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A review on model updating in structural dynamics

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Abstract. This paper is a review of information and related studies concerning topic of model updating in structural dynamics. It is purposed to introduce and explain the important concept of the discussed subject in model updating area as well as to summarize the development and available guidance and method of conducting the study in this area. The review is structured by presenting an overview of general concept of finite element model updating in structural dynamics and the capabilities of finite element method as a tool in model updating. After the concept introduction, the reliable methodology to perform model updating, the limitation and the critical issues in model updating is discussed. The limitation and problems arise concerning correcting inaccurate finite element model is also discussed. This lead to issue of parameterization and regularization which the limitation and uncertainty in choosing the updating parameter is shown able to be overcome. Further studies on the elimination of systematic errors from both the measurements and the finite element model so that it can provide more reliable model updating is recommended.

1. Introduction

Model updating techniques are about updating a finite element model of a structure so that it can assume more accurate dynamics of a structure. Finite element method is widely used to model the dynamics of a certain structures as it is considered as reliable of providing accurate results. It is considered by Zienkiewics and Taylor [1], as the most appropriate tool for numerical modeling in structural engineering as it is capable of handling complex structural geometry, large complex assemblies of structural components and can perform many different types of analysis.

However, problems of inaccuracies in the finite element model will arise and sometimes viewed as poor reflection of actual structure. It may be caused by poorly known boundary conditions of the structure, the unknown material properties of the structure or because of the simplification in the modeling of very complex structural systems [2, 3]. For example, modelling joints is particularly not easy as it is difficult to predict its finite stiffness. These uncertainties in the modelling process cause the predicted dynamics of a structure to be different from the measured dynamics of the real structure. If there is accurate measured data, then general improvement on the numerical model and uncertain parameters of the model can be made based on this data.

Many model updating techniques have been proposed, tested and published. Mottershead [2] stated that the methods can be divided according to the type of measured data they used and the model parameters that are updated. The measured data may be in form of frequency response function (FRF) data or natural frequencies and mode shapes. The updating process may estimate physical parameters, complete mass, damping and stiffness matrices or groups of individual matrix elements. So far, research has concentrated on updating physical parameters using either FRF or modal data.

Parameter uncertainty has become an important research topic when discussing model updating according to Mottershead and Friswell [2, 4]. This is because the key to success in model updating is always the choice of parameters. The critical issues that have been stressed by Friswell [5] in modal updating also is about deciding the way finite element model of a structure is to be parameterized and how to estimate the unknown parameters from ill-conditioned equations. Therefore consideration on these issues is really crucial.

There are a few issues that also important and being studied in model updating apart from parameterization such as parameter uniqueness, efficient computation, ill-conditioning and use of incomplete data. Regularization method is needed in model updating to modify the poor or ill conditioned system of equations toward a well-conditioned one so that parameters can be identified.

In this paper, an overview of general concept of finite element model updating in structural dynamics and the capabilities of finite element method as a tool in model updating is presented. The first part will discuss the methods of model updating. The issue of parameterization and regularization which the limitation and uncertainty in choosing the updating parameter can be overcome are also included**.**

2. Finite element model updating

2.1. Methods of model updating

There have been several extensive reviews [2, 4, 6] of different kinds of model updating methods that have been developed.

Based on the comparative study of damped finite element model updating methods by Arora et al. [7], model updating technique can be classified into non-iterative or also called direct methods and iterative methods which also called sensitivity method.

The direct method shows precise results. Thus, the model assumptions match the experimental modal data. The way the measured modal data is reproduced is more computationally cheaper. Nevertheless, the updated finite element model result may have poor physical meaning as the methods violate the structural connectivity and updated structural matrices are difficult to interpret. This is the reason why the methods have not been generally used in practice.

Iterative methods or the sensitivity methods, which concern of reducing an objective function that is generally a non-linear function of selected updating parameters, are carried out by either using Eigen data or frequency response function (FRF) data. Therefore it provides wider choice of parameters for updating. These methods considered as capable of overcoming the limitations of the direct methods [3]. It also has been applied successfully to large-scale industrial problems.

A brief explanation and tutorial on this sensitivity method in finite element model updating is provided by Mottershead, Link and Friswell [8]. Example of model updating of a helicopter airframe is also showed in the paper. The sensitivity method is based upon linearization of the generally non-linear relationship between the measurable outputs such as natural frequencies, mode shapes or displacement responses, of the model's parameters in need of emendation. The most important quality is to define an error function of modal data obtained from computer simulation and experimental. The estimated parameters are attained by minimizing the error function with respect to the updating parameters.

The simplified flow diagram for the model updating method is shown in figure 1 below.

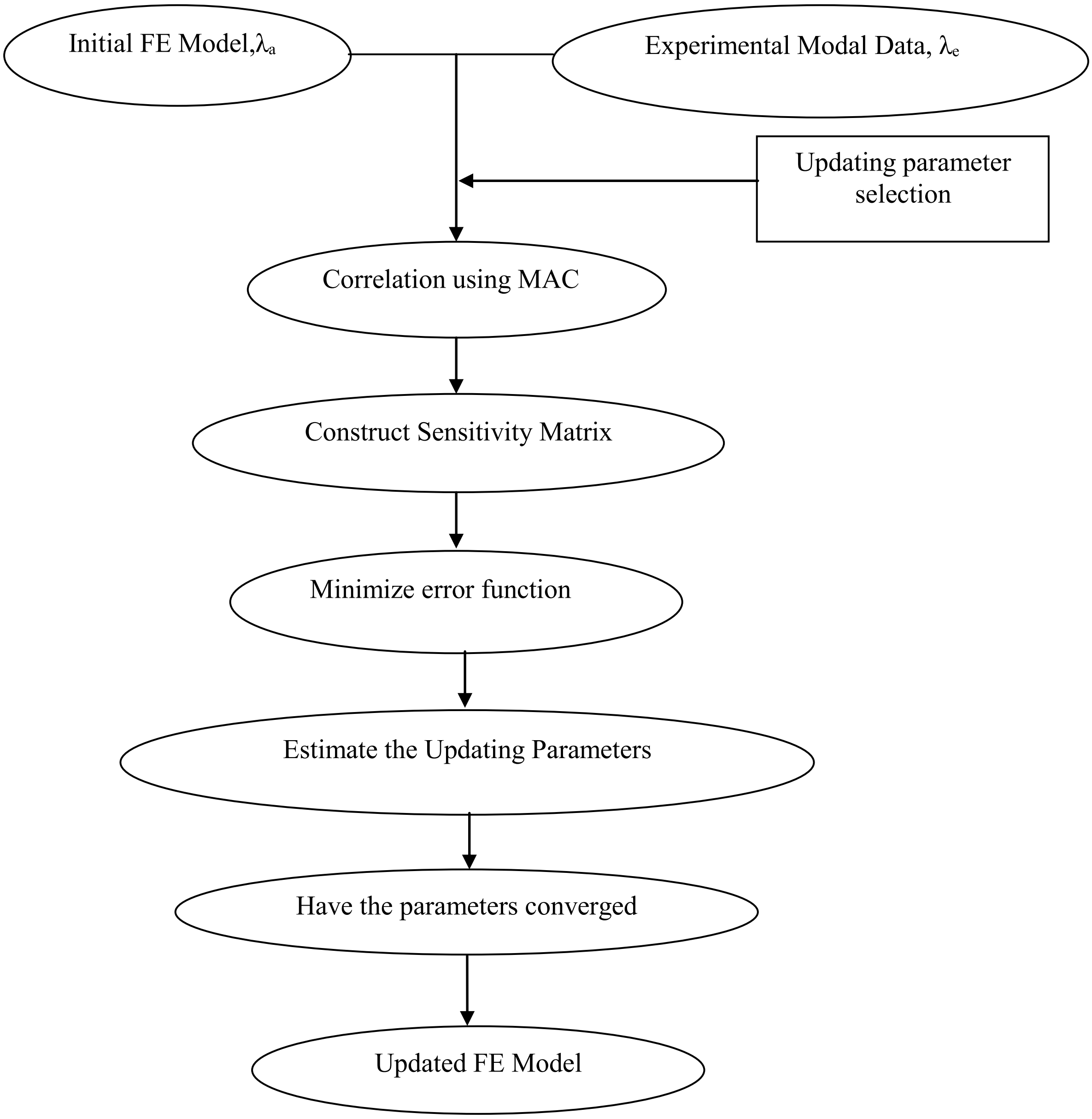

Figure 1. Simplified flow diagram for the model updating method [3].

Another study on other model updating method called 'coupled inverse Eigen-sensitivity method' is carried out [9]. This study had shown concern on updating a finite element model that take into account the acoustic loading on the structure. The study was applied to a 3D rectangular cavity backed by a flexible plate in order to investigate the effectiveness of the approach to obtain an accurate structural finite element model. It was also to study the influence of ignoring the effect of acoustic loading in updating process. Based on the results obtained, the approach shown to be effective in estimating the updating parameters and in predicting the natural frequencies, the eigenvectors and the frequency response function in case of complete and incomplete data accurately.

Model reduction technique can usually be used in model updating process. An investigation of an iterative method associated the model updating method with the model reduction technique is carried out by Li [10]. Using existing iterative method, the errors out coming from replacing the reduction matrix of the experimental model with the finite element model are not fully considered, which needs more iterations and computing time. A new iterative method with correction term related to errors is added to reduce to error produced in the replacement.

There is also a study to identify limitation of the existing iterative methods of model updating [11]. The paper raises a solution to overcome the limitation in the form of new method of finite element model updating that accepts both correlated and uncorrelated modes of updating. This is different to the existing iterative modal data based on methods of modal updating that are based on the prediction of availability of correlated mode pairs and hence cannot use uncorrelated mode shapes and corresponding natural frequencies in the updating process. Formulation of this new method was explained and a couple of numerical examples based on a beam structure were presented to validate the method.

2.2. Parameterization of Finite Element Model

In model updating, there is a process of estimating certain parameters of the models on the basis of dynamic tests carried out on the corresponding actual structures. Physical variables are measured at several points of the structures and recorded in the time domain during tests. These data will be transformed to the frequency and modal domains. The parameters are then obtained when the discrepancies between the experimental data and estimation of simulated model are minimized. In the method of minimizing the error function, the process has been formed in simple algorithm that is capable of solving both global and local phases of updating.

The aim or parameterization in mode updating is fitting the parameters of a given initial analytical model so that the model behaviour corresponds as closely as possible to the measured behavior. In finite element model updating, the selected parameters should be able to explain the uncertainties of the model. It is a requirement for the model output to be sensitive to the parameters. Joint in model is always facing difficulties in doing adequate parameterization using physical design variables such as stiffness and dimensions. Thus, geometric or generic parameterizations are views as significant application area.

As stated previously, direct methods of model updating are not well-approved because elements in the mass and stiffness matrices perform very poorly as candidate parameters [4]. This poor performance is because the stiffness matrix element values are dominated by the high-frequency modes, but instead the low-frequency modes are measured [5]. Mottershead et al. in their paper [12] had used geometric parameters like beam offsets for the updating of mechanical joints and boundary conditions. Ahmadian et al. [13] in separate paper had showed the effectiveness of parameterizing the modes at the element level and used both geometric parameters and element-modal parameters to update mechanical joints.

There is also a study by Terrell et al. [14] that shows parameters obtained from generic element and substructure transformations are able to increase the choices in parameters and therefore capable to correct structural errors. The method proposed assumes that substructure eigenvector matrix is to be made as effective to enforce the connectivity constrains. This method has been successfully demonstrated on a simple L shape structure with substructure is the corner. Approach with respect of this method also conducted by Weng et al. [15] in the study of substructure-based finite element model updating. Applications of the proposed substructure-based model updating to a frame structure and a bridge show that the method is computationally efficient.

A review on finite element model updating of spot welds in structural dynamics [16] also discuss the parameterization issue. Analysis on structures with spot welds, for example car body, will contain too much degree of freedom to be used in practice. Study of geometric non-linear characteristics of spot welded joints [17-19] is carry out by using finite element models. In order to validate the model, a six spot weld model is created as benchmark model. The results show that most models reach same level of accuracy after updating as they are all able to approximate the local stiffness due to the spot weld.

A method for finite element model updating in field of structural dynamics is proposed by Valle et al. [20] which focus on minimization of error function in the time domain. An error function is representing the discrepancies between the experimental data and the simulation test on the model. It is defined and minimized with respect to the parameters.

The paper that discuss physical realization of generic-element parameters in model updating [21], generic element models for updating are developed by forcing the model to have appropriate null space, positivity properties, total mass and moments of inertia and geometric symmetry. The parameters are obliged to follow the requirements of internal-force equilibrium at each node. Then the generic-element models obtained by this approach can be used in updating the model. In this study, the methodology for parameterization is carried out by updating a model using experimental data obtained from a cracked beam.

Esfandiari [22] had published a paper on finite element model updating of structures using frequency response function (FRF) data. Response sensitivities related to mass changes and stiffness parameters are indirectly determined using the decomposed form of frequency response function data. Findings of this study show the reliability of this method to identify the location and severity of parameter change at the elemental level in a structure. Furthermore, the finite element parameter estimation results are improved using higher excitation frequencies.

2.3. Regularization

There is a study on regularization method for finite element model updating by Ahmadian et al. [23] that highlights the problem of choosing side constraint and determining the regularization parameter in model updating. Author stated that noise contamination in test data is a problem in finite element model updating. Therefore, he demonstrated the regularization methods that can be used for modifying the ill-condition and noisy equations systems that arise during correcting the finite element models by using vibration measurements. Selection of good side constraint was shown to be important and lead to updated parameters with physical understanding. The methods considered in this study were based on singular value decomposition, cross-validation, and L-curves. The outcome received by applying these methods to a numerical example has provided the basis for a comparative study.

An overview of two approaches, a non-probabilistic fuzzy approach and a probabilistic Bayesian approach of dealing with uncertainty in model updating is presented by Simoen et al. in their review paper [24]. This work shows interest to the treatment of uncertainties in model updating problems with more focus on vibration-based finite element model updating. Both approaches stated in this paper are fundamentally different naturally because of their contrasting interpretations of uncertainty. This mean that the results are only can be compared qualitatively. Gathering results from probabilistic method can be quite challenging and computationally demanding. Generally, the most suitable method is dependent on the nature size of model updating problem, the available information and the needed end purpose of uncertainty quantification procedure.

Hansen [25] in his study proposed regularization methods for obtaining a solution of the inverse problem. He applied the theory that the conventional output error which is the vector if differences between the computed and measured responses, can be made subjectively small if the process of damage identification is allowed to behave poorly.

Tikhonov regularization is then applied [26] and from the experiences gained in model updating with simulated structures, it was found that Tikhonov regularization can give optimal solution when there is noise in measurement. An adaptive regularization approached for solving the nonlinear model updating inverse problem was presented by Li and Law [27]. The results obtained from proposed method in this study are well improved over the one obtained from Tikhonov regularization even though there are larger noise contamination in the measurements.

A paper of study of an approach for directly updating finite element model from measured incomplete vibration modal data with regularized algorithm is presented by Chen [28]. The suggested method is based on the relationship between the perturbation of structural parameters such as stiffness change and the modal data measurements of the tested structure which in this case is the measured mode shape readings. Structural updating parameters were selected at a critical point level to represent the modelling errors at the joints of structural elements. These parameters were then evaluated by iterative and direct solution procedure, which in the end gives optimize solutions. The Tikhonov regularization method incorporating the L-curve criterion is then applied to produce more effective solutions for the chose updating parameters in order to reduce the influence of modal measurements uncertainty. The findings of this study had demonstrated a reliable estimation method for finite element model updating using measurements of incomplete modal data.

References

[1] Zienkiewicz O C, Taylor R L, Zienkiewicz O C, Taylor R L 1977 *The finite element method* **3** McGraw-hill London)
[2] Mottershead J, Friswell M 1993 *Journal of sound and vibration* **167** 347-75
[3] Sinha J K, Friswell M I 2003 *Nuclear Engineering and Design* **223** 11-23
[4] Friswell M, Mottershead J E 1995 *Finite element model updating in structural dynamics* **38** Springer Science & Business Media)
[5] Friswell M I, Mottershead J E, Ahmadian H 2001 *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* **359** 169-86
[6] Imregun M, Visser W 1991 *The Shock and vibration digest* **23** 9-20
[7] Arora V, Singh S, Kundra T 2009 *Mechanical Systems and Signal Processing* **23** 2113-29
[8] Mottershead J E, Link M, Friswell M I 2011 *Mechanical Systems and Signal Processing* **25** 2275-96
[9] Nehete D, Modak S, Gupta K 2015 *Mechanical Systems and Signal Processing* **50** 362-79
[10] Li W-M, Hong J-Z 2011 *Mechanical Systems and Signal Processing* **25** 180-92
[11] Modak S 2014 *Journal of Sound and Vibration* **333** 2297-322
[12] Mottershead J, Friswell M, Ng G, Brandon J 1996 *Mechanical Systems and Signal Processing* **10** 171-82
[13] Ahmadian H, Gladwell G, Ismail F 1997 *Journal of Vibration and Acoustics* **119** 37-45
[14] Terrell M, Friswell M, Lieven N 2007 *Journal of sound and vibration* **300** 265-79
[15] Weng S, Xia Y, Xu Y-L, Zhu H-P 2011 *Computers & Structures* **89** 772-82
[16] Palmonella M, Friswell M I, Mottershead J E, Lees A W 2005 *Computers & structures* **83** 648-61
[17] Sonsino C, Fricke W, De Bruyne F, Hoppe A, Ahmadi A, Zhang G 2012 *International Journal of Fatigue* **34** 2-16
[18] Sonsino C, Radaj D, Brandt U, Lehrke H 1999 *International Journal of Fatigue* **21** 985-99
[19] Chang B, Shi Y, Dong S 1999 *Journal of Materials Processing Technology* **87** 230-6
[20] Zapico-Valle J L, Alonso-Camblor R, González-Martínez M P, García-Diéguez M 2010 *Mechanical Systems and Signal Processing* **24** 2137-59
[21] Ahmadian H, Mottershead J, Friswell M 2002 *Journal of Vibration and Acoustics* **124** 628-33
[22] Esfandiari A, Bakhtiari-Nejad F, Sanayei M, Rahai A 2010 *Computers & structures* **88** 54-64
[23] Ahmadian H, Mottershead J, Friswell M 1998 *Mechanical Systems and Signal Processing* **12** 47-64
[24] Simoen E, De Roeck G, Lombaert G 2015 *Mechanical Systems and Signal Processing* **56** 123-49
[25] Hansen P C 1998 *Rank-deficient and discrete ill-posed problems: numerical aspects of linear inversion* **4** Siam)
[26] Weber B, Paultre P, Proulx J 2009 *Mechanical Systems and Signal Processing* **23** 1965-85
[27] Li X, Law S 2010 *Mechanical Systems and Signal Processing* **24** 1646-64
[28] Chen H-P, Maung T S 2014 *Journal of Sound and Vibration* **333** 5566-82