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Wavelet-based detection of abrupt changes in natural frequencies of time-variant systems

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ABSTRACT

Detection of abrupt changes in natural frequencies from vibration responses of time-variant systems is a challenging task due to the complex nature of physics involved. It is clear that the problem needs to be analysed in the combined time–frequency domain. The paper proposes an application of the input–output wavelet-based Frequency Response Function for this analysis. The major focus and challenge relate to ridge extraction of the above time–frequency characteristics. It is well known that classical ridge extraction procedures lead to ridges that are smooth. However, this property is not desired when abrupt changes in the dynamics are considered. The methods presented in the paper are illustrated using simulated and experimental multi-degree-of-freedom systems. The results are compared with the classical Frequency Response Function and with the output only analysis based on the wavelet auto-power response spectrum. The results show that the proposed method captures correctly the dynamics of the analysed time-variant systems.

1. Introduction

Identification of natural frequencies and their in-operational changes is important for many engineering structures. It is well known that natural frequencies depend on structural mass and stiffness. Both physical parameters are often constant over the entire life of structures. However, mass and stiffness changes are quite common during the construction or operation of structures. Stiffness gain due to concrete curing process over construction time or mass gain due to additional non-structural systems and components (e.g. precast cladding) can lead to changes in natural frequencies that are often observed during the construction [1,2]. Mass additions – due to structural re-design or placement of heavy interior equipment – and stiffness reduction – that builds up over a long period of time due to structural deterioration – are also common during the operation of many structures and result in changes of natural frequencies [3]. The dynamics of such phenomena can be easily captured using experimental modal analysis and operation modal analysis. The changes of natural frequencies are temporal and can be monitored using one of the state-of-the-art input–output identification methods—such as Observer/Kalman Filter Identification combined with Eigensystem Realization Algorithm (OKID-ERA) [4] – and output-only identification methods – such as for example Data-Driven Stochastic Subspace Identification (SSI-DATA) [5] or Natural

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Excitation Technique combined with Eigensystem Realization Algorithm (NExT-ERA) [6] techniques or with the use of modal filtering [7,8].

The real challenge relates to detection of abrupt changes in natural frequencies due to sudden stiffness reduction. In contrast to continuous changes of stiffness abrupt changes are more likely caused by structural damage. This event is quite common in construction engineering and results from sudden structural damage that can be related to continuous degradation of material or beam/truss failures and to sudden collapse of soil or earthquake events. Time-variant systems that exhibit abrupt changes of physical parameters are not easy to analyse. This is mainly due to the uncertainty of various transient states that need to monitored continuously. Abrupt changes in natural frequencies are often associated with sudden disappearing and/or appearing of one or several vibration modes at a given moment of time. This is a very common problem when dealing with high-speed rail systems [9,10]. Analysis of such events require specific tools that have been developed for time-variant systems.

Various input–output and output-only approaches can be used for identification of time-variant systems. Altogether these approaches can be divided into two major groups, i.e. parametric and non-parametric methods. The former methods are based on models that are often of the form of polynomials with unknown coefficients. Examples within this group of methods include various time-dependent parametric methods such as the well-known Time-dependent Auto-Regressive (TAR) and Time-dependent Auto-Regressive Moving-Average (TARMA) techniques, Recursive Maximum Likelihood estimated TARMA (RML-TARMA), Smoothness Priors TARMA (SP-TARMA), Functional Series TARMA (FS-TARMA) and other variations of these models, are discussed in [11,12]. The latter – i.e. non-parametric – group of method for the analysis of time-variant systems assumes no *a priori* information about such systems. These methods usually involve the analysis of both, i.e. time and frequency contents of excitation and/or response. Therefore the Cohen's class of time–frequency representations [13] provides a natural non-parametric framework for the non-parametric time-variant approaches. Although there are many members of the Cohen's family of methods – such as the well-known Short Time Fourier Transform (STFT) or the Wigner–Ville distribution – the continuous wavelet transform [14,15] is a time-scale method that is qualitatively different from all other members. Wavelet-based methods employ different types of shifted and dilated wavelet functions to analyse and/or decompose signals. Various wavelet-based approaches have been developed for time-variant system identification, as reviewed in [16,17]. Examples include: damping estimation techniques [18–20], methods for estimation of instantaneous frequency and rotational velocity [21], methods for nonlinear system analysis [22], online identification techniques based on adaptive wavelets [23–25], identification of sudden changes with use of Discrete Wavelet Transform [26], wavelet-based transfer functions [27], or wavelet based state-space methods [50].

Other than time–frequency and time-scale approaches investigated include the empirical mode decomposition [28,29,49] and various adaptive transfer functions that have been used mainly for periodic rather than abrupt time-variances [30–35]. Output-only methods can be also used for the analysis of time-variant systems. Application examples includes: peak picking, frequency domain decomposition, random decrement technique, Ibrahim time-domain method, least square complex exponential method, stochastic subspace identification algorithm, various modified ARMA approaches, as reviewed in [16].

A few important attempts have been made to introduce time-variant FRFs. Methods based on evolutionary spectra [36,37], frozen spectra [11,38–40], Littlewood–Paley wavelets [23], time–frequency analysis [41] have been proposed. The majority of these developments are adaptive approaches. The wavelet-based FRF – proposed in [42,43] – is one of the non-adaptive exceptions. This method has been recently extended to give theoretical background together with physical interpretation [44] and to provide a full framework for modal analysis and system identification [44–46].

It appears that the majority of the methods previously proposed for the analysis and identification of time-variant systems do not provide accurately the time instant that can be associated with abrupt changes to modal parameters. The major objective of the paper is to propose the application of the input–output algorithm – that utilises the wavelet-based FRF – for detection of abrupt changes in natural frequencies (or frequencies dominating the response) of time-variant systems. The magnitude and phase of the wavelet-based FRF is used for the identification. The major focus is on ridge extraction and occupation measures applied to the FRF characteristics and the estimation of time instants for the abrupt changes in natural frequencies. It is well known that ridge extraction algorithms produce smooth ridges that can blur the accurate moment when the abrupt change occurs.

The structure of the paper is as follows. The wavelet spectra and the wavelet-based FRF are briefly described in Section 2. Numerical implementation of the method used is presented in Section 3. The proposed methodology for detection of abrupt changes in natural frequencies of time-variant systems is illustrated using multi-degree-of-freedom simulated and experimental examples in Sections 4 and 5, respectively. The experimental work utilises the model of a three-floor building structure. The results presented in Sections 4 and 5 demonstrate good performance and practicality of the approach used. Finally, the paper is concluded and the future work is proposed in Section 6.

2. Wavelet-based methods for the analysis of time-variant systems

This section briefly introduces wavelet-based output-only and input–output approaches for the analysis and identification of time-variant systems. The former involves the wavelet auto-power spectra that can be applied to vibration responses from time-variant systems. The latter applies the wavelet-based FRF.