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Damage identification by response surface based model updating using D-optimal design

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ABSTRACT

Statistical tools, as well as mathematical ones, have been widely adopted and their performance has been shown in different engineering problems where randomicity usually exists. In the realm of engineering, merging statistical analysis into structural evaluation and assessment will be a tendency in the future. As a combination of mathematical and statistical techniques, response surface methodology has been successfully applied to design optimization, response prediction and model validation. This methodology provides explicit functions to represent the relationships between the inputs and outputs of a physical system, which is also a desirable advantage in damage identification. However, so far little research has been carried out in applying the response surface methodology to structural damage identification. This paper presents a damage identification method achieved by response surface based model updating using D-optimal designs. Compared with some common designs constructing response surfaces, D-optimal designs generally require a minimum number of numerical samples and this merit is quite desirable when analysts cannot obtain enough samples. In this study, firstly D-optimal designs are used to establish response surface models for screening out non-significant updating parameters and then first-order response surface models are constructed to substitute for finite element 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. Physical properties such as Young's modulus and section inertias were chosen as the input features and modal frequency was the only response feature. 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.

1. Introduction

There has been a large volume of research devoted to vibration-based methods for damage identification of engineering structures during recent years [1,2]. Besides some approaches by establishing precise finite element (FE) dynamic models for direct damage detection [3,4], damage evaluation techniques using measured modal data are often based on the model

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updating strategy. 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 the measured data and the predictions from the model [5–9]. These methods have been widely employed since they allow a wide choice of physically meaningful parameters and a certain degree of control over the optimization process. However, when these traditional methods are applied to large-scale redundant structures with many unknowns, it is not practical to identify all of the structural parameters at the same time since ill-conditioning and non-uniqueness in the solutions of inverse problems appear as inevitable difficulties. Furthermore, considerable computation expenses would be necessary.

Recently, artificial intelligence techniques such as neural networks (NNs) have been increasingly utilized owing to their excellent pattern recognition capability since the process of model-based damage identification using modal data eventually reduces to a pattern recognition problem. Many researchers have studied NNs approaches for damage estimation of structures due to the versatility in dealing with various types of inputs and outputs and the quick computational capability [10,11]. However, the difficulty of obtaining a reliable NN increases with the complexity of the problem since for this kind of problems if there are numerous input parameters, the required number of training samples would exponentially increase resulting in considerable computational efforts.

In this sense, response surface methodology (RSM) might constitute a good alternative for solving model updating problems. By using RSM the relationships between several explanatory variables and one or more response variables are explored by using a set of designed experiments with the aid of the design of experiment (DOE) technique [12]. The major benefit of using RSM is the significant reduction in the number of numerical/physical experiments needed to explore the design space. Introduced originally by Box and Wilson [13] for chemical processes, RSM is able 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. Since then, RSM has gone through several stages of development that were aimed at making it more applicable to wider experimental situations under less stringent assumptions covering many useful applications in a variety of fields. See the texts by Box and Draper [14] and Myers and Montgomery [15] for the fundamentals of this methodology and the relevant research.

Related to the problem concerning our work, some research has been conducted into the application of RSM to model updating [16–18]. Guo and Zhang [16] constructed two high-order polynomial RS models to update an H-shaped structure using the central composite design (CCD) and the D-optimal design. Stiffness and frequencies were chosen as the input and response features, respectively. They found that compared with the traditional sensitivity-based FE model updating methods, the RSM-based method was much more cost-efficient accompanying likewise accurate predictions. Uniform designs were employed by Deng et al. [17] to construct RS models for updating a numerical two-span continuous beam using the static deflections at the middle of spans as the responses. After compared to traditional sensitivity-based FE model updating methods, the same conclusions as those obtained in [16] were drawn. Similar observations are also presented in [18] where a tested full-scale box–girder bridge was updated using the factorial design (FD) and the CCD with the modal frequencies being the responses. These applications, although not many, have served to show the potential of RSM in the model updating field. However, so far very little work has been performed to extend the concepts of RSM in damage identification problems. To the knowledge of the authors, only the work developed by Cundy [19] has explored the feasibility of applying RSM to structural damage identification (SDI) by using the FD and the CCD to construct RS models for identifying the damage existing in a simulated mass–spring–damper system and a tested cantilever beam. This motivated the authors to further explore the potential of RSM for identifying damage locations and severities in more complex structures [20]. To this end, a systematic procedure has been proposed using the 2^k FD and the CCD for parameter screening and SDI, respectively, which was successfully verified against two experimental structures of a reinforced concrete (RC) frame and a full-scale bridge [20]. One point should be clarified that RSM-based model updating methods for SDI do not focus on giving likewise accurate predictions as do the traditional updating methods where refined optimization algorithms and considerable computation efforts are generally required. The primary merit of such methods consists in their high cost-efficiency in modeling and computing without losing adequate accuracy, which can be highlighted especially when they are applied to complex problems. At the same time, like other SDI methods, RSM-based methods also have some drawbacks such as: (a) for a specific problem choosing a suitable RS model (model order, type, etc.), is a tough issue and it should be done by trial and error when no previous experience can be used for reference; (b) in general, RS models give reliable interpolation predictions but not extrapolation ones; (c) experimental variations are not considered in RS models constructed using numerical samples, which reduces the robustness of RS models. However, the influence of aforementioned drawbacks can considerably decrease once a careful design is achieved and thus satisfactory predictions can be obtained, as demonstrated in this study.

There is a large variety of robust designs for desired RS modeling which are well-documented in the literature. CCDs and 2^k FDs are included among these designs. However, there is a considerable and continuing interest in devising new designs to accommodate specific problems and need also arises within the RSM framework. Due to it, in this work the feasibility and efficiency of a computer-generated design (CGD) named the D-optimal design is explored for SDI problems in complex civil structures and compared with standard designs like the CCD. Unlike the standard designs, D-optimal designs require far fewer samples for a desirable RS model which is a valuable advantage since it reduces the number of experiments needed when limited experimental resource can be offered. At the same time, satisfactory predictions for both parameter screening and SDI can still be obtained using D-optimal designs. To reach this objective, a systematic method is employed in this paper as a four stage procedure ((a) feature selection, (b) parameter screening, (c) primary RS modeling and