Mechanical Systems and Signal Processing 48 (2014) 247–259

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Nonlinear structural damage detection based on cascade of Hammerstein models

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ARTICLE INFO

Article history:
Received 12 September 2013
Received in revised form
6 March 2014
Accepted 19 March 2014
Available online 6 April 2014

Keywords:
Structural health monitoring
Nonlinear system identification
Principal component analysis
Damage detection
Damage quantification

ABSTRACT

Structural damages result in nonlinear dynamical signatures that can significantly enhance their detection. An original nonlinear damage detection approach is proposed that is based on a cascade of Hammerstein models representation of the structure. This model is estimated by means of the Exponential Sine Sweep Method from only one measurement. On the basis of this estimated model, the linear and nonlinear parts of the outputs are estimated, and two damage indexes (DIs) are proposed. The first DI is built as the ratio of the energy contained in the nonlinear part of an output versus the energy contained in its linear part. The second DI is the angle between the subspaces obtained from the nonlinear parts of two sets of outputs after a principal component analysis. The sensitivity of the proposed DIs to the presence of damages as well as their robustness to noise is assessed numerically on spring–mass–damper structures and experimentally on composite plates with surface-mounted PZT-elements. Results demonstrate the effectiveness of the proposed method to detect a damage in nonlinear structures and in the presence of noise.

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1. Introduction

The process of implementing a damage detection strategy for aerospace, civil, and mechanical engineering is the first step of structural health monitoring (SHM) [1]. In many cases, damages that appear on complex structures (such as cracks, impacts, or delaminations) generate nonlinear dynamical responses that may be used for damage detection [2–5]. Furthermore, complex structures often exhibit a nonlinear behavior even in their healthy states. A robust and reliable SHM system must then be able to deal with nonlinear damages, and to distinguish between their effects and inherent nonlinearities in healthy structures. Several limitations of existing methods that are facing these issues have been recently identified in a report by Farrar et al. [2]. The first problem to be addressed is that "*nonlinear behavior does not generalize*". This implies that the nonlinear models already in use are never general enough to encompass all the structures encountered in real life. The second problem is that "*nonlinear approaches are computationally cumbersome, expensive, and requires too many parameters to be defined*". Currently developed nonlinear models are thus not adequate for practical use of SHM systems. The work presented here attempts to face these two problems on the basis of a simple nonlinear model identified by means of standard signal processing procedures.

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http://dx.doi.org/10.1016/j.ymssp.2014.03.009
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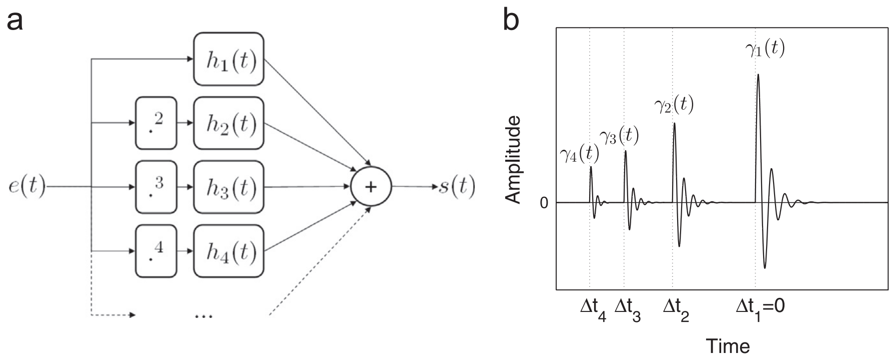

Fig. 1. (a) Cascade of Hammerstein model and (b) temporal separation after deconvolution.

In order to build a damage index (DI) that is sensitive to nonlinearities, different approaches have already been proposed [2,3]. Some DIs are based on a physical modeling of the damaged structure whereas some are computed without any physical assumption (black-box models). Among these black-box approaches, some assume a parametric underlying signal processing model, whereas some are fully non-parametric. To feed these models, random inputs as well as deterministic broadband or narrowband inputs are used. In this paper, the focus is put on nonlinear damage detection approaches based on DIs built using a non-parametric black-box model estimated using a deterministic broadband signal.

There have been relatively few works in that direction. In a linear framework, some authors [6,7] have shown that a nonlinear damage will impact the transmissibility functions (*i.e.* the frequency domain ratio between two different outputs of the system) and they used such information to detect and locate the damage. Extending the notion of transmissibility functions to nonlinear systems that can be described by Volterra series, Lang et al. [8,9] were able to quantify the decrease of linearity generated by a nonlinear damage and thus to effectively detect and locate it. However, as such approaches are focusing on the loss of linearity, they do not seem to be able to deal with systems that are nonlinear in their healthy states, a fact that is quite common in real life. To overcome this drawback, several authors attempted to fit a nonlinear model to the nonlinear structure under study and to compare the actual and predicted outputs, or directly the model coefficients, under different damage conditions [10–14]. By doing so, they were able to detect numerically and experimentally a nonlinear damage even in an initially nonlinear structure. However, the models they used were parametric (mainly frequency domain ARX models) and thus were not easy to manipulate and neither able to model, without any *a priori* on it, a general nonlinear structure.

We propose here an original approach devoted to nonlinear damage detection in possibly nonlinear structures based on a simple nonlinear model estimated by means of standard signal processing tools. This approach is based on the assumption that the structure under study can be modeled as a cascade of Hammerstein models [15], made of N branches in parallel composed of an elevation to the nth power followed by a linear filter called the nth order kernel, see Fig. 1(a). The Exponential Sine Sweep Method [16,17], previously developed and validated by the authors for different purposes, is then used to estimate the different kernels of the model. Exponential sine sweeps are a class of sine sweeps that allow estimating a system's N first kernels in a wide frequency band from only one measurement. Two damage indexes are then built on the basis of this estimated model. The first one reflects the ratio of the energy contained in the nonlinear part of the output versus the energy contained in its linear part and is specially suited for single-input single-output (SISO) systems. The second one is the angle between subspaces described by the nonlinear parts of two sets of outputs after a principal component analysis [18–22]. This one is specially suited for single-input multi-output (SIMO) systems. As a first step toward the use of this method for SHM, the sensitivity of the proposed DIs to the presence of damages as well as their robustness to noise is assessed numerically on SISO and SIMO systems and experimentally on two actual composite plates with surface-mounted PZT-elements (one healthy and one damaged).

The cascade of Hammerstein models as well as the mathematics behind it is first described in Section 2. The two proposed DIs are then defined in Section 3. Their sensitivity to the presence of damages as well as their robustness to noise is assessed numerically in Section 4 and experimentally in Section 5. A general conclusion is finally drawn in Section 6.

2. Cascade of Hammerstein models estimation using the exponential sine sweep method

2.1. Cascade of Hammerstein models

A possible approach to non-linear system identification is to assume that systems have a given block-structure. Following the "*sandwich*" approach [15], a non-linear system can be represented as N parallel branches composed of three elements in series: a static non-linear part sandwiched between two linear parts. Such systems are a subclass of Volterra systems and it can be shown that any continuous non-linear system can be approximated by such a model [23].

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