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Function-weighted frequency response function sensitivity method for analytical model updating

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ABSTRACT

Since the frequency response function (FRF) sensitivity method was first proposed [26], it has since become a most powerful and practical method for analytical model updating. Nevertheless, the original formulation of the FRF sensitivity method does suffer the limitation that the initial analytical model to be updated should be reasonably close to the final updated model to be sought, due the assumed mathematical first order approximation implicit to most sensitivity based methods. Convergence to correct model is not guaranteed when large modelling errors exist and blind application often leads to optimal solutions which are truly sought. This paper seeks to examine all the important numerical characteristics of the original FRF sensitivity method including frequency data selection, numerical balance and convergence performance. To further improve the applicability of the method to cases of large modelling errors, a new novel function-weighted sensitivity method is developed. The new method has shown much superior performance on convergence even in the presence of large modelling errors. Extensive numerical case studies based on a mass-spring system and a GARTEUR structure have been conducted and very encouraging results have been achieved. Effect of measurement noise has been examined and the method works reasonably well in the presence of measurement uncertainties. The new method removes the restriction of modelling error magnitude being of second order in Euclidean norm as compared with that of system matrices, thereby making it a truly general method applicable to most practical model updating problems.

1. Introduction

Analytical model updating using vibration test data is a growing and active field of research in structural dynamics as discussed in a recent comprehensive review by Mottershead and Friswell [1]. Much of early research efforts were devoted to establishing useful mass and stiffness matrices by directly using measured vibration modes only. Young and On [2] devised a procedure from which a system mass and stiffness matrices can be derived from experimentally observed incomplete vibration modes. Due to cost and test limitations on the number of physical coordinates and vibration modes that can be measured, the dimension of the thus-established model tends to be very limited. By invoking mass orthogonality condition, as an additional constraint, Berman and Flannelly [3] developed a method to construct simple system mass matrix using measured modal data. This mass matrix was subsequently used together with “incomplete” set of modes to derive the so-called “incomplete” stiffness matrix in which contributions of higher unmeasured modes, which are the major part of the

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stiffness matrix, are not included. Based on conventional multiple force excitation technique, Link and Vollan [4] and Link [5] developed a method which can be used to estimate system mass and stiffness matrices from measured forces and vibration responses. Thoren [6] devised a technique by which orthonormal modes, computed from dynamic test response data, were used to derive mass, stiffness, and damping matrices of a distributed elastic system. Based on the mathematical concept of pseudoinverse, measured incomplete modal data were used by Luk [7] to derive mass and stiffness matrices by directly pseudoinversing rank-deficient matrices. Identification of general nonproportional damping matrix was discussed by Minas and Inman [8] by using reduced mass and stiffness matrices and measured modal data in a weighted least-squares approach.

Having recognized the fact that analytical finite element models are usually precise and refined in coordinates as well as in modes, while contain modelling errors which are localized due to difficulties in modelling structural joints, error location methods have been developed to pinpoint first where modelling errors are so that limited measured data can offer better prospect to their correction. Zhang and Lallament [9] presented a technique to locate dominant modelling errors before they are corrected using incomplete test data. Lin [10] developed a unity check method to locate physical positions of modelling errors in stiffness matrix. Based on force balance, an effective method was developed by Fissette and Ibrahim [11] to locate modelling errors. Simple eigendynamic equations were used by He and Ewins [12] to locate modelling errors and to subsequently correct them. Based on first order linear approximation, an error matrix method was proposed by Ewins and Sidhu [13] to update analytical stiffness matrix. Mottershead and Stanway [14] extended the invariant imbedding filter to estimate system parameters from vibration tests. Foster and Mottershead [15] further generalized the method to allow corrections of Guyan-reduced finite element models. Ladeveze et al. [16] discussed a parametric tuning of system matrices based on computation of error from the constitutive relations. Jaishi and Ren [17] presented a practical and user friendly approach to updating civil engineering structures using ambient vibration test data. Lin and Zhu [18] developed a technique for model updating of microsystems using vibration tests under base excitation. Bagchi [19] used an iterative approach to update finite element models of bridge structures. Full-field vibration mode shapes were measured, image processed and then used to update finite element models by minimizing the distance measures between the shape feature vectors [20].

Alongside these studies, sensitivity based iterative methods, either eigensensitivity or frequency response function sensitivity, have been sought. Earliest attempt to use inverse eigensensitivity analysis to improve analytical model was due to Collins et al. [21]. Later, Chen and Garba [22] modified the procedure in [21] by introducing matrix perturbation analysis to circumvent the costly eigensolutions repeatedly required. Zhang and Lallemant [23] extended the method to pinpoint significant modelling errors first to reduce the number of unknowns involved to improve numerical condition. An excellent review and applications of sensitivity-based methods to practical aerospace structures was given by Mottershead et al. [24]. An improved inverse eigensensitivity method was developed by Lin et al. [25] by incorporating measured modes in the computation of sensitivity coefficients. Having recognized the difficulties of updating analytical models when limited coordinates and modes are measured, a frequency response function sensitivity method was developed [26] which is mathematically a generalization of the eigensensitivity method as demonstrated by Lin et al. [27], together with performance comparisons of the two methods. More recently, sensitivity-based methods have been extended to model updating of damped structures. Brown et al. [28] extended sensitivity-based model updating to lightly damped structures. Lin and Zhu [29] extended the FRF sensitivity method to model updating of damped structures. Arora et al. [30,31] developed a model updating method by using measured complex frequency response functions directly to update system mass and stiffness matrices as well as to identify system damping matrix. By separating the updating of mass and stiffness matrices from that of the damping matrix, Pradhan and Modak [32] presented a technique which can be applied to generally damped structures. Using vibration test data under base excitation, Yuan and Yu [33] proposed a method to update finite element models with damping. To date, sensitivity-based methods have since become the most powerful methods and have been successfully applied to numerous cases of model updating of practical structures as evidenced in [24], these methods however fail to converge when the magnitudes of modelling errors become large due to the inherent theoretical limitation of first order approximation. To deal with model updating problems with large modelling errors effectively, one needs somehow to further extend the applicability of the sensitivity-based methods. This paper seeks to examine all the important numerical characteristics of the FRF sensitivity method including frequency data selection, numerical balance and convergence performance. To further improve the applicability of the method to cases of large modelling errors, a new novel function-weighted sensitivity method is developed. The new method has shown much superior performance on convergence even in the presence of large modelling errors. Extensive numerical case studies based on a mass-spring system and a GARTEUR structure have been conducted and very encouraging results have been achieved. The new function-weighted sensitivity method has achieved convergence in the presence of modelling errors more than 3 times the magnitude as compared with the conventional FRF sensitivity method. It is believed that such an extended range of applicability should cover almost all possible cases of analytical model updating, thereby making the function-weighted sensitivity method a truly general method of choice for model updating applications.

2. Mathematical development

The original FRF sensitivity method was developed and discussed in detail in [26]. Since this paper discusses how the method can be further improved and also for the sake of self-completeness of discussions, a brief introduction to the