Special Section on Uncertainty Quantification and Management in Nonlinear Dynamical Systems in Aerospace and Mechanical Engineering

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Guest Editorial

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With the increasing integration of lightweight structures, multibody systems, and multidomain coupled systems into aerospace systems, the study of nonlinearities on their dynamical response is becoming an important area of research. These nonlinearities can arise from various sources, such as large structural deformation, multiple joints within complex mechanisms, as well as multiphysical couplings such as fluid–structural and electrical–mechanical interactions. The effects of these nonlinearities on dynamics and control can be very significant, such as changing flutter boundary in tiltrotor systems and shifting the aerodynamic center of certain wings affecting control. However, the influence of these nonlinearities is often neglected in the analysis of engineering structures due to added computational complexity, nonlinearities characterization, and high computational cost, leading to significant uncertainties in the durability and reliability of critical aerospace system designs. In addition, the dynamics of spacecraft motion also have strong nonlinearity due to the perturbations from the nonsphericity of the earth, the atmospheric drag, solar radiation pressure, and the gravitation of the sun and moon. These nonlinearities could make the motion of the spacecraft very sensitive to the initial state and unmodeled forces.

However, the nonlinear forces usually could not be modeled accurately and have uncertainties that could be magnified during the often nonsmooth nonlinear phenomena. It is therefore important to effectively characterize these uncertainties associated with nonlinear dynamical systems and quantify their influence on dynamical performance for improved design and analysis. It can help effectively mitigate the severe lack of knowledge in the identification of these nonlinear systems in the presence of noisy measurements and their high sensitivity to dynamic behaviors. The classical uncertainty quantification methods for linear systems may be limited to large-scale nonlinear systems since these require significant computational costs for estimating the uncertain parameters and the statistics of the response. The strong nonlinearities can also drastically reduce the accuracy of some linear UQ methods such as surrogate modeling technical and propagation methods. It requires further development of the current uncertainty quantification techniques to enhance the trustworthiness of computational simulations in complex nonlinear structural dynamics to address the challenges in particularly in multiscale and multiphysics uncertainties, efficient sampling, and propagation methods. Accurately quantifying both aleatory and epistemic uncertainties is especially important for robust space mission design, which requires accurate quantification and propagation. The focus of this Special Section is to advance the UQ techniques for complex nonlinear dynamical systems in aerospace and mechanical engineering. Five papers were collected to address some of the above challenges.

In a paper by Ma et al., the nonlinear dynamical challenges inherent in spline-shafting systems caused by tooth surface internal friction were examined. The system's uncertainty is compounded by factors such as design tolerances, manufacturing errors, and time-varying influences. The authors utilized nonintrusive generalized polynomial chaos expansion and Sobol analysis to propagate uncertainty and conduct a global sensitivity analysis, highlighting the amplitude dispersion and randomness of friction-induced self-excited vibrations of the spline-shaft systems and its key influencing parameters.

Mahajan and Cicirello developed a new method to determine the governing equation of motion and accurately identify the unknown Coulomb friction force of a mass-spring-dashpot system due to uncertainty related to the friction force on the structural interface. They used an extended SINDy algorithm to investigate a single-degree-of-freedom system both numerically and experimentally. The proposed approach provides a better estimate of the uncertain system parameters, including stiffness, viscous damping, and magnitude of friction force, for various signal-to-noise ratios when compared to SINDy.

In a study by Chen and Hao, the impact of assembly uncertainties on shock propagation through a bolted lap joint was analyzed. The study took into account several factors that could affect the impact response of the joint, including preload, friction coefficient, slip between the connected parts, bolt-to-hole offset, and nonparallelism of the contact surfaces. The results showed that the interface dislocation slip, eccentricity, and nonparallelism are important factors that impact the response of the bolted joint to impact loading.

When devising space missions for reusable spacecraft, ensuring structural reliability in the face of numerous uncertainties is paramount. To address this, Gao et al. have developed an advanced dynamic reliability prognosis method, leveraging a digital twin framework. This method involves the use of a dynamic Bayesian network to accurately predict the evolution of structural reliability, enabling maintenance points to be efficiently scheduled. By utilizing this approach, condition-based maintenance can be facilitated, ensuring timely and effective safety measures are taken, and ultimately reducing maintenance costs. An illustrative example of this method in action is its ability to predict single-point crack growth under multiple loads.

Zhao and their colleagues conducted a study that investigated a technique for assessing fatigue reliability in welded structures of railway freight cars. Using digital twin-based methods, they examined both static and dynamic fatigue evaluation, with a focus on the main S–N curve and its expansion methods. Their findings suggest that virtual testing can effectively overcome the limitations of traditional quasi-static analysis. Additionally, the combination of both methods enhances the evaluation of fatigue reliability in the carbody.

Finally, the guest editors wish to extend their heartfelt thanks to the authors and reviewers who have played a crucial role in the development of this Special Section. We would like to express our sincere appreciation to Professor Michael Beer, Editor-in-Chief of the ASCE-ASME *Journal of Risk and Uncertainty in Engineering Systems, Part B*, and to Mr. Torsten Ilsemann for the incredible support during the organization of this Special Section. Jie Yuan and Enora Denimal also acknowledge the funding support from the Royal Society of Edinburgh Saltire Facilitation Workshop Award (Ref: 1865).

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