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An efficient approach for dynamic global sensitivity analysis of stochastic train-track-bridge system

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ABSTRACT

The parameters in time-varying train-track-bridge system (TTBS) are inevitably subjected to uncertainty, leading to variability in its dynamic responses. This work provides an investigation as to how uncertainty in the parameters influences the dynamic responses of time-varying TTBS, which refers to dynamic sensitivity analysis in the context of stochastic dynamic system. A powerful global sensitivity analysis (GSA), which maintains numerous attractive advantages over local sensitivity analysis (LSA), is proposed to measure the impact of uncertain system parameters on dynamic responses in a quantitative manner, thereby ranking them in order of importance. Furthermore, an analytical Gaussian process model (GPM)-based approach is developed to greatly alleviate the computational cost involved in dynamic GSA of time-varying TTBS. The proposed analytical GPM-based approach possesses the capacity to calculate the sensitivity indices of individual parameters as well as parameter clusters. The effectiveness of the proposed GPM-based dynamic GSA methodology is evaluated by comparison with the brute-force Monte Carlo simulation (MCS) on a mass-spring-damper system. The perfect agreement between the analytical GPM-obtained and MCS-derived time-varying sensitivity indices verifies the feasibility and reliability of the proposed methodology. An illustrative example is further provided to fully demonstrate the application of the developed GPM-based approach to dynamic GSA of time-varying TTBS. The dynamic GSA results enable us to gain insight into the temporal evolution of the global influences of individual parameters and groups of parameters on dynamic responses of TTBS.

1. Introduction

The vibrations of the train-track-bridge system (TTBS) have always been capturing substantial attention of engineering community. The excessive vibrations will undermine the operational safety of both train and bridge. More specially, vibration-induced detrimental effects are the cause of out-of-round defect of wheels (such as wheel-flat and polygonization) and even catastrophic derailment [1,2] and fatigue damage [3,4]. Apparently, a better understanding of the dynamic behavior of TTBS is essential to the effective mitigation of such vibration-induced threats. On the other hand, characterization of dynamic behavior of TTBS relies on the use of its representative mathematical model that plays an important role in studying, simulating, and predicting complex real-world phenomena. The mathematical model usually involves a great number of

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system parameters including physical and geometric properties such as elastic modulus, stiffness, length, cross-section, and loading characteristics.

In the previous studies, for the most part, TTBS has been assumed to have well-defined properties, that is, the system parameters are considered to be constant without variation. As a consequence, the dynamic analysis of TTBS was carried out in a deterministic fashion. The past decades have seen considerable efforts devoted to the research on deterministic dynamic analysis of TTBS (see e.g., Refs. [5–10] herein). However, treating TTBS having constant parameters would be improper since uncertainty inevitably exists in the system parameters. The parameter uncertainty can arise from a variety of sources, including but not limited to manufacturing-induced geometric tolerances, inherent material variability, alterable mass and stiffness properties, and aggressive environmental agents. In recent years, research attention has increasingly been drawn to stochastic dynamic analysis of TTBS with consideration of uncertainty existent in the system parameters. Although stochastic dynamic analysis is currently an active research topic, there has been little work done in this direction. The limited studies on stochastic dynamic analysis have been restricted to evaluating the uncertainty in dynamic responses of TTBS propagated from system parameter uncertainty. The uncertain dynamic responses are usually quantified in terms of probability distribution, statistical moments, or upper and lower bounds [11–18].

As opposed to the uncertainty quantification for dynamic responses, sensitivity analysis refers to the investigation on how the uncertainty in the model responses can be apportioned to different sources of uncertainty in model parameters [19]. More specifically, the task of sensitivity analysis is to determine the contributions of either individual parameters or groups of parameters to the total uncertainty of model responses. Uncertainty quantification and sensitivity analysis are two ingredients critical to the modeling and risk assessment of physical systems in the presence of uncertainty. Sensitivity analysis of TTBS, however, has seldom been explored in the context of stochastic dynamics. The sensitivity analysis offers a quantitative approach to investigating the influence of system parameters, either in isolation or in combination, on dynamic responses of TTBS, which enables modelers to have a better insight into the dynamic behavior of TTBS and to reveal the fundamental mechanism of interplay among various system parts (train, track, and bridge). Through the execution of sensitivity analysis, one is able to distinguish between the influential and non-influential system parameters and rank them in order of importance [20]. Based on the results of sensitivity analysis, attentions can be focused on dealing with highly sensitive parameters that are the major contributors to the variation in dynamic responses, while keeping the non-sensitive parameters at their nominal values. Fixing the unimportant parameters lowers the dimensionality of stochastic dynamic analysis problem of TTBS, thus leading to a considerable reduction in computational expense and allowing for focusing our attention on the dominant system parameters. In this regard, sensitivity analysis would provide useful guidance on how to adjust certain system parameters so as to eschew vibration-induced threats. This study concentrates on the characterization of how the uncertainty in system parameters affects the dynamic responses of TTBS by means of sensitivity analysis.

Sensitivity analysis techniques can be divided into local and global versions with or without consideration of the whole variation of model inputs [20]. Local sensitivity analysis (LSA) measures the impact of variation in model inputs within the vicinity of their nominal values on model outputs, which are usually evaluated by partial derivatives or finite difference approximations. In contrast, global sensitivity analysis (GSA) assesses the sensitivity of model output to the model inputs over their entire domains, which is characterized by the ratios of a partial variance contributed by each model input to the total variance. LSA will produce unreliable or even inaccurate results when the model under investigation is neither linear nor additive [21,22], whereas GSA does not impose any assumption of linearity or monotonicity on the model and is also capable of measuring interaction effects among inputs, the effects of the entire input variation, and the influences of subsets of inputs [19]. In recognition of its appealing strengths, GSA is amenable to perform sensitivity analysis of time-varying TTBS. The applications of GSA in civil engineering can be found in [23–26].

Although GSA is effective for large-scale complex systems whose input-output relationships are often highly nonlinear, the attractive advantages of GSA come with the drawback of high computational expense. More specifically, calculations of sensitivity indices require the evaluation of high-dimensional integrals associated with the quantities of partial and total variances, which needs a large number of model runs. In applying a Monte Carlo simulation (MCS) procedure with different sampling techniques, the total number of model realizations required for computing the sensitivity indices is either $N(2K+2)$ or $N(K+2)$, in which N is the sample size and K is the parameter dimensionality [27]. As a result, the high computational cost involved in GSA restricts the usage of brute-force MCS scheme that is performed directly based on the expensive-to-run simulation models. What is worse, the time-varying nature of TTBS and high computational expense limit the use of the traditional MCS implementation in the GSA of TTBS. To overcome the shortcoming of high computational cost, the most promising approach tends to adopt an easy-to-use and fast-to-run surrogate model (also known as metamodel) to replace the computationally demanding model solver. In this study, Gaussian process model (GPM) is preferred for this attainment because of its attractive features of high modeling flexibility and great expressive power in conjunction with its analytical capability in GSA, which are not enjoyed by other general-purpose parametric modeling tools [28–31].

In view of the related work outlined above, the main contributions of this paper are twofold. The first is to investigate the sensitivity of probabilistic dynamic responses of TTBS to system parameters in a global fashion by GSA. To the best of the authors' knowledge, the work on GSA in the context of stochastic dynamic analysis of TTBS does not appear to have been reported to date, and the present study aims to make up for this gap. The second is to extend the GPM-based approach [31], which enables the calculation of sensitivity indices of individual parameters and parameter clusters, to cope with dynamic GSA of time-varying TTBS. The adoption of the GPM-based approach is to alleviate the high computational expense involved in the GSA of TTBS while maintaining high computational accuracy. The rest of this paper is organized as follows. In