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Combined non-parametric and parametric approach for identification of time-variant systems

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ABSTRACT

Identification of systems, structures and machines with variable physical parameters is a challenging task especially when time-varying vibration modes are involved. The paper proposes a new combined, two-step – i.e. non-parametric and parametric - modelling approach in order to determine time-varying vibration modes based on input-output measurements. Single-degree-of-freedom (SDOF) vibration modes from multi-degree-of-freedom (MDOF) non-parametric system representation are extracted in the first step with the use of time-frequency wavelet-based filters. The second step involves time-varying parametric representation of extracted modes with the use of recursive linear autoregressive-moving-average with exogenous inputs (ARMAX) models. The combined approach is demonstrated using system identification analysis based on the experimental mass-varying MDOF frame-like structure subjected to random excitation. The results show that the proposed combined method correctly captures the dynamics of the analysed structure, using minimum *a priori* information on the model.

1. Introduction

In-operational vibration analysis is important for many engineering applications. Vibration modes can be used to track abrupt or gradual deterioration of mechanical systems, structures and machines from pre-assumed operating conditions. It is well known that natural frequencies and damping ratios of time-variant systems depend on variable physical parameters. In many cases this dependency is not straightforward due the complex nature of physics involved.

Mass-variable systems studied in this work are special class systems of variable physical parameters. The dynamics of such systems can be tracked using time-varying data-driven models. Mass is generally not conserved when a supply of mass is present, or when open systems with a flow of mass are considered [1,2]. Variable-mass structures and machines can change mass due to operation principle in tank-piping systems, aircrafts, vehicles, excavators, ball mills [3] or wind turbines [4]. The variable-mass effect is also common to systems with redistributed mass due to operation in space structures, cranes, elevators, ropeways, offshore machines, bridges or conveyors. Time-varying mechanical systems, structures and machines need to be monitored in order to evaluate changes in their structural dynamics and to assess stability margins to minimise the risk of undesired vibration under various excitation conditions. System identification is also a key step for designing dampers in time-varying systems [5]. It is well known that identification through vibration modes, natural frequencies and damping ratios can be used in practice to analyse the dynamics of such systems, e.g. active vibration control [5]. Various

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time-varying non-parametric and parametric approaches have been developed to achieve this task. Both approaches are associated with negative and positive attributes with respect to data availability/quality and identification results.

Non-parametric approaches are especially useful when the prior system knowledge is very limited and only when good quality (i.e. low noise) data sets are available. Non-parametric models are not recommended in the case of random excitation and short signal realizations [6] corrupted by significant measurement noise [7]. Non-parametric approaches follow the parsimony principle [8,9], which is required to describe the dynamics with limited number of parameters. On the other hand, non-parametric approaches provide flexibility in approximation of variable-parameter and nonlinear systems with minimum initial assumptions. The major advantage of parametric approaches also relates to the parsimony that is necessary in simulation and prediction. Thus parametric models are commonly used in fault detection, automatic decision making and in control applications. Nevertheless, parametric models are not capable to track critically damped or discontinuous modes, i.e. modes abruptly initiated, overlapped or abruptly vanishing. In summary, it is clear that a combined approach - that brings together non-parametric and parametric methods - could trade off pros and cons of both approaches in order to achieve the best identification of time-varying mechanical systems, structures and machines.

The paper proposes a combined parametric/non-parametric approach for the identification of time-varying systems. The combined approach involves two major steps. The first step involves the non-parametric extraction process. Time-varying vibration modes are extracted from the MDOF input-output data with the use of wavelet-based analysis. The second step involves the parametric identification procedure. Extracted vibration modes are identified using SDOF recursive parametric models. It is important to note that the proposed two-step procedure should be considered as complementary, since the application of non-parametric modelling may effectively guide the subsequent more elaborated application of its parametric counterpart. The first step consists of few sub-steps. Firstly, the Continuous Wavelet Transform (CWT) is used to obtain time-frequency spectra and consequently the wavelet-based Frequency Response Function (FRF). Then wavelet ridges - closely related to natural frequencies of the investigated system – are extracted. Time-frequency filtration is involved in this procedure to decouple all relevant vibration modes for further parametric identification. Finally, time domain signals are reconstructed from filtered time-frequency spectra. The input/output signals are used to identify SDOF PEM-ARMAX models and determine frequency and damping ratio components of all vibration modes. The identified models are validated using goodness measures in the time domain. The proposed procedure is tested using a mass-varying frame-like structure.

The remaining part of the paper is divided into four sections. The non-parametric model, namely wavelet spectra and the wavelet-based FRF including numerical implementation are briefly described in Section 2. The parametric model identification process is described in Section 3. These two sections also provide the theoretical background with relevant references related to the previous work in the field. The combined non-parametric and parametric method is tested using experimental time-variant data. The investigated structure and identification results are presented in Section 4. Finally, the paper is concluded in Section 5.

2. Non-parametric identification procedure

The classical input-output non-parametric approach that is used for linear time-variant (LTV) systems considers output and input spectra - obtained via the Fourier transform - leading to the Frequency Response Function (FRF). Various extensions of this classical approach are based on the combined time-frequency analysis, as discussed in [10,11]. The most commonly used approach utilises the well-known Short Time Fourier Transform (STFT), which is both simple and relatively powerful. The STFT-based concept breaks the entire signal into small time intervals and then performs the Fourier Transform for all short intervals. This operation enables localisation of short-time events in the time and frequency domains. Another widely used time-frequency approach is based on the Wigner–Ville distribution. These two methods are considered to be members of the so-called Cohen's class of distributions [11,12,13]. There are many other members of this class, including for example the Rihaczek [14] and Choi- Williams [15] distributions. The continuous wavelet transform [16,17] is a time-scale method that is qualitatively different from the other members of the Cohen's class. This approach employs different types of shifted and dilated wavelet functions to decompose signals.

The analysis in the combined time-frequency domain is the first step of the entire process of modal identification. Modal models have to be extracted from the time-frequency domain. Methods for damping estimation are presented in [18,19,20]. Methods for the analysis of nonlinear systems are described in [21]. Methods for estimation of instantaneous frequency and rotational velocity from vibration responses are presented in [22]. More recently online identification approaches based on adaptive wavelets were developed, as demonstrate in [23,24,25]. A different approach based on wavelets has been proposed in [26], where the transfer function is used for system identification. A good overview of a various wavelet-based approaches can be found in [27,28]. A few attempts have been made to introduce time-variant FRFs. This includes the well-known concepts based on evolutionary spectra [29,30], frozen spectra [10,31], identification algorithms based Littlewood-Paley wavelets [23], time-frequency based methodology [32] and the wavelet-based FRF [33]. The latter approach has been extended to provide the theoretical background, physical interpretation based on the wavelet convolution [34,32] and numerical implementation [35].

The first step of the proposed identification method – based on the non-parametric approach -- is built upon recent developments related to the wavelet-based FRF reported in [32,34,36]. In what follows the theoretical background behind this step is briefly introduced.