Mechanical Systems and Signal Processing 105 (2018) 36–50

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Estimation of hysteretic damping of structures by stochastic subspace identification

Anela Bajrić *, Jan Høgsberg

Technical University of Denmark, DTU Mechanical Engineering, Nils Koppels Allé Building 403, 2800 Kgs. Lyngby, Denmark

ARTICLE INFO

Article history:
Received 14 April 2017
Received in revised form 6 September 2017
Accepted 27 November 2017

Keywords:
Output-only system identification
Non-linear restoring force
Hysteretic damping
Linearization
Relaxation damping
Random vibrations

ABSTRACT

Output-only system identification techniques can estimate modal parameters of structures represented by linear time-invariant systems. However, the extension of the techniques to structures exhibiting non-linear behavior has not received much attention. This paper presents an output-only system identification method suitable for random response of dynamic systems with hysteretic damping. The method applies the concept of Stochastic Subspace Identification (SSI) to estimate the model parameters of a dynamic system with hysteretic damping. The restoring force is represented by the Bouc-Wen model, for which an equivalent linear relaxation model is derived. Hysteretic properties can be encountered in engineering structures exposed to severe cyclic environmental loads, as well as in vibration mitigation devices, such as Magneto-Rheological (MR) dampers. The identification technique incorporates the equivalent linear damper model in the estimation procedure. Synthetic data, representing the random vibrations of systems with hysteresis, validate the estimated system parameters by the presented identification method at low and high-levels of excitation amplitudes.

1. Introduction

The validation of models for structures and machinery operating under random environmental and operational conditions is a crucial step for reliability and safety analysis. To such purpose, various system identification techniques [1–3] have been developed in order to estimate and validate the dynamic properties of the investigated structure, based on vibration measurements. However, the most commonly used output-only dynamic identification method [4] has been developed for linear time-invariant systems, and the extension of such to non-linear system parameter identification has still not received much attention.

The increasing complexitiy and flexibility of modern engineering structures give rise to nonlinearities in various forms, and often these become progressively more significant as the vibration amplitude increases. In this context, the target of the paper is to propose a parametric output-only identification methodology suitable for a single-degree-of-freedom oscillator driven by random excitation which exhibit hysteretic behavior. The detailed formulation of the nonlinear benchmark identification problem addressed is described in [5].

Hysteresis is usually triggered by high levels of dynamic loading that emphasize the nonlinear nature of dissipative and restoring forces, which depend on the history of the motion rather than instantaneous motion. The nonlinear nature of the

* Corresponding author.
E-mail address: abaj@mek.dtu.dk (A. Bajrić).

https://doi.org/10.1016/j.ymssp.2017.11.042

forces is significant in hysteretic behavior observed in large scale structures, when subjected to high levels of dynamic loading. Other examples of hysteretic properties can be encountered in magnetic, ferromagnetic and ferroelectric materials which are found in vibration mitigation devices such as Magneto-Rheological (MR) dampers [6].

Identification methods of systems affected by hysteretic behavior classified as input–output techniques are discussed in [7]. These include approaches based on evolutionary algorithms [8,9], Bayesian inference methods [10], Markov Chain Monte Carlo methods [11] and a recent frequency domain approach with black-box optimization for nonlinear estimation [12]. The input–output methods are limited to structures for which the excitation is measurable. A different identification strategy is necessary for dynamically excited structures with unmeasured and uncertain excitation, often experienced in connection with large structures or machinery where no straightforward way allows the excitation to be measured.

A classical approach for estimation of stochastic dynamic systems is the Kalman filtering for a state estimation [13] or the realization theory for estimation of the system based on random response. The latter is incorporated in the time domain operational modal analysis methods [14], which are limited to linear and time-invariant systems. Extensions of the classical Kalman filtering approach enable joint input and state estimation at locations of interests of sparsely monitored dynamic structures [15,16]. The state prediction of structures can also be applied for structural health monitoring as in [17], which demonstrates that the statistical properties of the states can be regarded as a damage indicator. The joint state and input estimation for structural applications assume a known representative finite element model of a linear system, and are associated with a heavy computational burden when using the Kalman filter, which can be reduced by a model reduction scheme [18]. Moreover the joint state and input estimation is numerically unstable and results in unreliable input estimation when based on acceleration measurements [19], which are unfortunately often the only measurable signal available for a dynamic structure.

The numerical issues associate with observability and rank deficiency are treated in the augmented joint state-input estimation proposed in [20] and experimentally demonstrated in [21], also for a system with known model parameters. In [22–24] an online parametric identification based on Kalman filtering for state estimation is proposed for the non-linear hysteretic system. More recently [25] also proposed a joint state-parameter-input estimation method for linear time varying systems, which has the advantages of being able to cope with mode veering effects. It has been applied in [26] for tracing the time varying stiffness properties of an offshore wind turbine structure. The drawback of the method in [25] is that the number of measurements must be at least as many as the number of parameters and inputs of interest, and at least as many displacement measurements as unknown inputs. This approach is therefore not suitable for the parametric output-only identification of the hysteretic system in the present benchmark challenge, where only a single response output is available.

The existing output-only identification strategies offer limited estimation accuracy for identification of nonlinearities in dynamic structures and limited attention is in particular offered for the estimation of mechanisms related to energy dissipation, which may be a dominant source of nonlinearity. The existing output-only techniques may therefore in particular fail for nonlinear systems which are excited by high-levels of amplitude. Systems with nonlinear damping mechanisms can be well represented by equivalent linear models [27], but may not be representative when the nonlinearities in the stiffness are severe and cause jump and bifurcation phenomena. A review of the diverse sources of nonlinear damping in practical systems is given in [27] as well as linearization techniques. Regardless of the philosophy of the identification method, the dynamic nonlinearities in hysteretic systems are difficult to identify, since it is not possible to directly measure the internal state variable which controls the hysteretic evolution. The parameter identification of the hysteretic system is herein treated by deriving an equivalent linear relaxation model, whose parameters depend on the magnitude of the excitation and frequency. Such an implicit model offers a system format that is observable and controllable, and simplifies the analysis. This leads to a computationally efficient identification methodology that extends the classical output-only covariance driven stochastic subspace identification [4] and its ability to estimate the model stiffness and damping at varying amplitudes of excitation.

The Bouc-Wen model [28,29] is proposed for the synthetic generation of data for the identification challenge, which is used extensively in modeling of the hysteresis phenomenon in dynamically excited nonlinear structures [30,31]. Various suitable methods are developed in structural dynamics as means for solving nonlinear stochastic problems [32–34], such as the Bouc-Wen model. These rely on linearization techniques and are commonly useful for approximate techniques in the first design stage. Therefore, an obvious method for solving the nonlinear identification challenge is to replace the governing set of nonlinear differential equations by an equivalent set of linear equations. The linearization turns out to be an advantage, which enables the output-only covariance driven stochastic subspace identification to be applied for the benchmark challenge. The starting point of the system identification is the ability to estimate the model parameters of single output.

The proposed method is therefore an approach suitable for a single-degree-of-freedom oscillator with viscoelastic properties. In the case of a Gaussian excitation, the response of a weakly nonlinear system can be assumed to approach a Gaussian distribution [34]. The identification procedure can therefore be appropriately based on the statistical properties which are necessary for the covariance driven identification methods. The novel method estimates the parameters of a dynamic model in the form of coupled ordinary differential equations, wherein the hysteresis phenomenon is represented by the Bouc-Wen model. The model parameters are related through derived expressions of the parameters of a linear relaxation damping model. To validate the proposed identification method a synthetic data set with unknown signal noise is made available from the source [5]. The effect of the equivalent linear model on the identification of the hysteretic system is discussed and the