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Original Research Paper

Finite element model validation of bridge based on structural health monitoring—Part I: Response surface-based finite element model updating

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ABSTRACT

In the engineering practice, merging statistical analysis into structural evaluation and assessment is a tendency in the future. As a combination of mathematical and statistical techniques, response surface (RS) methodology has been successfully applied to design optimization, response prediction and model validation. With the aid of RS methodology, these two serial papers present a finite element (FE) model updating and validation method for bridge structures based on structural health monitoring. The key issues to implement such a model updating are discussed in this paper, such as design of experiment, parameter screening, construction of high-order polynomial response surface model, optimization methods and precision inspection of RS model. The proposed procedure is illustrated by a prestressed concrete continuous rigid-frame bridge monitored under operational conditions. The results from the updated FE model have been compared with those obtained from online health monitoring system. The real application to a full-size bridge has demonstrated that the FE model updating process is efficient and convenient. The updated FE model can relatively reflect the actual condition of Xiabaishi Bridge in the design space of parameters and can be further applied to FE model validation and damage identification.

1. Introduction

According to the definition by Thacker et al. (2004), model verification and validation (V&V) is an enabling methodology for the development of computational models that can be used to make engineering predictions with quantified confidence. Verification is the process of determining that a model implementation accurately represents the developer's conceptual description of the model and its solution. Validation is the process of determining the degree to which a model is an accurate representation of the real world from

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the perspective of the intended uses of the model. Both verification and validation are processes that accumulate evidence of a model's correctness or accuracy for a specific scenario.

Model V&V procedures are currently needed by government and industry to reduce time, cost, and risk associated with full-scale testing of products, materials, and weapon systems. For example, AIAA and ASME have issued guidelines for the V&V of computational fluid dynamics and solid mechanics respectively (AIAA, 1998; ASME, 2006). Some researchers from Los Alamos National Laboratory (LANL) (Thacker et al., 2004), Sandia National Laboratories (SNL) (Oberkampf et al., 2003) and Lawrence Livermore National Laboratory (LLNL) (Logan and Nitta, 2002) have built the general philosophy, definitions, concepts, and processes for conducting a successful V&V program. The expected outcome of the model V&V process is the quantified level of agreement between experimental data and model prediction, as well as the predictive accuracy of the model. This is consistent with the requirements of structural health monitoring (SHM) in civil engineering.

The damage identification and damage prognosis are the theme issues on structural health monitoring (Farrar and Lieven, 2007; Farrar and Worden, 2007). In the past 20 years, there is a large volume of literatures relating to the dynamic- and static-based methods for damage identification and prognosis using the model updating strategy (Farrar et al., 2007; Friswell and Mottershead, 1995; Weber and Paultre, 2009; Xia and Brownjohn, 2004). In general, there are two kinds of model updating methods. Sensitivity-based FE model updating methods rely on the parametric model of a structure and the minimization of certain objective function based on the errors between measured data and prediction from the model. This method is time-consuming and has limited freedom domain. An alternative meta-model, which is fast-running and less parameter involved, can replace the sensitivity-based model updating, and response surface is one of the commonly used meta-models (Zong and Ren, 2012).

Response surface methodology (RSM) was firstly proposed by Box and Wilson (1951). The basic idea of RSM is to build a model relating inputs and outputs using a small number of data sets even for large-scale structures by providing a way of rigorously choosing a few points in the design space to efficiently represent all possible points. In this sense, RSM has been applied in the fields of experimental design and analysis (Guo et al., 2006; Rijpkema et al., 2001), optimization (Jones, 2001) and structural safety and reliability analysis (Bucher and Bourgund, 1990; Cheng et al., 2007), etc. Box and Draper (2002), Myers and Montgomery (2002) summarized the fundamentals of this methodology, as well as the relevant research, applications and developments.

Related to the model updating problem, RSM might reconstruct the relationship of the design and objective variables in the design space of parameters. The optimization iteration can be conducted in the reconstructed RSM, so that errors between FE model and test model are minimized. In recent years, some researches have been conducted into the application of RSM for model updating. Among them, Marwala (2004), Guo and Zhang (2004) first introduced the use of response surface method to structural model updating. Marwala (2004) used the multilayer perception (MLP) to approximate the implicit function between the response and parameters. Guo and Zhang (2004) constructed two high-order polynomial RS models to update an H-shaped structure using the central composite design (CCD) and the D-optimal design. In their study, stiffness and frequencies were chosen as the input and response features, respectively. They found that the RSM-based method was much more cost-efficient than the traditional sensitivity-based FE model updating considering likewise accurate predictions. Ren and Chen (2010) used the factorial design (FD) to quantitatively identify the relative significance of each updating parameter with respect to the responses, and the CCD was also employed to construct the RS models for updating a tested full-scale box-girder bridge in structural dynamics. With the response surface to replace the original FE model, the model updating process becomes efficient and converges quickly compared with the traditional sensitivity-based model updating method.

Deng and Cai (2010) presented a new practical and user-friendly FE model updating method using the response surface method and genetic algorithm. Natural frequencies from modal analysis and strains/deflections from static tests are used as responses in the objective function. CCD was adopted to conduct the experimental design. Numerical examples of a simply supported beam and an existing bridge were used to demonstrate the proposed method. Results show that this method works well and achieves reasonable physical explanations for the updated parameters.

Ren et al. (2011) proposed a response surface based FE model updating method using measured static responses of structures. The proposed method is verified against a numerical beam and an experimental full-scale continuous box-girder bridge. It is demonstrated that the proposed response surface-based FE model updating in structural statics has the advantages of easy implementation, high cost-efficiency, and adequate updating accuracy.

Furthermore, some work has been performed to extend the concepts of RSM in damage identification problems. Cundy (2003) has explored the feasibility of applying RSM to structural damage identification (SDI) by using FD and CCD to construct response surface models for identifying the damage existing in a simulated mass–spring–damper system and a tested cantilever beam. In addition, Fang and Perera (2011) presented a damage identification method achieved by response surface based model updating. In this study, firstly D-optimal designs were used to establish response surface models for screening out non-significant updating parameters, and then first-order response surface models were constructed to substitute for FE models in predicting the dynamic responses of an intact or damaged physical system. Three case studies of a numerical beam, a tested reinforced concrete frame and a tested full-scale bridge have been used to verify the proposed method. It has been observed that the proposed method gives enough accuracy in damage prediction of not only the numerical but also the real-world structures with single and multiple damage scenarios, and the first-order response surface models based on the D-optimal criterion are adequate for such damage identification purposes.