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BRIDGE HEALTH MONITORING TECHNIQUES
Integrating Vibration Measurements and Physics-based Models

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ABSTRACT: A structural health monitoring (SHM) system, integrating vibration measurements and physics-based finite element (FE) models, is reviewed and the importance of FE model updating techniques is emphasized. Novel methods to speed up computations in SHM systems are presented, including the integration of component mode synthesis techniques into existing state-of-the-art FE model updating methods. The developed methodology is illustrated using selected applications from instrumented bridges of the Egnatia Odos motorway.

KEY WORDS: Structural monitoring; Structural identification; Model updating; Damage detection; Bayesian inference.

1 INTRODUCTION

Vibration measurements from bridges can be used to understand the dynamic behavior of the various bridge components (superstructure, soil, bearings, dampers) and their interaction under actual operational conditions, estimate the dynamic characteristics of bridges, assess the mechanisms activated under the different vibration levels experienced by the bridge, validate or improve modeling procedures, select the most appropriate models for the bridge components, calibrate the parameters of the selected finite element (FE) models, assess structural damage (detect, identify location and severity of damage), quantify and propagate uncertainties in structural performance predictions, estimate damage accumulation due to fatigue in the entire body of steel bridges [1], as well as predict the remaining lifetime of bridge components under uncertainty. An effective bridge monitoring system requires the development of computationally efficient techniques and specialized software that integrates information from physics-based mathematical models of bridge components with the information collected from vibration measurements under various operational conditions, including normal operation under the action of everyday traffic loads, wind loads and environmental effects (e.g. temperature), as well as sudden extreme events such as moderate to strong earthquakes or strong winds.

This work reviews structural health monitoring techniques based on FE models. It concentrates on FE model updating techniques for damage detection, localization and severity. Novel algorithms to speed up computations in SHM systems are presented that integrate component mode synthesis (CMS) techniques with existing state-of-the-art FE model updating methods.

2 HEALTH MONITORING TECHNIQUES

2.1 Overview

Successful health monitoring of structural systems depends to a large extent on the integration of cost-effective intelligent sensing techniques, accurate physics-based computational models simulating structural behaviour, effective system identification methods, sophisticated health diagnosis algorithms, as well as decision-making expert systems to guide management in planning optimal cost-effective strategies for system maintenance, inspection and repair/replacement. Structural integrity assessment of highway bridges can in principle be accomplished using continuous structural monitoring based on vibration measurements. Taking advantage of modern technological capabilities, vibration data can be obtained remotely, allowing for a near real-time assessment of the bridge condition. Using these measurements, it is possible to identify the dynamic modal characteristics of the bridge and update a theoretical FE model. The results from the identification and updating procedures are useful to examine structural integrity after severe loading events (strong winds and earthquakes), as well as bridge condition deterioration due to long-term corrosion, fatigue and water scouring.

Algorithms and graphical user interface (GUI) software has been developed for monitoring the condition of bridges [2]. The bridge SHM system combines information from FE structural models representing the behaviour of bridges and vibration measurements recorded using an array of sensors. It incorporates algorithms related to (1) modal identification from ambient and earthquake-induced vibrations, (2) finite element model validation and updating based on identified modal properties, and (3) structural damage detection and identification based on finite element model updating.

2.2 Identification of modal models

Experimental modal identification algorithms for bridges process either ambient or earthquake-induced vibrations in order to identify the modal characteristics. In the SHM system, the modal characteristics are used as damage detection indices. Also, they are used to validate and update FE models and to identify the location and severity of damage. A brief overview of modal identification methods is given in [2-3]. Recent efforts have been concentrated on developing algorithms and GUI software for automated modal identification based on ambient vibrations with minimum user interference (e.g. [4-5]). As part of the proposed bridge monitoring system, GUI software has also been developed from the University of Thessaly group for computing the modal properties by processing either ambient or earthquake acceleration recordings [2].

2.3 Finite element model validation and updating

FE model updating methods based on modal data are used to develop high fidelity models so that predictions are consistent with measured data. The need for model updating arises because there are always assumptions and numerical errors associated with the process of constructing a theoretical model of a structure and predicting its response using the underlined model. Moreover, model updating methodologies are useful in predicting the structural damage by continually updating the FE models using vibration data [6-8]. Such updated models obtained periodically throughout the lifetime of the structure can be further used to update the response predictions and lifetime structural reliability based on available data [9]. Graphical user interface software has been developed from the University of Thessaly group as part of the bridge monitoring system for automating the FE model updating process using various modal-based model updating methodologies [10]. The software interfaces with the commercial COMSOL Multiphysics [11] software that provides the necessary finite element modeling tools.

2.4 Damage identification/localization

A framework for damage identification has been introduced in [8] and has been applied to bridge SHM in [12]. The damage detection algorithm is based on reconciling FE models with data collected before and after damage using a Bayesian methodology for selecting a model class from a family of competitive parameterized model classes. The Bayesian methodology is outlined in [8,12] based on measured modal characteristics. The structural damage identification is accomplished by associating each parameterized model class in the family to a damage pattern in the structure, indicative of the location of damage. Using the Bayesian model selection framework, the probable damage locations are ranked according to the posterior probabilities of the corresponding model classes. The severity of damage is then inferred from the posterior probability of the model parameters derived for the most probable model class. Based on asymptotic approximations, the damage diagnosis involves solving a series of FE model updating problems for each model class in the family.

The effectiveness of the methodology depends on several factors, including (a) model classes and parameterization (number and type of parameters) that are introduced to simulate the possible damage scenarios, (b) type, location and magnitude of damage or damages in relation to the sensor network configuration and (c) model and measurement errors in relation to the magnitude of damage. At least one member in the family of model classes should contain the actual damage scenario, otherwise the damage prediction from the methodology is ineffective. Measurements should contain adequate information for simultaneously identifying all model classes introduced for monitoring possible damage scenarios. Damages of small magnitude in relation to model error and measurement noise may be hidden and difficult to be identified. Damage predictions can be improved by introducing high fidelity finite element model classes and estimation algorithms that provide more accurate values of the modal characteristics.

3 EFFICIENT COMPUTATIONAL TECHNIQUES

3.1 Computational requirements for FE model updating and SHM

Finite element (FE) model updating techniques based on modal measurements are often formulated as single or multi-objective optimization problems. The objectives are related to the modal residuals that measure the discrepancies between the measured and the FE model predicted modal characteristics (modal frequencies and mode shapes). Non-gradient and gradient-based optimization algorithms are used to compute the optimal solutions based on the measured data. These iterative algorithms require repeated solutions of the FE model for various values of the model parameters. Gradient-based optimization algorithms also require repeated computation of the gradients of the modal characteristics (frequencies and mode shapes) involved in the residuals. For high fidelity FE models with very high number of degrees of freedom, of the order of millions, repeated solutions of the modal characteristics and the gradients of the FE models are computationally very demanding. Dynamic reduction techniques can be incorporated in the finite element model updating formulation to alleviate the computational burden. In particular, component mode synthesis methods (CMS) [13] can be used to substantially reduce the number of generalized coordinates by several orders of magnitude.

3.2 Integration with CMS methods

CMS methods are well suited methods for substantially reducing the number of generalized coordinates and consequently the computational effort required for solving iteratively the single- and multi-objective optimization problems. CMS techniques divide the structure into sub-structural components with mass and stiffness matrices that are reduced using fixed-interface and constrained modes. Exploiting certain parameterization schemes often encountered in FE model updating, it can be shown that CMS allows the repeated computations to be carried out efficiently in a significantly reduced space of generalized coordinates [14], avoiding the repeated solution of the fixed-interface and constrained modes and the assembling of reduced system matrices for each function evaluation involved in the iterative process.

Specifically, for structural components behaving linearly, an efficient model updating technique arises for component mass and stiffness matrices that depend linearly on only one of the free model parameters to be updated. In this case the reduced mass and stiffness matrices of a component also depends linearly on the free model parameter, allowing significant computational savings to be achieved during optimization by avoiding the repeated computation of the fixed-interface and constrained modes of each component during the iterative process [14]. Using the resulting linear representation of the assembled mass and stiffness matrices of the reduced system in terms of the model parameters, computationally efficient algorithms [15] can be used to further reduce the computational cost involved in estimating the gradients and Hessians of the objective functions representing the modal residuals

4 APPLICATIONS

4.1 Health monitoring of Egnatia Odos Motorway bridges

A SHM system has been implemented on ten Egnatia Odos motorway bridges, instrumented by accelerometer networks and continuousely monitored for structural evaluation and maintenance purposes by the Bridge Maintenance Unit of Egnatia Odos S.A. These bridges include from East to West: Γ2 Kavala bridge, Γ9 and Γ10 Polymylos bridges, Γ1, Γ7, Γ8 bridges in Malakasi A-C motorway section, Metsovo bridge, T9 Peristeri bridge, Γ4 Krystallopigi Bridge and Mesovouni bridge. Recently, detailed high fidelity FE models based on solid tetrahedral elements have been developed for five of these bridges in an effort to improve the modelling of the bridges and the reliability of the SHM system. Bridge soil-foundation-structure interaction has been included in the modelling. In addition, nonlinearities manifested in structural components, such as bearings and dampers, under larger amplitude response can also be incorporated in the modelling. The sources of complexities in the FE modelling are the nonlinearities, activated under moderate and strong earthquake excitations, and the very large number of DOFs, of the order of hundred of thousands or even millions, due to the high fidelity FE models required for reliable SHM results. The CMS technique is a computationally efficient tool to handle these linear and nonlinear models for finite element model updating and SHM by reducing the large number of DOFs to a very small number.

4.2 FE model updating and SHM of Metsovo bridge

An application on the Metsovo bridge shown in Figure 1 is used to demonstrate the computational efficiency and accuracy of the reduced models in CMS-based FE model updating and SHM methodologies. The Metsovo bridge is the highest reinforced concrete bridge of Egnatia Motorway, with the height of the taller pier M2 equal to 110m. The total length of the bridge is 537m. The bridge has 4 spans, of length 44,78m, 117,87m, 235,00m, 140,00m and three piers of which pier M1, 45m high, supports the boxbeam superstructure through pot bearings (movable in both horizontal directions), while M2 and M3 piers (110m and 35m, respectively) connect monolithically to the superstructure and are founded on huge circular Ø12,0m rock sockets in the steep slopes of the Metsovitikos river, in a depth of 25m and 15m, respectively.

The commercial software package COMSOL Multiphysics [11] is used for developing the FE models of the bridge. The models were constructed based on the design plans, the geometric details and the material properties of the structure. Soil structure interaction is neglected in the present analyses. If needed, the soil can also be modeled by FEs or simplified spring models and be included as an extra component on the FE modeling. Detailed FE models for the bridge are created using three-dimensional tetrahedron solid FE to model the whole structure. An extra coarse mesh and quadratic Lagrange elements are chosen to predict the lowest 20 modal frequencies and mode shapes of the bridge. The selected size of the elements in the extra coarse mesh is the maximum possible one that can be considered, corresponding to the order of the thickness of the deck cross-section. The selected FE model, shown in Figure 2, has 563,586 DOFs. For demonstration purposes, the bridge is divided into fifteen physical components shown in Figure 3. Nine components are related to the four spans of the bridge, three components relate to the three piers, while the last three components relate to the head of the piers. The components associated with the piers also include the foundation of each pier. The retained modes per component and interface are based on the value of the component fixed-interface modal frequencies and interface constrained modal frequencies. Modes with modal frequencies less than $\rho\omega_c$ are retained, where ω_c is the cut off frequency selected to be the 20^{th} modal frequency for the whole structure that is of interest in our present application. The number of internal and

Figure 1. Metsovo bridge

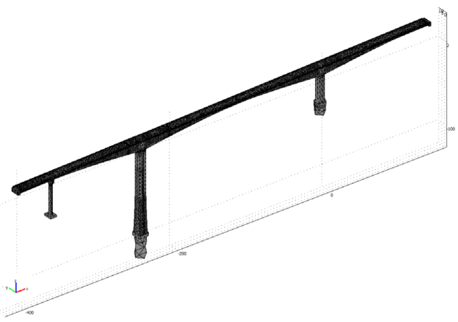

Figure 2. FE model (563,586 DOFs)

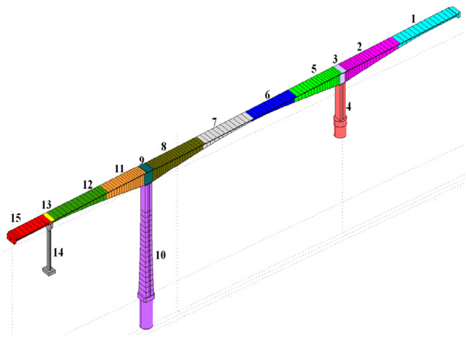

Figure 3. Substructuring (15 Components)

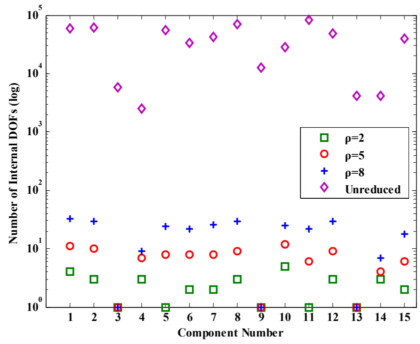

Figure 4. Number of GC per component

boundary DOFs along with the number of retained modes per component for three representative values of ρ=8, 5 and 2 are shown in Figure 4.

The finite element model is parameterized using seven parameters. The first four parameters θ_1 to θ_4 account for the stiffness of the four deck components, while the next three parameters θ_5 to θ_7 account for the stiff\ness of the piers of the bridge. The parameters scale the nominal values of the properties that they model so that the nominal finite element model corresponds to values of $\theta_1=\cdots=\theta_7=1$. The model updating is performed using 10 measured modes. Measured modal frequencies and mode shapes are simulated from the nominal FE model and are used for FE model updating. In order to examine the computational efficiency and the effectiveness of the proposed reduction techniques, results for the retained number of generalized coordinates and the achieved error between the estimated optimal model parameters and the exact values of the model parameters are given in Table 1. It is clear that extremely accurate results can be achieved by reducing the number of DOFs by more than three and even four orders of magnitude.

Table 1. Generalized coordinates (GC) and error in parameter estimates

	Reduction in Internal DOFs only	Error (%)	Reduction in Internal & Boundary DOFS	Error (%)
Full Model	563,586	0.00	563,586	0.00
Retained ρ=8	8,325	0.00	360	0.00
Retained ρ=5	8,150	0.10	155	0.10
Retained ρ=2	8,084	1.00	66	1.00

5 CONCLUSIONS

The proposed CMS techniques allow one to efficiently handle detailed linear and nonlinear high fidelity computational models of bridge components and thus improve damage identification capabilities in FE model-based SHM methodologies. The SHM framework can be used by highway managing authorities as part of an intelligent bridge management system to provide information useful for bridge monitoring and integrity assessment.

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