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Identification of modal parameters of non-stationary systems with the use of wavelet based adaptive filtering

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ABSTRACT

The Operational Modal Analysis (OMA) is a common tool for identification of parameters of mechanical structures during operation. Modal analysis can be applied for linear, stationary and undamped systems or systems with small and proportional damping. To apply this technique to other systems, mainly to non-stationary systems, new procedures are required.

The paper focuses on the application of time–frequency signal filtration to the recursive method of the modal parameters' identification based on operational measurements, dedicated for non-stationary systems. The presented technique uses an adaptive wavelet signal filtering method to separate signal components and reduce the model order. This approach considerably facilitates selection of the wavelet function parameters and significantly improves the quality of the separated modal components. Thanks to the reduction of model order, estimation of modal parameters can be performed using a relatively simple mathematical formula. This approach significantly reduces the demand for computing power which has a direct impact on system's costs and modal parameter's estimation time. This is particularly an important problem when the system parameters are changing rapidly and the information about this changes is required in real-time. The algorithm allows assessing the quality of the estimated parameters by simultaneous estimation of confidence bounds. The method has been tested on numerical models, experimental laboratory test rig and applied to real data.

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1. Introduction

The operational modal analysis is based only on response measurements of the structure in order to identify the modal characteristics. It is widely used in civil, mechanical and aerospace engineering communities and applied to identify the modal parameters of such structures as buildings, towers, bridges, offshore platforms, airplanes, etc. [1]. However, the OMA has some limitations. Among them, the following are the most important [2]: the structure is assumed to be linear, the structure is time invariant, the structure is observable and in the system of interest damping is small or proportional. Due to these assumptions, results which can be achieved with modal technique are an approximation of the real structure behavior, but still, they are good enough to be applied in diagnostics, monitoring, control, etc. In practice, many engineering structures like traffic-excited bridges, rotating machinery working with varying speed, aircrafts, robots, cranes and many others should be treated as non-stationary systems.

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The classical methods of modal parameters identification do not allow for variability of eigenvector and eigenvalue matrices [3,4]. For this reason, these methods cannot be applied directly to the non-stationary systems' identification process. A common solution of this problem is the assumption of "quasistationarity" in a given time interval. This requires a compromise between the quality of results (small number of samples) and the speed of adaptation of algorithm to parameters' changes. Another approach is the use of recursive methods of identification. In this case, the eigenvalue matrix can be estimated for every moment of time.

Despite the aforementioned limitations, the OMA techniques adapted to identification of non-stationary systems are widely used e.g. as methods of damage detection, where algorithms based on subspace identification [5], modal filter [6] or 3D vision measurements [7] are known. Furthermore, the OMA is commonly used for identification of: systems containing rotating parts (such as turbines, helicopters, engines, etc) where the assumption of broadband of excitation is not fulfilled [8], structures with variable mass [9] and geometry [10], systems with closely spaced modes [11], large structures [12] and systems with varying boundary conditions [13].

Even though there are many applications that use the OMA techniques to identify the modal parameters, in some cases it is still a very complicated issue. In addition to the above-mentioned limitations there are practical problems associated with the implementation of the OMA methods:

- Length of the data required for analysis – to get a good enough estimate of the results it is necessary to ensure an adequate data length.
- Duration of the estimation procedure – very often information about the dynamic state of the structure must be provided online. Long data series and complex (in terms of time consumption) methods of estimation of modal parameters are not conducive to obtain results rapidly.
- Necessity of an experienced operator's intervention in order to select the correct results from a set of solutions. This disadvantage limits applicability of these methods only to offline identification of modal parameters.
- Influence of the operating condition's variation on the identification of results.
- Selection of an algorithm for modal parameters estimation.
- Influence of estimation procedure sequence in case of data obtained during a series of partial experiments (runs or set-ups).

This article attempts to resolve several of the aforementioned problems through the use of recursive identification methods combined with the technique of non-stationary signals' analysis. The use of a wavelet filter allows decoupling individual frequency components of the signal, reduction of the signal model and simplification of the process of the modal parameters estimation. Additionally the adaptive approach to wavelet filtering simplified the process of wavelet function selection. Authors in [14] showed that the process of wavelet filter selection (in particular bandwidth parameter) is the critical part of non-adaptive variant of the algorithm. The presented method utilizes the Continuous Wavelet Transform (CWT) with the Complex Morlet Wavelet function. The algorithm consists of two main parts. The first part is responsible for signal filtering and is based on the CWT. The second part estimates modal parameters of the system and it is based on the Recursive Least Square (RLS) algorithm. The novelty of this approach is the application of an adaptive formula of a wavelet filter. Existing solutions utilize the non-adaptive approach, where the wavelet function is determined once for the identification process. This results in a constant-bandwidth signal filtering and reduces application of the algorithm only to the cases in which the tracked parameters are included within a fixed range (bandwidth of wavelet filter). Ensuring the correctness of the algorithm requires a very precise selection of wavelets functions' parameters in order to obtain proper filter characteristics. In addition, increasing the range of the bandwidth causes reduction of resolution in the frequency domain, in accordance with the Heisenberg relation [15]. The proposed approach does not have these drawbacks. Thanks to the adaptation of the wavelet filter bandwidth to the currently tracked frequency, it is possible to use the algorithm even for large variability in the natural frequencies tracked.

The paper is organized in the following way. Section 2 describes the method for model parameters estimation. Section 3 presents the adaptive wavelet based signal filtration. In Section 4 the algorithm is presented. The next sections contains the results of verification of the method on simulated data. Identified parameters are compared with the results obtained by using a non-adaptive formula of presented algorithm.

2. Recursive identification of modal parameters

The applied RLS algorithm contains the following steps:

Step 1: Acquiring current system response signal $y(i)$ from measuring device.
Step 2: Estimating a priori prediction error $\hat{\varepsilon}(i)$, based on evaluation from previous iteration.

$$\hat{\varepsilon}(i) = y(i) - \varphi^T(i)\hat{\theta}(i-1) \tag{1}$$

where i indicates successive number of sample. $\varphi(i)$ – regressor vector, $\hat{\varepsilon}(i)$ – estimator of prediction error, and $\theta(i)$ – vector of model parameters.

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