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Finite element model updating in structural dynamics by using the response surface method

Wei-Xin Ren *, Hua-Bing Chen

Department of Civil Engineering, Central South University, Changsha, 410075, China
National Engineering Laboratory for High Speed Railway Construction, Changsha, 410075, China

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ABSTRACT

Fast-running response surface models that approximate multivariate input/output relationships of time-consuming physical-based computer models enable effective finite element (FE) model updating analyses. In this paper, a response surface-based FE model updating procedure for civil engineering structures in structural dynamics is presented. The key issues to implement such a model updating are discussed such as sampling with design of experiments, selecting the significant updating parameters and constructing a quadratic polynomial response surface. The objective function is formed by the residuals between analytical and measured natural frequencies. Single-objective optimization with equal weights of natural frequency residual of each mode is used for optimization computation. The proposed procedure is illustrated by a simulated simply supported beam and a full-size precast continuous box girder bridge tested under operational vibration conditions. The results have been compared with those obtained from the traditional sensitivity-based FE model updating method. The real application to a full-size bridge has demonstrated that the FE model updating process is efficient and converges fast with the response surface to replace the original FE model. With the response surface at hand, an optimization problem is formulated explicitly. Hence, no FE calculation is required in each optimization iteration. The response surface-based FE model updating can be easily implemented in practice with available commercial FE analysis packages.

1. Introduction

Nowadays the finite element (FE) method has become an important and practical numerical analysis tool. It is commonly used in almost all areas of engineering analysis. However, the FE model of a structure is normally constructed on the basis of highly idealized engineering blueprints and designs that may not truly represent all the aspects of an actual structure. As a result, the analytical predictions from a FE model often differ from the results of a real structure. These discrepancies originate from the uncertainties in simplifying assumptions of structural geometry, materials as well as inaccurate boundary conditions. It is often required to update or calibrate the uncertain parameters of a FE model that leads to the better predictions of the responses of an actual structural.

Finite element model updating is such a procedure that modifies or updates the uncertainty parameters in the initial finite element model based on the experimental results so that a more realistic or refined model can be achieved [1]. In other words, FE model updating is the process of using experimental results to refine a mathematical model of a physical structure. Basically, FE model updating is an inverse problem to identify or correct the uncertain parameters of FE models. It is usually posed as an optimization problem. Setting-up of an objective function, selecting updating parameters and using robust optimization algorithm are the three crucial steps in FE model updating. In a model updating process, not only the satisfactory correlation is required between analytical and experimental results, but also the updated parameters should preserve the physical significance. The updated FE models are used in many applications for civil engineering structures such as damage detection, health monitoring, structural control, structural evaluation and assessment.

Finite element model updating is a topic of significant interest in the field of structural dynamics. A number of FE model updating methods in structural dynamics have been proposed. The direct updating methods compute a closed-form solution for the global stiffness and/or mass matrices using the structural equations of motion and the orthogonality equations. These non-iterative methods that directly update the elements of stiffness and mass matrices are one-step procedures [2,3]. The resulting updated matrices reproduce the measured structural modal properties well but do not generally maintain structural connectivity and the corrections suggested are not always physically meaningful.

* Corresponding author at: Department of Civil Engineering, Central South University, Changsha, 410075, China. Tel.: +86 731 82654349; fax: +86 731 85571736.
E-mail addresses: renwx@mail.csu.edu.cn, renwx@yahoo.com (W.-X. Ren).

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The iterative parameter updating methods involve using the sensitivity of the parameters to find their changes. The sensitivity-based FE model updating methods are often posed as optimization problems. These methods set the errors of the structural response features between analytical and experimental results as an objective function and try to minimize the objective function by making changes to the pre-selected set of physical parameters of the FE model. Link [4] gave a clear overview of the sensitivity-based updating methods in structural dynamics. It is noted that the mathematical model used in the model updating is usually ill posed and the special attention is required for an accurate solution [5]. Jaishi and Ren [6–8] used either single-objective or multi-objective optimization technique to update the FE models of civil engineering structures in structural dynamics. However, the sensitivity-based method involving in the determination of local gradients at points may cause not only computational intensive, but also convergence difficulty.

If the structure of interest is represented by, e.g. a large finite element model, the large number of computations involved can rule out many approaches due to the expense of carrying out many runs. For such a large FE model where so many elements are involved, there are huge of both geometric and physical possible parameters to be updated. In addition, there are now many commercial finite element analysis packages available such as ANSYS, ABAQUS and SAP2000 et al.. The structural FE models are often constructed by using these packages. In all the iterative parameter updating methods, each iteration needs to go back to run the finite element analysis package with any parameter updated, which limits the popular applications of structural FE model updating in practice.

One way of circumnavigating the time-consuming and FE analysis package-related problems during the sensitivity-based model updating is to replace the FE model by an approximate surrogate/replacement meta-model that is fast-running and less parameters involved [9]. Such a meta-model is easier to compute with, because it is controlled only by a few explanatory variables. The FE model updating is carried out on the meta-model instead of the analytical FE model. Response surface is one of the commonly used meta-models. Response surface methodology is originally an experimental design approach for selecting design parameters for experiments with the objective of optimizing some function of a response [10–12]. It provides a mechanism for guiding experimentation in search of optimal settings for design parameters or optimal values of unknown response. Many additional applications (largely a consequence of the increased use of computational analyses) have broadened the range of application of response surface methods in the statistical and engineering literature. Recent literature has addressed more flexible functional forms for modeling the response, new methods of response surface construction [13], alternate approaches to updating the surface estimate [14], new sampling methods [15], etc.

In many fields of engineering, the term "response surface" is used synonymously with "meta-model" or "surrogate model", which refer to any relatively simple mathematical relationship between parameters and a response, often based on limited data [16]. In the case of structural finite element model updating, once the response surface of a structure has been constructed, updating the model is reduced to the task of finding the smallest value on the response surface. The parameter values that correspond to this smallest value are those that are used to update the model. Recently, the response surface that is represented by a simple least-squares multinomial model has been adopted in structural FE model updating, verification and validation [17–20].

The response surface method for damage detection and reliability analysis is not quite new [21,22]. However, the response surface method for structural finite element model updating is somewhat new, especially with the civil engineering communities. This paper is intended to present a response surface-based finite element model updating procedure in structural dynamics and to take advantages of response surfaces for the FE model updating of civil engineering structures in practice. Its purpose is to estimate the values of structural parameters (moment of inertia, cross-sectional area and modulus of elasticity) based on the measured response quantities (natural frequencies). The proposed procedure is based on constructing quadratic response surfaces. Those surfaces represent an estimate for the relation between the unknown parameters of the finite element model and response quantities of interest. With the response surface at hand, an optimization problem, whose solution is the estimate for the values of the structural parameters, is formulated explicitly. Hence, no further finite element simulations are required. The objective function is formed by the residuals between analytical and measured natural frequencies. Single-objective optimization with equal weights of each natural frequency is implemented for optimization computation. The presented procedure is illustrated by a simulated simply supported beam and a full-size precast continuous box girder bridge tested under operational vibration conditions. The results have been compared with those obtained from the traditional sensitivity-based FE model updating method. The real application to a full-size bridge has demonstrated that the response surface-based FE model updating procedure is simple and fast so that it can be easily implemented in practice.

2. Response surface-based finite element model updating

Response surface-based finite element model updating is an approach to achieve the global approximations of the structural response feature objectives and constrains based on functional evaluations at various points in the design space. It often involves experimental strategies, mathematical methods, probability and statistical inference that enable an experimenter to make efficient empirical exploration of the structure of interest. The flowchart of response surface-based finite element model updating is shown in Fig. 1. The main steps include the following.

- The selection of the structural parameters and the definition of a number of "level" for each selected parameters by using the design of experiments (DOE) techniques.
- In design space, the response features are calculated by carrying out finite element analysis (FEA).
- Performing the final regression followed by a regression error analysis to create the response surface model of the structure.
- The response features of the structure are measured and corresponding objective functions (feature residuals) to be minimized are constructed.
- The finite element model updating (iteration) is carried out within the established response surface model. Updated parameters are obtained and transferred to the original finite element model.

2.1. Sampling and parameter selection

To create a response surface that will serve as a surrogate for the FE simulation model, the basic process is one of calculating predicted values of the response features at various sample points in the parameter space by performing a experiment at each of those points. A number of feature values from the experiment ran across the parameter domain are fit with a response surface. The key is to select the parameters carefully, to minimize the number of dimensions in the parameter space, and then to select