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Methodology for model updating of mechanical components with local nonlinearities

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ABSTRACT

In this work, we propose a new nonlinear model updating strategy based on global/local nonlinear system identification of the dynamics. The main objective of this study is to construct and update reduced-order models (ROM) of a dynamical system based solely on measured data. The approach relies on analyzing transient system responses (local dynamics) in the frequency–energy domain, and based on these, constructing damped frequency–energy plots – FEPs (global dynamics) under the assumption of weak damping. The system parameters are characterized and updated by matching the backbone branches of the FEPs with reduced-order model FEPs using experimental or computational data. The main advantage of this method is that the system model is updated solely based on simulation and/or experimental results. It follows that the approach is purely data-driven. By matching the frequency–energy dependences of the dynamics of the physical dynamical system and its reduced order model, we are able to identify, update and reconstruct not only the global features of the dynamics in the frequency and energy ranges of interest, but also the local dynamics, i.e., individual time series for specific initial or excitation conditions. Hence, this work paves the way toward a nonlinear model updating methodology with broad applicability. The main features of the proposed methodology are demonstrated with a system of nonlinearly coupled beams excited by a concentrated transient force.

1. Introduction

Predictions from analytical and computational models are often called into question when they conflict with test results. *Model updating* concerns the correction of these models by processing and integrating dynamic response data from test structures [1]. More specifically, finite element – FE model updating emerged in the 1990s as a topic thought to be very crucial for the design, construction and maintenance of mechanical systems and other engineering structures [2]. Reviews of existing FE model updating techniques are given in [1–4]. These give a clear overview of sensitivity-based updating

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Abbreviations: dof, degree-of-freedom; FE, finite element; NNM, nonlinear normal mode; FEP, frequency–energy plot; ROM, reduced-order model

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methods. Sensitivity-based FE model updating methods have been embraced for damage assessment and structural health monitoring applications, e.g., [5–7], but have been limited in application to linear systems.

Data-driven modeling and updating is an increasingly important field in science and engineering. There have been recent attempts to utilize this “data-driven” approach in model updating, e.g., [8–10]. Another model updating strategy proposed by [11] for nonlinear vibrations of structures, is based on proper orthogonal decomposition and its nonlinear generalizations as well as auto-associative neural networks [9] used data from relatively large-scale experimental soil–foundation–superstructure interaction (SFSI) systems to develop reduced-order computational models for response prediction, employing trained neural networks [10] applied a particle filtering algorithm on experimentally measured tip accelerations using Bayesian principles to estimate the changes in damping and flexural rigidity of a beam. Another Bayesian approach was proposed by Jensen et al. [12], wherein a Bayesian FE model updating strategy using dynamic response data is employed for structural response prediction.

Application of structural modification methods for data-driven modeling and updating were shown to be useful for large structures when the modifications remain local, i.e., when the nonlinearities in a dynamical system do not affect the global dynamics significantly [13]. We note, however, that these methodologies do not account for strongly nonlinear effects on the global dynamics, i.e., of the system dynamics over broad frequency and energy ranges, so they are only applicable to specific classes of dynamical systems; in addition, some functional form must be assumed for modeling the system nonlinearities. On the contrary, the nonlinear model updating methodology proposed in this work relies solely on measured time series, with no a priori assumption regarding the nonlinearity of the system. Hence, the proposed methodology is data driven and applicable to a broad range of dynamical systems.

In Fig. 1, the general outline of the proposed nonlinear model updating approach for a given dynamical system is presented. The first step is the measurement of the time series of the system responses. In order to estimate the global frequency–energy relationship in the dynamics we measure time series from a number of sensors throughout the system under transient excitation. Afterwards, we estimate the instantaneous frequency, amplitude, and the energy of the measured time series by applying numerical wavelet transforms (WTs), and superposing the resulting WT spectra onto a ‘reference’ frequency–energy plot – FEP representing the different branches of nonlinear periodic solutions of the underlying Hamiltonian system (i.e., the dynamical system with damping and forcing terms removed). A very useful feature of the ‘reference’ FEP for system identification purposes is its relation to the transient dynamics of the corresponding weakly damped system. This is due to the fact that *the effect on the dynamics of weak damping is expected to be parasitic*; that is, instead of introducing ‘new’ dynamics, weak damping just causes transitions of the transient damped dynamics between branches of normal modes of the underlying Hamiltonian system leading to multi-frequency nonlinear dynamical transitions. It has been shown that the superposition of a frequency–energy plot (FEP) depicting the periodic orbits of the underlying Hamiltonian system to the wavelet transform (WT) spectra of the corresponding weakly damped responses represents a suitable tool for analyzing energy exchanges and transfers taking place in the damped system [14–16]. Therefore, by utilizing this (empirical) frequency–energy dependence obtained from the superposition of the WT spectra onto the ‘reference’ FEP, we arrive at a nonlinearity model, since we can infer the properties of the nonlinearities in the frequency–energy domain, provided that the transient data covers the energy and frequency range of interest to the study. The parameters of the nonlinearity model are then optimized by comparing the numerical frequency–energy dependence derived from the simulations to the ‘reference’ Hamiltonian FEP computed numerically, e.g., using the software NNMcont as described by Peeters et al. [17].

In the following analysis we demonstrate the proposed nonlinear model updating technique by considering a system of two cantilever beams coupled by means of a geometrically nonlinear flexible element. Treating the nonlinear coupling element as the subject of model updating, we perform nonlinear system identification of this system and use the results for

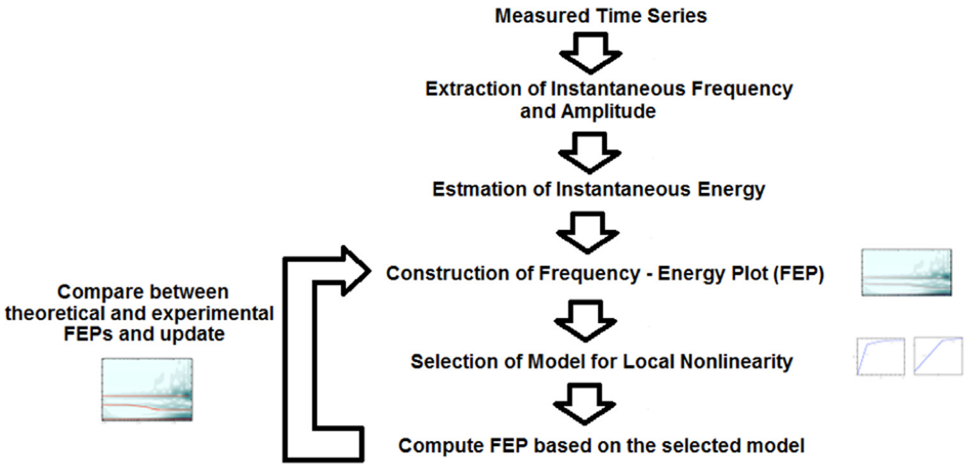

Fig. 1. Schematic diagram of the proposed nonlinear model updating approach.

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