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FINITE ELEMENT MODEL UPDATING METHODS FOR STRUCTURAL APPLICATION

METODE POBOLJŠANJA NUMERIČKIH MODELA KONAČNIH ELEMENATA U ANALIZI KONSTRUKCIJA

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Sažetak

Numerički modeli konstrukcija predstavljaju suvremeni alat za kontinuirano praćenje konstrukcija, detekciju oštećenja, predviđanje životnog vijeka te definiranje optimalne strategije njihova održavanja. Poznato je da zbog ulaznih parametara kao što su krutosti, masa i rubni uvjeti dobivamo nepouzdane numeričke modele. Kako bi se navedeni problem riješio, primjenjuju se metode poboljšanja numeričkih model primjenom rezultata eksperimentalnih ispitivanja kojima se određuju dinamički parametri konstrukcije. U radu je dan kratak pregled postupka poboljšanja numeričkih modela konstrukcija primjenom eksperimentalno određenih dinamičkih parametara-frekvencije, oblika titranja. Navedene su neke od metoda koja se najčešće primjenjuju te su istaknute njihove prednosti i nedostaci.

Ključne riječi: Poboljšanje numeričkog modela, praćenje konstrukcija, dinamička analiza konstrukcija, ispitivanje konstrukcija

Abstract

Structural finite element models are a modern tool for continuous monitoring of structures, damage detection, prediction of service life and determination of optimal strategy for maintenance. It is well known that we get uncertain numerical models due to the input parameters such as stiffness, mass, and boundary conditions. To solve this problem, finite element model updating methods are used in combination with the results of structural dynamic tests or structural health monitoring data. In this paper, a brief overview of the procedure for updating finite element models using experimentally determined structural dynamic parameters - natural frequencies and natural modes - is given. Some of the most commonly used methods are listed and their advantages and disadvantages are highlighted.

Keywords: Finite element model updating, Structural Health Monitoring, Dynamic analysis of structures, experimental investigation

1. Introduction

Finite element model updating (FEMU) emerged in the 1990s as a topic of the great importance for the design [1], construction [2], and maintenance of mechanical systems [3] and structures [4]. As for civil engineering structures, it refers to the updating of its models to assume its dynamics behaviour more precise and accurate (Figure 1.). To minimize the differences and maximize the correlation between the numerical model and the real structure, the model updating (MU) of the civil engineering structure is most often performed by applying the structural dynamic test results.

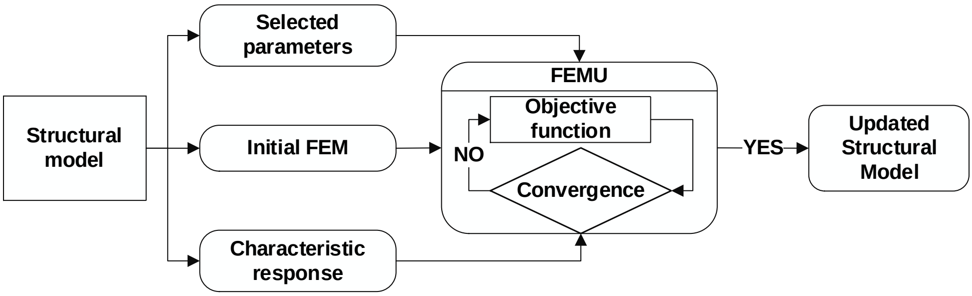

Figure 1. Flowchart of finite element model updating iterative procedure

In addition to dynamic, the static test results [4] or its combination with dynamic test results is also apply [5].The conducting of FEMU is mainly focused on the determination of most relevant structural parameter values such as geometry, material properties, and boundary conditions. Those parameters minimize the differences between the structural behaviours predicted by the numerical model from the actual behavior of the structure. The reasons why there are differences between the predicted behavior of a numerical model of the structure and its actual behavior include model structure errors [6], model order errors [7], model parameter errors, and errors in measurements [8]. Many of investigation is mainly focused on the finite element model updating using structural dynamic parameters - natural frequency, mode shapes and damping ratio. The advantages of using these parameters are that they are easy to apply for damage detection. Also, they are most appropriate when there is a large error in the numerical modelling, and they are directly related to the topology of the structure. In this type of data, most of the structural parameters that best describe the global behavior are include [9]. On the other hand, the determination of the structural dynamic properties for identification is computationally intensive and prone to additional noise. Moreover, it is not able to extract the modes of the frequency bandwidth and is only suitable for highly damped and linear structures.
The FEMU method can generally be classified as the automated and manual methods [10], and iterative(non-direct) and non-iterative (direct) methods [8]. The main difference between the manual and automated method lies in the number of selected updating parameters and in the way the model updating is performed - using trial and error methods (manual FEMU) or automated process. The division of MU methods into iterative and non-iterative methods is somewhat more concrete. As their name say, the differences between them are in the way the model updating is implemented, using iterative process or not. The iterative methods are further divided into deterministic methods and Bayesian method. Based on the targeted responses used to update the numerical model, deterministic methods can be further divided into two groups: (1) methods that use eigenvalues and eigenvectors (eigenfrequencies, mode shapes, damping coefficient) and (2) methods that use frequency response data. The following

chapters describe the process of FEMU and give a brief overview of the methods, categorized into matrix update methods, sensitivity-based methods, iterative optimization methods, Bayesian methods, and computational intelligence methods.

2. Selection of updating parameters

The success of the finite element model update implementation depends on the selection of the updating parameters. It is very important to properly define the model parameterization and estimate the unknown parameters from ill-conditioned equations. In addition to parameterization, the uniqueness of the updating parameters, computational efficiency, ill-conditioned equations, and the use of incomplete data is also important. The selected parameters of the numerical model that are being updated should be able to explain the uncertainties or inaccuracies of the model, provided that the output data are sensitive to the input parameters of the model. There are several methods that are used for selection of updating parameters (Figure 2).

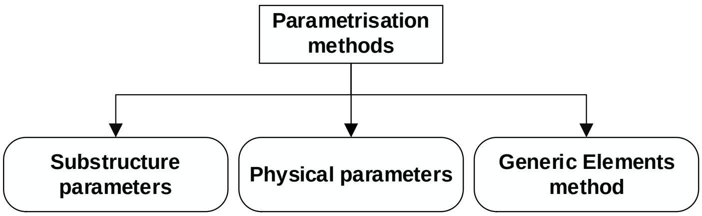

Figure 2. Parametrisation methods for FEMU

One of them is to define the scalar multipliers associated with the mass, stiffness and damping matrices. Second parametrization method employs the direct material and geometrical properties of structures [11]. Third one, generic method by adjusting the eigenvectors and eigenvalues of individual elements or sub-structure update the stiffness and mass matrices. Regardless of the selected parameterization method, the set of selected updating parameters should be as small as possible to eliminate unnecessary parameters and reduce computational cost [11].

3. Definition of the objective function

Formulation of the objective function for the FEMU problem must take into account the residuals that are sensitive to the selected updating parameters [12]. Objective function in FEMU formulation is defined in form of the residuals which describe the differences between structural behaviour predicted by numerical model and its actual behaviour. Usually, it is defined by considering two types of residuals: the first one is associated with the natural frequencies while the second is associated with the corresponding mode shapes. The influence of those two residuals on the objective function can be evaluated via two approaches: the single objective function (1) and multi objective function (2) approach.

$$F(x) = \sum_{i=1}^{NF} w_i F_i(x) \tag{1}$$

$$\big(F_i(x)\big) = (F_1(x), F_2(x), .., F_{NF}(x)\ ) \tag{2}$$

Single objective function (1) approach is characterized by only one objective function. in terms of the sum of weighted residuals usually obtained using the trial-and-error method. In the multi objective function approach (2) each component of the objective function is defined in terms of unweighted residuals. Several no-dominated solutions are obtained. For those solutions, no objectives can be improved without sacrificing at least one the objectives. In defining the FEMU problem in probabilistic method instead of the objective function the probability density function is defined [13].

4. Finite element model updating methods

4.1. Matrix update methods

The matrix update method is mainly based on updating the structural mass, stiffness, or damping matrices. They are implemented to minimize the differences between the analytical and measured matrices. The main concept is based on changing the global stiffness, mass or damping matrices to an improved numerical model that accurately reproduces the experimental results [14]. Their application directly minimizes the differences between experimentally and numerically obtained structural dynamic parameters. These methods are computationally expensive and it is difficult to find a global minimum through the optimization techniques since there are several stationary points [8].

4.2. Sensitivity based methods

In the sensitivity based FEMU methods the experimentally obtained structural dynamics parameters – natural frequencies and mode shapes are adopted for updating the initial numerical model. These methods allow a wide choice of the parameters for model updating and measured outputs to be weighted. With the respect to parameters, determination of the sensitivity of the measurements is computationally intensive and the approximation of the sensitivity may only be obtained. The sensitivity is most often the non-linear function of the updating parameters, an iterative procedure is necessary. This iterative procedure is associated with the convergence problem to solve for the selected parameters [15]. Sensitivity based method has some limitations related to request of existence of a sensitivity matrix with the respect to all updating parameters, computational costs and they may not be applicable for structure which contain a considerable amount

4.3. Dynamic perturbation method and regularization algorithm

For the situation in which the difference between actual and predicted structural behaviour is sufficiently large, the linear or first order approximations may be inappropriate. An exact relationship between the perturbation of structural parameters and the perturbation of the associated dynamic parameters is used for the FEMU. This method directly adopts the measure incomplete structural dynamic parameters and in the FEMU process it doesn’t require mode shape expansion or reduction. This method needs much less computational effort to estimate updating parameters. It provides optimised solutions for MU in the least squares sense without requiring optimisation techniques. Also, this method offers reliable estimates of structural updating parameters, even in the cases where relatively large modifications in structural parameters and/or in modal properties exist between the finite element model and the tested structure [16].

4.4. Iterative optimization and computational intelligence algorithm

Iterative optimization methods transform the FEMU into the optimization problem. On this way the objective function is defined as the relative differences, i.e., residuals, between the behaviour of structure predicted by numerical model and its actual behaviour. There are two different ways in which these residuals can be defined. The first one is as single objective optimization problem, while the second one is the multi-objective optimization problem. To solve the optimization problem of FEMU the computational intelligence algorithms are used (Figure 3)[17].

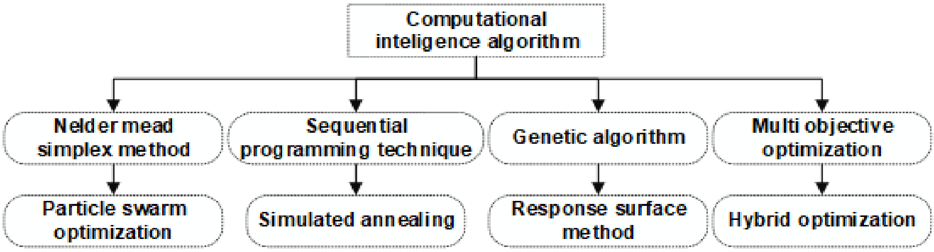

Figure 3. Computation intelligence algorithm for FEMU[8]

4.4.1. Bayesian method

The Bayesian FEMU method approaches are based on the development of the numerical model as a statistical problem focusing on estimation the probabilistic density function of the numerical model physical parameters. This method uses Bayesian probability theory for defining the posterior probability density function of the physical parameters of the model. Density function is estimated in terms of the likelihood and prior probability density functions [18]. This method has some disadvantage related to a complex numerical model, which is often time consuming and computationally limited, limiting its application on large real structures.

5. Conclusion

With the ever-advancing development of computer software and structural health monitoring techniques, ever-increasing demands are being placed on the numerical modelling of structures. This has created a need for the development of methods that combine computer software and SHM techniques into numerical models to describe real structure as accurately and precisely as possible. The numerical models obtained can be used for various purposes, from monitoring the construction phases, to the maintenance of the structure and its restoration, to important related decisions. This paper gives a brief overview of the process of implementing model updating and the most used methods for this purpose. Their advantages and disadvantages are highlighted. The aim of this paper is to learn about the process of implementing finite element model updating through its various stages and the advantages and disadvantages of the methods used for updating numerical models

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