head differences near incipient submergence. In this context, and beyond the juxtaposition with available experimental data, the developed model can yield statistical insights relevant to operational and safety assessments of the critical MoSE system.

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Sturm-Liouville problem with Generalized Gaussian initial condition

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ABSTRACT

The Sturm-Liouville problem leads to the drift term of the Fokker-Planck-Kolmogorov (FPK) equation that remain valid for any distribution of Random Variable (RV) as initial condition. The aim of this presentation relies on the assumption that the Probability Density Function PDF of the initial condition belongs to the very large class of the Generalized Gaussian RV (GG RV) [1] whose PDF is an exponential distribution ruled by the scale s and by a parameter $r \in (0, \infty)$. The motivation of this choice, from the engineering point of view, is that GG RVs, with $0 < r < 1$, are able to represent rare events, like very strong earthquakes, tsunamis or hurricanes. Moreover, for $r = 2$ the GG RV reverts to the Gaussian one, when $r > 2$ the RV is Platykurtic and for $r = \infty$ reverts to the uniform RV. The solution of the drift term of the FPK for non-linear differential equations, for GG initial condition, is performed by using Complex Fractional Moments (CFM) [2], in case of power law non-linearity, or Shifted Characteristic Function (SCF), in case of exponential type non-linearity. The very accurate results for different cases (Leptokurtic and Platykurtic RV) are assessed by Monte Carlo simulations.

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Higher-Order Moments of Spline Chaos Expansion

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ABSTRACT

Spline chaos expansion, referred to as SCE, is a finite series representation of an output random variable in terms of measure-consistent orthonormal splines in input random variables and deterministic coefficients [1]. This paper reports new results from an assessment of SCE's approximation quality in calculating higher-order moments, if they exist, of the output random variable. A novel mathematical proof is provided to demonstrate that the moment of SCE of an arbitrary order converges to the exact moment for any degree of splines as the largest element size decreases. Complementary numerical analyses have been conducted, producing results consistent with theoretical findings. A collection of simple yet relevant examples is presented to grade the approximation quality of SCE with that of the well-known polynomial chaos expansion (PCE). The results from these examples indicate that higher-order moments calculated using SCE converge for all cases considered in this study. In contrast, the moments of PCE of an order larger than two may or may not converge, depending on the regularity of the output function or the probability measure of input random variables. Moreover, when both SCE- and PCE-generated moments converge, the convergence rate of the former is markedly faster than the latter in the presence of nonsmooth functions or unbounded domains of input random variables.

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Seismic assessment of optimal risk-based RC frames against progressive collapse

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ABSTRACT

Progressive collapse is a major concern for critical infrastructure and tall buildings exposed to extreme hazards. Risk-based cost-benefit analysis can be employed to evaluate if strengthening measures are appropriate, considering the low probability (and high consequences) of triggering events. For RC frames, risk-based solutions reveal optimal tradeoffs between beam and column flexural capacities [1-3]. Stronger rectangular-section columns enable catenary action development in weaker square-section beams, whereas weaker square-section columns only allow compressive arch action to be mobilized in stronger deeper beams. Hence, the "strong columns – weak beams" configuration, widely adopted in seismic design, relates to the first optimal compromise. This study formally investigates the compatibility between optimal solutions obtained from abnormal loads leading to localized element loss and loads due to strong earthquakes. Structural analyses are conducted in OpenSees. Failure probabilities are computed using Weighted Average Simulation Method. Risk optimization is conducted via PSO. To reduce the computational burden, surrogate models are used to estimate limit states and reliability indexes. Results highlight that "strong columns – weak beams" configurations, although costly for mitigating progressive collapse alone, provide superior performance against seismic loadings. Findings emphasize the importance of addressing multi-hazard scenarios in structural optimization, particularly for infrastructure in regions prone to earthquakes.

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A Stratified Stochastic Emulation Approach for Conditional Structural Response Modeling in Performance-Based Earthquake Engineering

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ABSTRACT

Performance-Based Earthquake Engineering (PBEE) frameworks often require nonlinear time-history analyses (NLTHA) to propagate record-to-record variability and evaluate the probabilistic distribution of Engineering Demand Parameters (EDPs). In the FEMA P-58 (2018) [1] methodology, a distinction is made between NLTHA conditioned on non-collapse, used to obtain response quantities (demands), and simulations that result in collapse, which are used to derive collapse fragility functions. Although this distinction is well established in FEMA P-58, it may lead to deviations from the conventional lognormal assumptions commonly adopted in PBEE due to the lack of consideration of the probability-absorbing boundary associated with collapse. This study proposes a stochastic emulation framework that integrates Stratified Sampling (SS) with Stochastic Polynomial Chaos Expansions (SPCE) to approximate the conditional distribution of EDPs given non-collapse, without imposing any predefined parametric form. The SS procedure partitions the input space according to seismic hazard intensity, ensuring balanced representation of rare but critical events, while separate SPCE emulators are trained for each stratum using only non-collapse responses. Record-to-record variability is represented through a latent random variable within the emulation process, making the emulator inherently stochastic. Results demonstrate that the proposed framework accurately reproduces reference EDP distributions while reducing computational costs by more than one order of magnitude compared with full NLTHA-based Monte Carlo simulations. The stratified emulators effectively capture the heteroscedasticity of structural responses across hazard levels and yield smooth cumulative distribution estimates consistent with the physical behavior of the system. Overall, the proposed approach provides a computationally efficient and non-parametric solution to PBEE, enabling scalable risk and reliability assessments under complex sources of uncertainty.

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Fractional-order filter approximations for efficient stochastic response determination of wind-excited multi-degree-of-freedom structural systems

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A fractional-order filter approximation has been developed recently in [1] for a wind turbulence stochastic excitation model [2]. Specifically, the unknown filter parameters have been determined by minimizing the error in the frequency domain between the original and the approximate power spectral densities (PSD). It has been shown that compared to the limiting case of a standard integer-order filter, and for the same number of parameters to be optimized, the determined fractional-order filter with derivative elements of rational order yields enhanced accuracy. Further, the developed filter approximation enables the analytical calculation of stationary response moments of linear structural systems at practically zero computational cost. This is done by employing a complex modal analysis treatment of the filter state-variable equations, and by relying on Cauchy's residue theorem for evaluating analytically the related random vibration integrals. In this paper, the methodology developed in [1] is extended to account for multi-degree-of-freedom (MDOF) systems excited by a vector stochastic process with a prescribed PSD matrix. In this regard, not only the auto- but also the cross-spectra matrix elements are represented by appropriate fractional-order filters. A representative example is considered for assessing the accuracy of the methodology in determining MDOF system second-order response statistics analytically, at virtually no computational cost.

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A Computationally Efficient Approach to Assess Structural Reliability

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ABSTRACT

Structural reliability is a crucial aspect of structural engineering, offering a quantitative framework for the assessment of safety, performance, and risk [1]. Traditionally, the estimation of the reliability function has relied on Monte Carlo Simulation-based approaches [2]. These techniques involve generating a large number of structural input samples by using Shinozuka's formula [3], computing the response to each input by deterministically solving the equation of motion, and evaluating the response statistics. However, deterministically solving the equation of motion for a high number of samples is computationally demanding and may require prohibitively long computational times.

In this work, a computationally efficient approach for the estimation of the reliability function of linear systems, based on direct simulation of the structural response, is proposed. Specifically, the Power Spectral Density (PSD) of the structural response is first derived through the input-output relationship, after which Shinozuka's formula is employed to generate samples of the structural output. The samples obtained through this procedure are then normalized to have unit standard deviation at each time instant and subsequently scaled by the theoretical standard deviation derived analytically. Finally, at each time instant, the samples that exceed a prescribed threshold are discarded, and the number of remaining samples is divided by the total number of generated samples to obtain the reliability function. Several numerical simulations, along with comparisons against classical Monte Carlo Simulation, are presented to demonstrate both the accuracy of the proposed approach and the staggering reduction of computational times.

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On a Novel Locally Resonant Double Beam with Interval Uncertainties: Concept and Computational Framework

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ABSTRACT

This study proposes an original concept of locally resonant (LR) double beam and a pertinent computational framework to analyze the effects of uncertainties on its dynamic response. The LR double beam consists of two parallel beams mutually connected by periodic pairs of stiffening transverse webs, with an internal block coupled to each pair of transverse webs by slender beams. Resonant motion of the internal blocks, relative to the two parallel beams, induces a local resonance band gap in the frequency response of the LR double beam and relevant attenuation of elastic waves through the system. The LR double beam is especially designed for resin 3D printing. In view of accounting for uncertainties inherent in the fabrication process of the LR double beam and, in particular, of the components (transverse webs, internal blocks and slender beams) whose geometry mainly affects opening frequency and size of the band gap, an interval model is adopted for the uncertainties and an efficient computational framework is developed to calculate lower/upper bounds for opening frequency/size of the band gap. Building on some assumptions on the dynamics of the transverse webs, in fact, the LR double beam is meaningfully reverted to a LR equivalent beam with periodically attached beam-like resonators and its interval frequency response is obtained via an exact expression of the transfer matrix obtained by the Sherman-Morrison-Woodbury formula [1]. Either a sensitivity-based method or a global optimization method can be applied to calculate lower/upper bounds for opening frequency/size of the band gap, the choice being driven by a preliminary monotonicity test. Computational efficiency and correctness of the proposed computational framework is assessed by comparison with the standard Monte Carlo method implemented on a 3D finite-element model of the LR double beam, implemented in COMSOL Multiphysics. Generalizations to LR multiple beams are discussed.

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Predictive modeling of incompressible fluid flows using conditional score-based diffusion models

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ABSTRACT

Well-posedness of the Navier-Stokes equations in both the deterministic and stochastic settings is an open problem [1, 2]. The existence of global weak solutions has been proven in both cases, however uniqueness has not been established so far. Besides, the existence and uniqueness of strong solutions is guaranteed only locally in time. Stochastic Navier-Stokes equations with random forcing have been considered for various reasons. From a mathematical point of view, a conjecture by Kolmogorov suggests that the addition of noise could possibly reduce the number of physically meaningful invariant measures, which are not unique in general. From an engineering point of view, structural vibrations for flow fields in aeronautical applications, or sun heating and industrial pollutions in atmospheric dynamics, for example, can be modeled as random loads. From a computational point of view, this framework paves the way for generative models based on score-matching [3], which learn the logarithmic gradient of the probability density of an underlying diffusion process. By parameterizing this field with a neural network, the statistical geometry of the velocity fields can be reconstructed without explicit knowledge of their probability distribution, allowing the flow statistics to be reconstructed or sampled via inverse diffusion processes. These methods rely on the rise of generative diffusion models in scientific machine learning, a class of models particularly powerful for learning complex distributions [4, 5]. Building on recent advances in generative modeling for computational fluid dynamics, we show in this communication how conditional score-based diffusion models can be adapted to account for physical constraints pertaining to the flow properties, in particular incompressibility or turbulence spectra, and illustrate our approach with numerical simulations [6].

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Mechanical behaviour of random TPMS structures

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ABSTRACT

Lattice materials [1,2], in particular the ones based on triply periodic minimal surfaces (TPMS), are a class of architected materials whose geometry is defined by implicit mathematical surfaces repeated periodically in space. Their structural continuity and periodicity enable the design of lightweight components with tunable mechanical properties, making them attractive for various engineering and biomedical applications. However, biological materials often deviate from periodicity due to adaptation to natural conditions, leading to random variations that can enhance their mechanical response.

This study investigates how introducing random variations into the geometry of TPMS lattices affects their overall behaviour. Starting from perfectly periodic configurations, random TPMS structures are generated by applying random perturbations to the orientation and periodicity of the unit cells, following the approach proposed by [3]. This method preserves the mathematical continuity of the surfaces while allowing controlled levels of randomness to be introduced into the geometry.

The aim is to explore how different types and magnitudes of random variation influence the mechanical performance of these lattices. Several random configurations are generated and compared to their periodic counterparts to assess how geometric disorder modifies their structural behaviour and effective stiffness characteristics.

The study provides insight into the relationship between the degree of randomness and the resulting macroscopic response, highlighting possible trends towards more mechanically effective lattice structures. The proposed framework provides a computational basis for analysing random TPMS lattices, aimed at realizing improved tunable lattices.

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Polynomial Chaos Expansions or Neural Networks: A brief comparison of capabilities for stochastic mechanics

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Polynomial chaos expansions (PCEs) and Neural Networks (NNs) are both widely used to develop surrogate models and perform uncertainty quantification for problems in stochastic mechanics. Each method presents its own distinct advantages. PCEs, for example, provide a comparatively compact representation with a natural basis from which to analytically estimate statistical moments. NNs, on the other hand, have greater expressivity. Recent advances in both models have demonstrated a convergence of capabilities between them such that PCEs can be developed for operator learning (similar to neural operators) and can incorporate physical constraints (comparable to physics-informed neural networks, PINNs) while NNs can be designed as generalized spectral expansions possessing data-driven orthogonality conditions with the flexibility to model arbitrary empirical distributions with complex dependence. In this work, we will briefly discuss these emerging capabilities in both methods, highlighting their complementary role in stochastic mechanics.

Advancements in Extrapolation Methods for Direct Stability Assessments

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ABSTRACT

Direct assessments of a ship's dynamic stability in random waves requires long exposure times to directly observe extreme motions constituting stability failures. Statistical extrapolation methods provide an avenue for characterizing the extreme events with limited datasets, thus making direct assessments of dynamic stability tractable for evaluating various operating and seaway conditions, as well as different vessels at various stages of design. At CSM's, the co-authors presented the state-of-the-art in two of these extrapolation methods: envelope peaks over threshold (EPOT) [1] and split-time or motion perturbation method (MPM) [2]. Since then, the two methods have been included in the Second Generation Intact Stability Criteria (SGISC) published by the International maritime Organization (IMO) [3] and the International Towing Tank Conference (ITTC) Recommended Procedure [4]. The talk will review some pilot applications and statistical validation of these methods.

Another method that allows for statistical characterization of extreme events, is the Critical Wave Groups (CWG) method [5]. The CWG method differs from EPOT and split-time, in that it develops deterministic wave groups with known statistical properties and then identifies which wave groups lead to events that results in a near-exceedance of a prescribed motion threshold. The talk will describe a free-running vessel implementation of the CWG method [6]. Additionally, all three methods will be applied to the same case study utilizing the same hydrodynamic simulation tools and compared with each other as well as compared against direct observations from a large volume dataset.

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Serviceability assessment of structures subjected to pedestrian loading considering uncertainties in human-structure interaction

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ABSTRACT

Pedestrian loading plays a crucial role in assessing vibration serviceability of lightweight footbridges and floors. To obtain reliable predictions of pedestrian-induced vibrations, human-structure interaction needs to be taken into account. To this aim, pedestrians are commonly modeled as single-degree-of-freedom (SDOF) systems (see, e.g. [1]). A key issue is the accurate definition of their dynamic properties, which are affected by significant uncertainty.

This study investigates the influence of uncertainty in pedestrian dynamic characteristics on both the dynamic properties of the coupled structure-pedestrian system and structural vibrations. The structure is modeled as a continuous dynamic system, while pedestrians are treated as SDOF systems. Due to the lack of sufficient data for the probabilistic characterization of the uncertain pedestrian parameters, the interval model is adopted. Specifically, pedestrian properties are modeled as interval variables, using the Improved Interval Analysis via Extra Unitary Interval [2], defining the lower and upper bounds based on values reported in the literature. Assuming that the structural dynamic response is dominated by a single vibration mode, an analytical expression of the interval Frequency Response Function of the coupled structure-pedestrian system is derived. The pedestrian-induced load is modeled as a stationary random process using an equivalent spectral model [3]. Under this assumption, closed-form expressions for the interval power spectral density and spectral moments of the response are obtained. Then, by interval extension of Davenport’s formulation, the interval mean value of the maximum acceleration is derived.

Uncertainty propagation focuses on the evaluation of the lower bound and upper bound of the interval spectral moments and the interval mean value of the maximum acceleration. Numerical results concerning a footbridge are presented to demonstrate the influence of uncertainty on vibration serviceability assessment.

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Transfer Learning-enabled Multi-fidelity Stratified Sampling for Rapid Failure Analysis of Nonlinear Stochastic Systems under Extreme Events

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ABSTRACT

To estimate small failure probabilities of engineered systems against extreme events (e.g., natural hazards), probabilistic frameworks relying on high-fidelity modeling environments often become computationally demanding due to the substantial number of model evaluations required [1]. To alleviate the computational burdens, low-fidelity models, such as data-driven emulators, have emerged as potential alternatives. Nevertheless, they may yield biased predictions if used directly for uncertainty propagation and probabilistic assessment [2]. To balance estimation accuracy with computational efficiency, this work proposes a multi-fidelity stratified sampling scheme embedded with adaptive transfer learning (MFSS-T) for efficiently estimating the small failure probabilities associated with limit states involving the nonlinear structural responses of system subject to extreme events. The core idea is to develop deep learning-based emulators, which are adequately correlated with the high-fidelity model for each stratified subspace/strata, thereby serving as low-fidelity models. To minimize the computational demand for training, an emulator associated with the critical stratum is first established through an adaptive training scheme. Subsequently, backpropagation-based transfer learning is employed to develop emulators for the remaining strata. By effectively integrating the information from strata-wise high- and low-fidelity samples through multi-fidelity Monte Carlo, probabilities of failure given various limit states of interest can be efficiently estimated. The practicality and efficiency of the proposed scheme are demonstrated through an application involving the estimation of small failure probabilities associated with nonlinear structural responses subject to seismic excitation. Compared to the stratified sampling scheme based solely on high-fidelity model evaluations, MFSS-T achieves comparable accuracy while providing remarkable computational benefits.

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System Reliability of Transmission Towers in a Changing Climate

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ABSTRACT

This paper presents a probabilistic framework for modelling cascading structural failures in electric power transmission tower lines subjected to wind hazard events in a changing climate. The systems reliability analysis captures the randomness of initial tower failures caused by wind, interdependencies among towers due to mechanical connectivity through conductors, and the subsequent clustering of tower failures resulting from structural imbalances. System-level fragility functions are derived from finite element simulations, and the transmission line system is modelled as a sequence of regular towers, with initial failures occurring independently. The failure patterns segment the system into intact intervals, where cascading is modelled as a stochastic process influenced by proximity to failed towers. An advanced virtual modelling technique combined with analytical expressions is developed to probabilistically analyse clustering failures due to extreme wind hazards. It was found that clustering of transmission tower failures increases with wind speed, resulting in up to eight adjacent towers failing at the same wind speed. This has implications for network repair and resilience. Outcomes may also be used for information on climate change risks and impacts for large-scale transmission tower line networks, which provides the foundation of decision support for climate change adaptation and resilience planning.

Characterising populations using hierarchical Bayesian inference with stochastic emulators

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ABSTRACT

In hierarchical Bayesian inference, the goal is to infer the population-wide hyperparameters θ_x , which govern the distribution of the individual realisations of the input parameters of a forward model $M(x)$. Each experimental dataset provides observations y , which are related to the model output through the likelihood function and population prior. Classical approaches are computationally demanding: computing the joint likelihood depending on x and θ_x requires evaluation of the forward model for every proposed set of unknown parameters [1]. The resulting computational cost quickly becomes prohibitive for high-dimensional or expensive forward models.

One step towards mitigating this challenge is replacing the forward model with a deterministic surrogate, such as Gaussian process models or polynomial chaos expansions [2]. These surrogates provide inexpensive-to-evaluate approximations of the forward model. However, this class of methods requires the construction of an accurate surrogate of the forward model, which can become infeasible, particularly for high-dimensional problems.

In this contribution, we demonstrate how the use of a stochastic emulation framework can bypass the inner loop entirely, focusing directly on the hyperparameters θ_x . Building on recent developments in stochastic emulators [3, 4], we directly emulate the stochastic population response as a function of the hyperparameters, rather than constructing deterministic surrogates that map the physical parameters x to the output. This effectively integrates over the individual parameters x , enabling direct calculation of the marginal likelihood $f_E(y | \theta_x)$ and thereby substantially reducing the dimensionality of the problem. The proposed framework therefore makes it feasible to solve hierarchical Bayesian inference problems that were previously computationally intractable, particularly in cases where only the population-level parameters are of interest or where the forward model is inherently stochastic.

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DR-PDEE-based Stochastic Dynamical Response Analysis for High-Dimensional Nonlinear Systems under Multiplicative Non-White Noise Excitation

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ABSTRACT

Multiplicative stochastic excitation plays an important role in modeling complex nonlinear dynamics across multiple fields. Further, random noise in physical systems is typically not ideal white noise. Furthermore, stochastic analysis of high-dimensional nonlinear systems, even under additive white noise, has been quite challenging for several decades. These difficulties are exacerbated by the multiplicative excitations and its non-white nature. To address these challenges, the dimension-reduced probability density evolution equation (DR-PDEE) is extended to capture the response probability density of such systems. The basic idea is to first augment the original system to a white noise excited higher-dimensional system, and then reduce the system by the DR-PDEE. In this approach, the multiplicative non-white noise excitation is modelled by an analog filter with white noise input. The original dynamical system combined with the filter then forms an augmented higher-dimensional system driven by additive white noise. Subsequently, the two-dimensional DR-PDEE is constructed for the joint process that combines the quantity of interest in the original system with a filter output, possessing a nonzero intrinsic diffusion function. Solving the DR-PDEE directly yields the probability density function (PDF) of the quantity of interest. Notably, it is found that, owing to the introduction of the analog filter, the original system driven by multiplicative non-white noise is converted into a problem involving additive white noise problem. Thus, the intrinsic diffusion function in the corresponding DR-PDEE for the joint process becomes a known constant. This feature distinguishes the DR-PDEE for systems driven by multiplicative white noise, where the intrinsic diffusion functions are state-dependent [1]. Consequently, only the intrinsic drift functions in the DR-PDEE need to be identified, and these terms can be reliably estimated through a small number of representative deterministic analyses. An example is presented to validate the proposed method. The numerical example demonstrates that the DR-PDEE yields PDF solutions with high tail accuracy using only a limited number of deterministic analyses.

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Dynamic response of bladed disks with uncertain geometry

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ABSTRACT

Bladed disks are fundamental components of turbomachinery employed for propulsion and energy production. They are composed by a large number of blades that are assembled forming a cyclic symmetric structure. Their modal properties are strongly conditioned by such a symmetry, which is characterized by eigenvalues grouped in pairs and modes with a traveling-wave nature [1]. This modal structure has deep consequences on the forced and self-excited response.

In practice, the shape and size of the blades slightly differ from their design geometry due to manufacturing tolerances. These differences brake the mentioned symmetry conditions producing a phenomenon called mistuning. It is well known that even a small mistuning can produces large effects amplifying the forced response and reducing the self-excited response [1].

This paper proposes a method to assess the probabilistic response of a bladed disk composed of blades having an uncertain geometry. The blade geometry is modeled through an empirical probabilistic model estimated from a set of blades measured by a structured-light scanner. Then, the effect of this uncertainty is introduced into the Finite Element (FE) model of the blades through a mesh morphing procedure. Finally, the Reduced Order Model (ROM) of the disk is obtained by assembling the uncertain blades using the Craig-Bampton method [2]. The result is a ROM whose properties depend on the random coefficients used to parametrize the blades' geometry and, therefore, should be regarded as a stochastic model.

The generation of samples of the disk ROM is time consuming, therefore they are approximated using a perturbative solution of the eigenvalue problem [3].

The method is applied to the dynamic analysis of the frontal stage of a large axial compressor during a resonance crossing. The effects of the geometric uncertainties expressed in terms of maximum transient amplification are obtained through a Monte Carlo simulation.

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Geometric Structure of Gaussian Coefficient Space in Spectral Models of Random Fields

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ABSTRACT

We present a unified spectral framework for generating one- and multi-dimensional random fields based on the Karhunen–Loève expansion with explicitly constructed eigenfunctions and analytically computable eigenvalues. Although our primary interest lies in non-periodic fields with monotonically decaying autocorrelation, we demonstrate that such fields can be efficiently synthesized as periodic over an extended computational domain, with the desired non-periodic field obtained by extraction of a subregion unaffected by periodicity. This approach enables the use of trigonometric eigenfunctions (sine and cosine), providing full analytical control over the spectrum and significantly simplifying implementation.

A key contribution of this work is a systematic mapping between constraints imposed on the random field (such as fixed values, inequality conditions, or derivative requirements at specific points) and their corresponding representations in the Gaussian coefficient space of the KL expansion. Because the KL coefficients are uncorrelated standard Gaussian variables, the constraint translation becomes geometrically interpretable and computationally tractable. This allows us to impose complex deterministic requirements on the field while retaining the full probabilistic structure of the underlying Gaussian measure.

We illustrate how these insights lead to practical and efficient algorithms for evaluating tail probabilities, particularly exceedance probabilities of extrema of random fields. By combining spectral synthesis, constraint mapping, and Gaussian geometry, we reveal several structural relationships that are not commonly explicit in standard treatments of random field theory but have strong practical implications for uncertainty quantification.

The proposed methodology thus bridges mathematically rigorous concepts with computationally effective procedures, yielding a versatile toolset for the simulation and analysis of random fields in engineering and applied sciences.

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The temperature influence on the non-linear stochastic vibrations of the guy lines in the three-cable guyed tower under seismic excitations.

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ABSTRACT

The earthquakes or sudden ground shaking, that can be observed in mining areas induced by explosions or ground collapse, lead to the seismic waves that are transmitted through the subsoil. That causes the excitation of the structures even if the distance from the source ground motion is significant [1]. Especially sensitive to this type of load are guyed towers as they experience not only rigid body motions but also bending deformations due to ground vibrations in the resonance area. To stabilize these slender structures of significant heights, three guy lines are most often used. However, an earthquake causes each cable to be excited by two sources: the movements of the support where it is anchored in the foundation and the horizontal displacements of the tower, which experiences bending deformations. Additionally, the three cables arranged spatially around the structure mutually interact. In order to ensure proper operation of the system, a significant pre-tension forces are introduced into the cables, which, due to the use of steel ropes, are sensitive to temperature changes that lead to the guy elements length variations. In the presented approach the coupled vibrations of the guy tower and three-guy lines assumed as a cables with the small-sags are considered [2]. The earthquake ground motion is modelled by a filtered Gaussian white noise process [3]. The set of nonlinear differential equations of motion is obtained by using the Ritz method and Lagrange's equation. Next the equivalent linearization technique is used to obtain the approximate mean values, variances and cross-covariances of particular random state variables [4]. The vibrations of the system due to various temperature changes will be investigated to determine the effect of changing thermal conditions on the dynamic response of the guy lines. The advantage and disadvantage of presented approach will be discussed in comparison to the Monte Carlo simulation.

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Physics-Informed Approach to Extreme Wave Loads on a Ship

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ABSTRACT

Wave loads that may be experienced during a ship's service life is one of the most important design parameters as it determines the weight of the ship structure and the payloads that the ship can carry. The focus of the talk will be on vertical bending moment (VBM) and its extremes, which are characterized by significant nonlinearity (with regard to wave input) and rarity, rendering direct numerical simulation impractical. The approach employs several reduced-order models (ROM), capable of producing a semi-analytical probability density function (PDF), going far enough into the tail, so that the lifetime/extreme loads can be estimated. For practical applications, the PDF is to be tuned with a short/practical size numerical simulation, so the ROMs only provide the shape of the distribution.

The ROM for wave-induced VBM utilizes a second-order Taylor approximation of transverse sections of ship's hull, leading to a quadratic polynomial for VBM [1]. The ROM also can provide the PDF of peaks of VBM, which are used in practical applications [2]. Another major nonlinear factor is the effect of deck submergence, when the buoyancy contribution to VBM stops increasing. The deck effect significantly influences the tail of VBM but can be accounted for with a correction [3].

The other aspect of wave loads is related to an impact occurring when the bow part of the hull reenters the water after emerging (slamming). Besides local structural loads, slamming leads to vibration of the entire ship as an elastic beam. To model the impact-induced contribution, upcrossing theory is applied to determine slamming instants together with a wedge approximation to estimate forcing and magnitude of the elastic beam vibration [4]. Handling peaks of wave- and impact-induced VBM is not trivial as these peaks do not occur at the same time [5].

The talk will review the computational approach and provide some comparison with large-volume numerical simulation data.

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Stochastic Analysis of Bond–Slip Wear Behavior at Steel–Concrete Interface under Cyclic Pull-out Loads

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ABSTRACT

Bond–slip behavior is a key factor influencing the reliability of reinforced concrete and steel–concrete composite structures. Since structural loads are inherently random and non-monotonic, the bond–slip response at the steel–concrete interface is affected by abrasive wear, which leads to a gradual reduction in bond strength. In this study, the wear effect is incorporated into the cohesive zone model (CZM) based on Alfano’s [1,2] cohesive law framework, explicitly considering the influence of loading paths and surface unevenness at the interface. The proposed model can accurately capture the degradation of traction force and stiffness with increasing slip, providing a refined mechanical description of interface deterioration.

The mechanical characteristics of the traction–separation relationship derived from this model are analyzed to elucidate the underlying mechanisms of bonding, slipping, damage, and wear. A finite element model of a cyclic pull-out test on a plain steel bar [3] is then established to validate the proposed formulation. Furthermore, the spatial variability of wear-related parameters—such as the initial surface roughness and wear rate—is modeled as one-dimensional random fields. The uncertainties associated with the nominal coefficient of friction and the wear-rate parameter are assumed to follow normal distributions and are represented using the stochastic harmonic function (SHF) method [4].

Numerical simulations demonstrate that the incorporation of wear significantly influences the evolution and variability of bond stress, particularly under cyclic loading. The stochastic analyses reveal that microscale surface irregularities and progressive wear lead to notable dispersion in the bond–slip response. The proposed stochastic wear–bond model provides a more realistic framework for evaluating the durability and reliability of steel–concrete interfaces under random and repeated loading histories.

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Random-Fields Updating and Inversion of Structural Model Parameters with Spatiotemporal Grid Data

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ABSTRACT

Addressing the challenge of parametric inversion for building structural models that account for spatial variability in the context of spatiotemporal grid data, this research proposes an efficient method for the Bayesian updating of random field parameters' stochastic properties. Through probability space transformation, the method first maps the correlated observational data into an independent standard normal space. An approximate likelihood function is then constructed based on the known probability distributions of statistics within this space, effectively solving the computational difficulty of directly computing high-dimensional joint probabilities. The posterior distribution is then obtained using Bayesian updating with structural reliability methods and subset simulation methods.

The method's effectiveness is first validated through a case study on steel structure corrosion deterioration. With a proper sampling scheme in terms of the step size, the method can accurately obtain the posterior distributions for the stochastic properties of the corrosion depth random field, while significantly reducing the associated uncertainties of the distribution models. Compared to the true values, the means of the posterior distributions yield relative errors of less than 2% for the mean value and standard deviation of the random field, and less than 10% for the correlation length.

Furthermore, the method is extended to address the problem of parametric inversion with spatiotemporal structural response data. By utilizing the corrosion depth data at various ages, the approach successfully updates the standard deviation and correlation length for the random field of corrosion rate. This research provides an effective framework for integrating spatiotemporal grid data to update structural models, holding promise for the data-driven structural lifecycle management.

Keywords: Random field; structural parametric inversion; structural reliability; Bayesian updating; spatiotemporal grid data

Stochastic Emulation of Multi-Output Responses and Its Application to Seismic Risk Assessment

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ABSTRACT

Surrogate modeling has emerged as a powerful tool for accelerating seismic risk assessment, providing computationally efficient approximations of complex structural dynamic behavior. A challenge, however, is the presence of aleatoric uncertainty in surrogate predictions, which arises when embedding high-dimensional stochasticity of earthquake ground motions into the low-dimensional input of the surrogate. The resulting indeterminacy of structural response prompts the application of stochastic emulation, which can provide the entire probability distributions of model responses as predictions. However, challenges exist in applying stochastic emulation methods readily available in literature: (i) one often needs to rely on existing databases of historic ground motions when selecting training points, making it impossible to obtain replicated samples and, at the same time, restricting the number of available training data points; and (ii) different structural outputs tend to exhibit significant correlations, that creates non-negligible influence to downstream analysis, requiring a new methodology to faithfully predict the joint statistics of multi-output predictions. In response to these gaps, we propose a Gaussian process (GP)-based multi-output stochastic emulation method capable of predicting the joint probability distribution of outputs, while not relying on sample replications [1]. This is achieved by introducing auxiliary surrogate models that predict the second-order statistics (i.e., covariance matrix) of the outputs as a function of input variables, leveraging observations of sample deviation statistics. The proposed multi-output prediction framework can straightforwardly accommodate Gaussian or non-Gaussian marginal predictions obtained using existing stochastic emulation methods without requiring extra simulations. The effectiveness of the proposed method is demonstrated within the context of structural seismic risk assessment.

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Reliability assessment of existing RC structures incorporating concrete strength and service loads considerations

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ABSTRACT

Reliability analyses based on statistical data for loads and material strengths primarily pertain to new buildings. For the reliability assessment of existing buildings, however, it is necessary to account for variations in material strength, and the probabilistic distribution of the loads throughout their service lives. Thus, a probabilistic model for the concrete strength in existing buildings is established, and subsequently updated by a Bayesian approach using additional site testing data as they become available. Further, a probabilistic analysis of sustained and temporary live loads in existing buildings is performed, and their corresponding statistical parameters are determined. The standard live load values for varying target service years are then calculated at a specific percentile. Furthermore, the resistance capacity of the existing concrete members is calculated. Finally, a time-varying reliability index is obtained, which is subsequently used to determine the safety ratings for the existing buildings. This approach is applied for the reliability assessment of beam and column specimens with various service years. The results show that the approach can be effectively used to determine the reliability and safety ratings of existing concrete structures at various service ages. These findings can provide a foundation for future reliability evaluations and safety appraisals of existing structures.

Active Inference-based Structural Integration Management

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ABSTRACT

Structural Integration Management (SIM) involves sequential decision-making under uncertainty, partial observability, and progressively evolving deterioration. While Partially Observable Markov Decision Processes (POMDPs) and deep reinforcement learning (DRL) have shown promise for maintenance planning, both approaches face challenges when state uncertainty is high, sensor information is limited, or model-based interpretability is required.

In this work, we propose an Active Inference-based decision-making framework for SIM, which unifies state estimation and maintenance planning within a single Bayesian inference process [1,2]. The method leverages expected free energy to jointly balance risk-minimizing behavior and information-seeking actions, naturally handling continuous deterioration states and noisy structural responses.

We integrate the framework with a physics-based deterioration model and will apply it to two benchmark structural systems: a deteriorating Euler–Bernoulli beam and a widely studied bridge maintenance scenario [3]. Preliminary results indicate that the approach produces sensible maintenance policies and robust state estimation without requiring explicit value-function optimization. Ongoing experiments compare Active Inference with optimal POMDP policies and DRL baselines in terms of cost efficiency, uncertainty reduction, and structural safety.

The study highlights the potential of Active Inference as a principled and unified paradigm for SIM decision-making.

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Constitutive Modeling and Reliability Evaluation of Interfacial Slip Damage in Three-Dimensional Stacked Micro/Nano-Scale Through-Silicon Vias

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Abstract:

Micro/nano-interconnect structures are critical components in three-dimensional high-density packaging, yet their reliability is critically constrained by the copper pumping effect induced by the thermal mismatch between copper and silicon. This study investigates interfacial failure at the copper/silicon interface in through-silicon via (TSV) composite structures. Based on continuum damage mechanics, a constitutive relation for interfacial slip is established using energy dissipation as a damage indicator. The reliability under thermoelectrical coupling is evaluated, and the model is further applied to analyze thermal residual stress and strain in common liner materials. A Bayesian support vector regression (BSVR) model is integrated into a cross-entropy-based framework for failure probability assessment. Within this framework, importance sampling is employed to optimize BSVR hyperparameter selection, while BSVR serves as a surrogate to reduce computational cost in constitutive simulations. To address the analytical intractability of the marginal likelihood integral in BSVR, a simulation-based sampling method is proposed as an alternative to Laplace approximation. The proposed computational framework effectively combines the advantages of cross-entropy methods and BSVR surrogate modeling in handling high-dimensional problems with small failure probabilities, thereby mitigating efficiency degradation caused by data sparsity and complex failure domains.

Keywords: Constitutive, Reliability, Cross entropy, BSVR, TSV

A Unified Framework for Probabilistic Inverse Problems in Physical Stochastic Systems Based on Probability Preservation and Convex Optimization

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ABSTRACT

This paper addresses the probabilistic inverse problem for physical stochastic systems, aiming to infer the joint probability density function (PDF) of unobservable random sources from observed system responses. A unified convex optimization framework is proposed, grounded in the principle of preservation of probability, which requires minimal prior assumptions and no specification of distribution types. The core method partitions the random source space into Voronoi cells, transforming the identification task into a constrained quadratic programming problem to determine the probability measure assigned to each cell. Two complementary approaches are developed. The first method employs the transient PDF of system responses, leveraging the Probability Density Evolution Method combined with Kriging surrogate models for efficient forward computation [1]. An error analysis based on singular value decomposition (SVD) reveals that problem solvability hinges on the injectivity of the system mapping. For cases where this injectivity holds, ensuring the problem is well-posed, the method reliably recovers complex and irregular joint PDF of random sources. The second method, termed the Diffusion Manifold Method [2], operates directly on raw, potentially noisy response data. It projects the data onto an intrinsic, low-dimensional Riemannian manifold embedded in the high-dimensional response space, explicitly handling measurement noise and avoiding the density estimation singularities common in high-dimensional spaces. This manifold-based formulation extends the probability preservation principle to Riemannian settings. When the inverse problem is ill-posed due to a non-injective system mapping, a two-step optimization procedure is applied: first, the identifiable eigenmodes of the source PDF are recovered via SVD-based truncation; second, the unidentifiable modes are regularized by maximizing a quality metric, such as entropy, to obtain a physically plausible solution. Numerical examples involving linear and nonlinear structures with dependent random parameters demonstrate that both methods accurately reconstruct complex joint distributions and marginal PDFs, exhibit robustness against noise, and effectively manage ill-posed scenarios, all without relying on strong prior distributions.

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