Mechanical Systems and Signal Processing 46 (2014) 91–113

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Experimental system identification of the dynamics of a vibro-impact beam with a view towards structural health monitoring and damage detection

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ARTICLE INFO

Article history:
Received 26 September 2012
Received in revised form
19 December 2013
Accepted 27 December 2013
Available online 24 January 2014

Keywords:
Nonlinear system identification
Empirical mode decomposition
Intrinsic modal oscillator
Nonlinear interaction model
Structural health monitoring

ABSTRACT

We perform nonlinear system identification (NSI) on the acceleration signals that were experimentally measured at ten, almost evenly spaced positions along a cantilever beam undergoing vibro-impacts between two rigid stops with clearances. Our goal is to characterize the nonlinear dynamics due to vibro-impacts with a view toward structural health monitoring (SHM) and damage detection (DD). The NSI methodology is based on the correspondence between analytical and empirical slow-flow dynamics, with the first step requiring empirical mode decomposition (EMD) analysis of the measured time series leading to sets of intrinsic modal oscillators (IMOs) governing the vibro-impact dynamics at different time scales. By comparing the spatiotemporal variations of the nonlinear modal interactions (and hence the IMOs), we examine how vibro-impacts influence the low- and high-frequency modes in global and local senses. In applications of the NSI results to SHM/DD, we calculate typical measures such as the modal assurance criterion (MAC) and the coordinate modal assurance criterion (COMAC) by extracting information about the mode shape functions from the spatiotemporal IMO solutions. Whereas the MAC provides a global aspect of damage occurrence (i.e., which modes are more affected by induced defects), the COMAC can narrow down the damage locations (i.e., where in the structure defects exist that yield low correlation values in specific modes).

Acronyms: COMAC, coordinate modal assurance criterion; DD, damage detection; DOF, degree-of-freedom; EMA, experimental modal analysis; EMD, empirical mode decomposition; FEP, frequency–energy plot; FT, Fourier transform; HF/LF, high-/low-frequency; HT, Hilbert transform; IMF, intrinsic mode function; IMO, intrinsic modal oscillator; MAC, modal assurance criterion; NIM, nonlinear interaction model; NSI, nonlinear system identification;
POD, proper orthogonal decomposition; ROM, reduced-order model; SHM, structural health monitoring; VI, vibro-impact

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http://dx.doi.org/10.1016/j.ymssp.2013.12.014

1. Introduction

It is only recently that a nonlinear system identification (NSI) methodology based on close correspondence between analytical and empirical slow-flow dynamics was proposed [1–3] and applied to studies of targeted energy transfers in 2-degree-of-freedom (DOF) coupled oscillators [2], the triggering and suppression mechanisms of aeroelastic instabilities [4], and study of the dynamics of an elastic continuum with an essentially nonlinear end attachment [5]. The NSI method utilizes empirical mode decomposition (EMD [6]) along with the use of mirror-image and masking signals to enhance its resolution [1]. EMD is suitable for analysis of measured time responses that exhibit strong nonlinearity and nonstationarity, in particular when the tested systems involve nonlinearities caused by multi-physics nonlinear interactions [7]. In this case, Fourier-transform (FT)-based methods, such as traditional experimental modal analysis (EMA) under the assumption of linearity and stationarity of the measured signals [8], may not be capable of properly isolating and extracting the nonlinearity and nonstationarity from the measured data, frequently leading to wrong conclusions (for example, to misinterpretations of internal and combination resonances as natural frequencies).

One of the basic assumptions for EMD analysis is that the measured time series can be decomposed in terms of a finite number of components oscillating at their own intrinsic time scales; in other words, they are in the form of fast, (nearly) monochromatic oscillations modulated by slowly varying amplitudes. Such slowly varying components enable us to establish empirical slow-flow models of the dynamics, which paves the way for constructing physics-based local nonlinear interaction models (NIMs) [2]. A NIM consists of a set of intrinsic modal oscillators (IMOs) that can reproduce the measured time series over different time scales and account for (even strongly) nonlinear modal interactions across scales. Hence, it represents a *local* model of the dynamics, identifying specific nonlinear transitions. By collecting energy-dependent frequency behaviors from all identified IMOs, a frequency–energy plot can be constructed, which depicts *global* features of the dynamical system. The method requires no *a priori* system information but only measured (or simulated) time series; i.e., it is purely an *output-based* approach and is suitable for *data-driven dynamics modeling* [3].

Reviews of NSI and reduced-order modeling methods are provided in Kerschen et al. [9,10]. Typical nonparametric methods include proper orthogonal decomposition (POD [11–14]), smooth orthogonal decomposition [15], Volterra theory [16,17], Kalman filter [18], and so on. As for the methods of nonlinear parameter estimation, there are the restoring force surface method [19], NARMAX (Nonlinear Auto-Regressive Moving Average models with eXogenous inputs) methods [20], the harmonic balance method [21], and methods based on Hilbert transform [22,23].

Use of POD has been rather popular in studying system identification and nonlinear normal modes of coupled beams and rods [24,25], and in structural damage detection [26]. For example, the method of POD has been utilized for studying chaotic vibrations of a 10-DOF impact oscillator and a flexible-beam impact oscillator in Cusumano et al. [27,28]. In these studies, the spatial structure of impacting responses under a harmonic excitation of the boundary was demonstrated to be close to what can be obtained by averaging over many impulse-response tests on the linear system (even if the system is strongly nonlinear). Moreover, POD was applied for model reduction of a vibro-impact (VI) rod [29], and also for extracting dominant *coherent* structures of a VI beam from experimental time-series data [30] with the goal of eventually deriving low-dimensional reduced-order models through a Galerkin reconstruction process based on the extracted mode shape functions. We note, however, that these techniques are only applicable to specific classes of dynamical systems, requiring certain functional forms for the system nonlinearity, and that some POD modes are often spurious in practical applications, lacking physically meaningful information.

On the other hand, the nonlinear dynamics of a VI beam (whose setup is similar to that used in [30]) was explored in Kurt et al. [31] by performing the aforementioned EMD-based NSI on the numerical simulation data. By comparing the spatiotemporal variations of the nonlinear modal interactions extracted from the empirical slow-flow models for the vibro-impact beam and the underlying linear beam, it was demonstrated that the lower intrinsic modes are more significantly affected by vibro-impacts through strongly nonlinear modal interactions, whereas the higher modes tend to retain their linear dynamics between impacts. In this work, we perform NSI analysis on experimental acceleration signals measured at ten, almost evenly spaced positions along a cantilever beam. Our results lead to similar conclusions as were drawn from the previous work based on a purely computational study [31]. Moreover, we discuss implications of the NSI results with a view toward structural health monitoring and damage detection in practical applications.

2. Nonlinear system identification methodology: a brief review

In this section, we provide a brief review of the nonlinear system identification (NSI) methodology introduced in [2,3], which was also provided in Kurt et al. [31]. The first step of the NSI methodology is to perform empirical mode decomposition (EMD) [1,6] on the measured time series, which yields a complete and nearly (but not completely) orthogonal basis of intrinsic mode functions (IMFs) at each sensing location. These are oscillatory modes embedded in the time series, each with its own characteristic time scale, whose linear superposition reconstructs the measured time series. Hence, EMD provides a multi-scale decomposition of a measured time series in terms of embedded oscillatory modes in the measured data at different time scales of the dynamics. Although EMD was originally conceived as an *ad hoc* decomposition method, as discussed below it can be provided with a physics-based foundation.

The main loop of the EMD algorithm [6] for extracting the IMFs from a signal $x(t)$ consists of the following steps: (i) identify all extrema of $x(t)$; (ii) perform (spline) interpolations between minima (maxima), resulting in an envelope