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Nonlinear finite element model updating for damage identification of civil structures using batch Bayesian estimation

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A B S T R A C T

This paper presents a framework for structural health monitoring (SHM) and damage identification of civil structures. This framework integrates advanced mechanics-based nonlinear finite element (FE) modeling and analysis techniques with a batch Bayesian estimation approach to estimate time-invariant model parameters used in the FE model of the structure of interest. The framework uses input excitation and dynamic response of the structure and updates a nonlinear FE model of the structure to minimize the discrepancies between predicted and measured response time histories. The updated FE model can then be interrogated to detect, localize, classify, and quantify the state of damage and predict the remaining useful life of the structure. As opposed to recursive estimation methods, in the batch Bayesian estimation approach, the entire time history of the input excitation and output response of the structure are used as a batch of data to estimate the FE model parameters through a number of iterations. In the case of non-informative prior, the batch Bayesian method leads to an extended maximum likelihood (ML) estimation method to estimate jointly time-invariant model parameters and the measurement noise amplitude. The extended ML estimation problem is solved efficiently using a gradient-based interior-point optimization algorithm. Gradient-based optimization algorithms require the FE response sensitivities with respect to the model parameters to be identified. The FE response sensitivities are computed accurately and efficiently using the direct differentiation method (DDM). The estimation uncertainties are evaluated based on the Cramer–Rao lower bound (CRLB) theorem by computing the exact Fisher Information matrix using the FE response sensitivities with respect to the model parameters. The accuracy of the proposed uncertainty quantification approach is verified using a sampling approach based on the unscented transformation. Two validation studies, based on realistic structural FE models of a bridge pier and a moment resisting steel frame, are performed to validate the performance and accuracy of the presented nonlinear FE model updating approach and demonstrate its application to SHM. These validation studies show the excellent performance of the proposed framework for SHM and damage identification even in the presence of high measurement noise and/or way-out initial estimates of the model parameters. Furthermore, the detrimental effects of the input measurement noise on the performance of the proposed framework are illustrated and quantified through one of the validation studies.

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1. Introduction

Existing vibration-based structural health monitoring (SHM) methods use measured input–output or output-only vibration data from a structure before and after a potentially damaging event. These methods typically track the changes in the identified modal properties to detect the occurrence of damage in the structural system. The modal properties are estimated assuming an equivalent linear elastic viscously damped structural model. Damage detection using structural modal identification methods is based on the premise that damage is manifested as a loss of effective stiffness over one or more regions of the structure. While loss of effective stiffness is a correct indication of damage, there are other important manifestations of damage in structural systems that cannot be identified by tracking the loss of effective stiffness. Loss of strength, loss of ductility capacity, softening, and/or residual deformations in one or more components of a structural system are all important physical expressions of damage that clearly cannot be addressed by SHM methods based on linear structural models. Furthermore, accurate SHM after a damage-inducing event requires the correct identification of these important manifestations of damage in the structural system.

This paper presents a framework for SHM and damage identification (DID) of structural systems by integrating advanced mechanics-based nonlinear finite element (FE) modeling and analysis techniques with Bayesian estimation methods. Bayesian methods are employed to update the nonlinear FE model of the structure using input–output data recorded during dynamic excitations of small, moderate, or large amplitude. A high-fidelity mechanics-based nonlinear FE model with updated model parameters is able to capture the complex damage/failure mechanisms in the structural system of interest. Therefore, the updated FE model can be interrogated for the purpose of post-earthquake SHM and DID. This can be accomplished by extracting from the updated FE model detailed information about various manifestations of damage in the structural components and system. Those damage features that are related to nonlinear material behavior such as strength deterioration, ductility demand, loss of ductility capacity, history of inelastic deformations, etc., are of particular interest for SHM and DID of civil structures. The proposed methodology can be used not only to detect the occurrence of damage, but also to localize, classify, and quantify the state of damage throughout the structural system at different scales, from the global system level to the local member, section, and fiber levels. This information is essential to accurately predict the remaining useful life of the structure, as well as the reliability and risk of operation. This paper is part of an extensive research effort that has been pursued by the authors in the field of SHM and DID of structural systems using a nonlinear FE model updating approach [1–5]. The authors have previously investigated the use of the extended Kalman filtering (EKF) [1,2] and the unscented Kalman filtering (UKF) [3,5] methods for nonlinear FE model updating. This paper investigates the use of a different class of approaches to solve the parameter estimation and nonlinear FE model updating problem.

The proposed framework for SHM and DID of structural systems is based on two long-lasting techniques in the field of SHM, namely FE model updating and nonlinear probabilistic (Bayesian) estimation. While the techniques employed are not new, the novelty of this paper lies in the careful integration of these well-established theoretical concepts and computational methods to provide a new framework for SHM and DID of civil structures. Defined as the process of calibrating or tuning a FE model to minimize the discrepancies between predicted and measured responses of the structure of interest, FE model updating is a powerful system identification methodology for structural systems [6,7]. Several FE model updating methods proposed in the literature are based on linear FE structural models (e.g., [6–9]). DID based on linear FE model updating has the ability to capture the loss of effective stiffness in the structural system; but, it can provide little or no information about other important manifestations of damage mentioned above. Moreover, since the behavior of actual civil structures is intrinsically nonlinear from the onset of loading, the assumption of linear elastic structural behavior underlying linear FE model updating is violated even for low amplitude loading. On the other hand, several nonlinear probabilistic estimation methods, including batch estimation methods (e.g., [10–13]) and recursive filtering methods (e.g., [14–22] to name a few) have been used in model-based methods for parametric identification of nonlinear structural models. However, applications of these estimation methods have been mostly limited to data simulated from highly idealized nonlinear structural models, such as single degree-of-freedom (DOF) systems, chain-like multi-DOF systems, and shear building models, which are very limited or unsuitable for realistic nonlinear response prediction of large and complex real-world civil structures. In other few research studies nonlinear estimation techniques have been used for nonlinear FE model updating of civil structures using experimental data [23,24]. These studies, however, have utilized simplified structural models with lumped nonlinearities modeled using empirical nonlinear material laws, such as the Bouc–Wen model. These simplified and empirical models are incapable of accurately representing the actual nonlinear behavior of civil structures. Other studies such as [25,26] have employed more advanced nonlinear FE modeling techniques and material constitutive models, but used simplistic estimation methods unable to evaluate the parameter estimation uncertainty.

The proposed SHM and DID framework based on nonlinear FE model updating provides a computationally feasible approach that is applicable to large and complex civil structures. The proposed framework also provides evaluation of the estimation uncertainty and hence, offers the proper tool for remaining useful life prediction (i.e., damage prognosis) and reliability analysis of civil structures following a damage-inducing event.