Journal of Sound and Vibration 417 (2018) 182–197

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Structural system identification based on variational mode decomposition

Abdollah Bagheri [a], [*], Osman E. Ozbulut [b], Devin K. Harris [b]

[a] Department of Mechanical Engineering, University of Maryland, College Park, MD 20742, USA
[b] Department of Civil and Environmental Engineering, University of Virginia, Charlottesville, VA 22904, USA

ARTICLE INFO

Article history:
Received 16 December 2016
Received in revised form 4 December 2017
Accepted 7 December 2017

Keywords:
Modal data identification
Response decomposition
Variational mode decomposition
Modal response
Modal frequency

ABSTRACT

In this paper, a new structural identification method is proposed to identify the modal properties of engineering structures based on dynamic response decomposition using the variational mode decomposition (VMD). The VMD approach is a decomposition algorithm that has been developed as a means to overcome some of the drawbacks and limitations of the empirical mode decomposition method. The VMD-based modal identification algorithm decomposes the acceleration signal into a series of distinct modal responses and their respective center frequencies, such that when combined their cumulative modal responses reproduce the original acceleration response. The decaying amplitude of the extracted modal responses is then used to identify the modal damping ratios using a linear fitting function on modal response data. Finally, after extracting modal responses from available sensors, the mode shape vector for each of the decomposed modes in the system is identified from all obtained modal response data. To demonstrate the efficiency of the algorithm, a series of numerical, laboratory, and field case studies were evaluated. The laboratory case study utilized the vibration response of a three-story shear frame, whereas the field study leveraged the ambient vibration response of a pedestrian bridge to characterize the modal properties of the structure. The modal properties of the shear frame were computed using analytical approach for a comparison with the experimental modal frequencies. Results from these case studies demonstrated that the proposed method is efficient and accurate in identifying modal data of the structures.

1. Introduction

Recent advances in sensor technology have accelerated the development of structural health monitoring systems on large-scale civil structures. Spatially sparse measurements from these sensors have enabled the identification of dynamic properties of civil structures, which have proven beneficial for validation of design assumptions [1,2], damage detection [3–8], rehabilitation assessment [9,10], vibration serviceability assessment [11–13], and condition assessment [14–16]. As forced vibration testing of buildings or bridges is not easy and often costly, system identification methods that utilize only measured response (e.g. output only) are attractive options for these large-scale civil engineering applications. In the domain of modal identification, numerous algorithms have been developed and employed using output-only data [17–19].

---

[*] Corresponding author.
E-mail addresses: ab8sa@virginia.edu, bagheri@umd.edu (A. Bagheri).

https://doi.org/10.1016/j.jsv.2017.12.014

One approach for identifying modal properties such as natural frequencies and mode shapes is to transform the measured time-domain signal into frequency domain. Most of these frequency domain algorithms are based on spectral density functions. The peak-picking method [20], frequency domain decomposition [21,22], enhanced frequency domain decomposition [23], and frequency—spatial domain decomposition [24] are among those algorithms. A fundamental challenge for many of these methods is that they are not effective for the closely spaced modes. In addition, modal identification becomes more challenging for the signals with high noise or nonstationary characteristics. Moreover, long data segments are usually needed for reliable spectral estimates. Another approach for system identification includes time-domain methods such as the stochastic subspace identification (SSI) methods, the proper orthogonal decomposition (POD), and the empirical mode decomposition (EMD) that are based on decomposing measured response to a set of sub-signals [25–30]. The SSI techniques are the most well-known time-domain method and perform the modal parameter estimation over raw measured time series [31,32]. SSI takes the advantage of state space modeling, which reduces the second order problem into two first order problems. In general, SSI looks for a set of parameters that will minimize the deviation between the predicted system response of the model and measured system response. The POD method has been widely applied in fluid dynamic field [33,34]. This method is also known as singular value decomposition, principal component analysis or Kahunen-Loeve expansion in other fields [33]. The basic idea behind this decomposition algorithm is to construct an optimal basis which represents most of the data variance with as few basic functions. This method has been used to extract modal properties as an eigenvalue problem which needs displacement signals and a prior knowledge of the mass matrix of system [35–37]. If acceleration signals are used for system identification, both mass and stiffness matrices of structure, which are unknown, are required. Therefore, displacement signals are obtained by integrating acceleration signals that is not an accurate approach. The empirical mode decomposition (EMD) is a well-known algorithm within this category that is widely used to decompose a signal. The EMD method decomposes a signal into intrinsic mode functions (IMFs), where each IMF has a separate spectral bond [38] and is considered as an estimate of the modal responses. Several researchers have even combined the EMD algorithm with the Hilbert transform to identify modal characteristics [25,26,39]. The Hilbert transform enables the representation of a signal in the frequency-time domain, which presents the instantaneous frequency at each time instant. For modal properties identification, the Hilbert transform is applied to each IMF of an acceleration signal to transfer the modal response into the time-frequency domain and then modal parameters are obtained. However, the IMFs extracted using the EMD method include mode mixing effects and have a range of frequencies, i.e. not a single frequency [40]. In addition, the EMD method has some limitations such as sensitivity to noise and sampling frequency used in recording signals, and its performance varies with the frequency ratio and amplitude ratio of modes [41].

To overcome these limitations, the variational mode decomposition (VMD) method has recently been proposed as a new approach for decomposing a signal [40]. The VMD method decomposes an input signal into a number of distinct sub-signals where each sub-signal has a center frequency and collectively reproduce the input signal. The method is entirely non-recursive and the sub-signals are extracted concurrently. It has been shown that the VMD approach outperforms the EMD method in its application to the areas such as tone detection and separation [40], seismic signal analysis [42], and mechanical fault diagnosis [43].

Building from this body of knowledge, this paper presents an output-only identification method based on the VMD for dynamic characterization of engineering structures. In this method, the measured acceleration signals from a structural system are first decomposed into the modal responses using the VMD algorithm. Then, damping ratios are computed by implementing a fitting process on the decaying amplitude of the modal response. Using this approach, all natural frequencies and damping ratios are able to be identified using only a single acceleration response measurement at a suitable location. When these results are combined with data obtained from multiple sensor locations on the structure, mode shapes can also be identified. In contrast with the POD-based modal data identification methods, the proposed method does not require the mass matrix of the system and displacement data for modal identification. The POD uses a classic approach that encourages reconstruction fidelity, whereas the VMD combines a quadratic penalty and Lagrangian multipliers. To illustrate the efficiency of the proposed method for modal identification, a series of numerical and experimental case studies were evaluated. These case studies included analysis of the vibration responses of a laboratory scale model of a three-story shear frame and full-scale in service pedestrian bridge.

2. Modal data identification algorithm

Fig. 1 illustrates the workflow for identifying modal characteristics using the VMD method for system identification. The workflow consists of three main steps: 1) modal responses and natural frequencies are extracted from a measured acceleration signal using the VMD; 2) modal damping ratios are obtained by fitting a function to the decaying amplitude of modal response; and 3) process is repeated for all installed sensors on the selected structure and mode shape vectors are identified. Each of these steps is described in detail in the following sub-sections.

2.1. Extracting modal responses and frequencies

The VMD is used to decompose an acceleration signal $S(t)$ into a set of sub-signals (modes), $S_k(t)$, $k = 1, 2, \ldots, K$, which have compact bandwidths in the spectral domain. It can be assumed each sub-signal is compacted around a corresponding center