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A heuristic approach to output-only system identification under transient excitation

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ABSTRACT

Output-only system identification is a very attractive technique for its implementation simplicity. However, it requires long records to validate the white-noise assumption of the excitation, mainly under transient forced vibration. Alternatively, free-vibration record segments can be selected before the identification process. This improves the accuracy, even using less data, but it requires human intervention or input recording. In the present paper, an approach is proposed for accurate system identification from short output-only records of vibration induced by transient excitation, without human intervention. The approach is based on a novel heuristic search algorithm to find free-vibration record segments, which is fully automatic and it handles the possibility of free-vibration absence. Tests with real-life data from Structural Health Monitoring (SHM) of a bridge showed that the free-vibration finding improves the accuracy of the modal parameter estimates up to ten times, as compared to using record segments starting at the response peak. The proposed approach drastically reduces the need to transmit large amounts of data, which impacts on hardware requirements of SHM implementations.

1. Introduction

Many civil structures continue to be used regardless of ageing, damage accumulation and unknown risk of collapse (Salem & Helmy, 2014). Therefore, the ability to monitor their structural health is becoming increasingly important (Collins, Mullins, Lewis, & Winters, 2014; Dong, Song, & Liu, 2010; Farrar, Doebling, & Nix, 2001; Ko & Ni, 2005; Wong, 2004). Among the many strategies available within the Structural Health Monitoring (SHM) literature (Dong et al., 2010; Ko & Ni, 2005; Miguel, Miguel, Kaminski, & Riera, 2012; Wong, 2004), vibration-based methods are very attractive because of their simple hardware implementation and in-operation possibilities (Kramer, Smet, & Peeters, 1999). These methods consist in exciting the structural system and, through vibration measurements, identifying modal parameters that are correlated with its effective stiffness and strength (Chen & Zang, 2011; Ko & Ni, 2005; Miguel et al., 2012). Since artificial excitation has important practical limitations mainly in civil structures (Kramer et al., 1999), ambient- and operational-excitation sources are commonly exploited through the *output-only* approach (Peeters, 2000), in which the input is unknown. Today, many SHM programs implemented on structures around the world include this technique (Dong et al., 2010; Ko & Ni, 2005; Wong, 2004).

In general, all of the output-only system identification methods, such as Random Decrement Technique (Ibrahim, 1977), Peak Picking and refinements such as coherence function (Peeters, 2000), Ibrahim Time Domain (Ewins, 1984), and Stochastic Subspace Methods (Peeters, 2000), necessarily make the assumption that the excitation is white-noise. A recent and strong method to identify nonlinear models characterized by some form of nonlinear viscous dissipation forces and nonlinear restoring forces is proposed by Cavaleri and Papia (2014). However, as in previous cases, the hypothesis of white-noise excitation also was assumed. In the cases in which the input contains some dominant frequency components (colored-power-spectral-density function of excitation), it is difficult to separate them from the natural frequencies of the system (Peeters, 2000) leading to significant estimation errors. These problems may also appear when the non-stationary excitation is composed of *transient* impulses, indeed, if the impulsive load is of the *short-duration* type (Clough & Penzien, 1995), in which the response peak occurs during the free-vibration phase, a conservative start limit for a free-vibration record segment is obtained from the response peak; however, more sophisticated tools are needed in general cases where *repeated short- or long-duration* impulses can

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excite the system, in which the response peak occurs during the application of excitation, e.g. traffic loading on short-span bridges and gust loads on long-span bridges. As in others, output-only system identification methods have two additional problems associated with the excitation which may lead to significant estimation errors (especially in short-span bridges Farrar, Cornwell, Doebling, & Prime, 2000): (1) system mass variability, e.g. effect of heavy trucks (Kim, Jung, Kim, & Yoon, 1999); and (2) interaction with the structure, e.g. resonance of vehicle suspensions due to unevenness of the road (De Roeck, Maeck, Michielsen, & Seynaeve, 2002).

For those reasons, in practice it is common to use long measurement records (ranging between 1000 and 2000 times the fundamental period of the structure) that lead to accurate estimates of the modal parameters (Gentile & Saisi, 2013). Alternatively, in this work, an approach which consists in finding *automatically* a free-vibration record segment (time interval with no excitation) within the full measured record of the structural response is proposed. Different methods used in *statistical pattern recognition, computer and robot vision, signal processing* and *system identification* are taken to develop the novel *heuristic* search algorithm. Unlike other proposed methods, this approach besides being output-only has the significant advantage of not imposing conditions on the type of excitation, i. e. the excitation could be non-stationary as in real cases, e.g. on short-span bridges excited by traffic. Classically, the problem of short-time non-stationary stochastic excitation is addressed through input-output methods (Jarczewska, Koszela, Sniady, & Korzec, 2011). Since the parameter identification in the last iteration is performed on the selected free-vibration segment, the proposed algorithm is very accurate and only requires, as input, a relatively short measured record containing it (e.g. 200 times the fundamental period of the structure).

Furthermore, within the *statistical-pattern-recognition damage-detection* paradigm (Farrar et al., 2001; Sohn, 2007; Sohn, Farrar, Hemez, & Czarnecki, 2002), the proposed algorithm can be advantageously used for *data cleansing* (i.e., the process of selectively choosing data to accept for, or reject from, the *feature selection* process), thus mitigating the problems of mass variability and loading interaction (De Roeck et al., 2002; Farrar et al., 2000; Kim et al., 1999). On the other hand, because the need for large amounts of data is drastically reduced, significant implications arise in the design of the SHM hardware (Collins et al., 2014; Dong et al., 2010; Ko & Ni, 2005; Wong, 2004; Wu et al., 2010): less data have to be transmitted; in modem communications, shorter duty-cycles are needed; and, consequently, the power consumption is lower (Collins et al., 2014). The last allows using smaller batteries and solar cells, thus reducing size, weight, cost of remote data-acquisition units and vandalism risk, problems that have been recognized in SHM (Gravengaard, 1986; Housner et al., 1997; Ko & Ni, 2005; Lester, 2001).

Irrespective of implementation details, SHM essentially involves the following stages: 1) *sensor and data acquisition*, 2) *data transfer and communication*, 3) *data analysis and interpretation*, and 4) *data management* (Dong et al., 2010). Thus, the proposed algorithm can be implemented on the first and third stage.

The first option requires a data-acquisition hardware having a relatively powerful processor, but less data have to be transmitted: only the free-vibration record segment or simply the identified modal parameters. In the second option, with less computational demand, the full records have to be transmitted; however, these full records have to be long enough to contain a free-vibration record segment, but not too long to validate the white-noise assumption of the excitation. For this reason, the algorithm is beneficial in both implementation options.

As a counterpart, to ensure that the algorithm finds a free-vibration segment, it is necessary that there is any measuring interval with no excitation. Moreover, the identified system has to be linear which limits its application e.g. systems under low excitation such as bridges excited by passing cars or moderate wind.

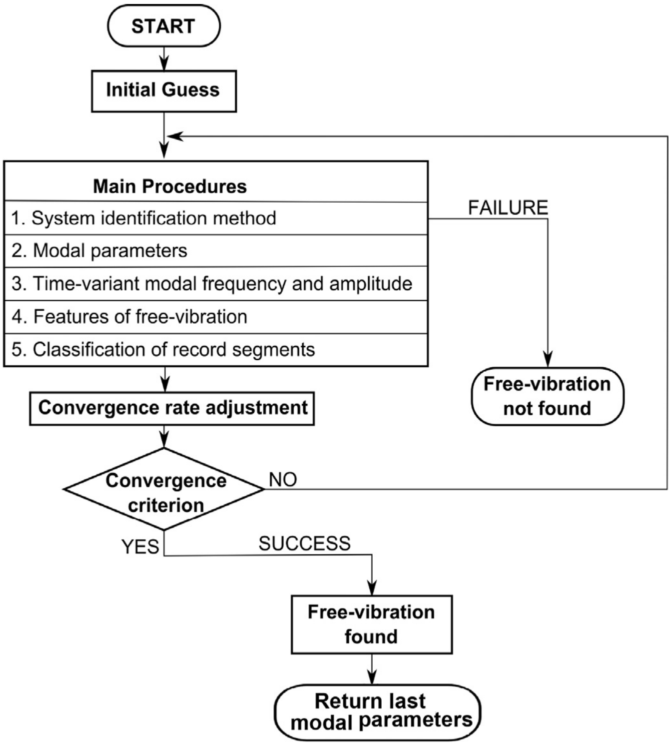

Fig. 1. Flowchart of the heuristic search algorithm.

2. Heuristic search algorithm

Heuristic techniques are methods which seek good solutions at a reasonable computational cost without being able to guarantee optimality or even to state how close the optimal solution is (Rayward-Smith, 1996). They are particularly suitable for problems that are hard to solve by classical approaches, as the problem at hand. Thus, in the present work a novel ad-hoc heuristic algorithm is developed to address the problem of finding a free-vibration record segment.

2.1. Overview

As Fig. 1 shows, the algorithm consists of a chain of *main procedures* that aim to search for a free-vibration segment from a measured full record. These procedures are embedded in an iterative scheme which tends to improve the search accuracy of the record segment by *successive approximations*.

The algorithm starts by applying a system identification method to a record segment (procedure 1). This allows finding modal parameters, in procedure 2, that are then used to extract modal responses (by modal filtering) in procedure 3. These modal responses are analysed by means of Hilbert Transform to obtain their respective instantaneous amplitude and frequency. In procedure 4, record samples are classified into free-vibration (decreasing instantaneous amplitude and stable instantaneous frequency) or non-free-vibration (increasing instantaneous amplitude and unstable instantaneous frequency). Finally, in procedure 5, the longest record segment containing samples of free-vibration is identified.

An interesting aspect of the algorithm is that, after each iteration, the accuracy in the search is improved. Thus, when the free-vibration record segment is finally found in the last iteration, the most accurate modal parameter estimates are already available.