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Local modal filters for automated data-based damage localization using ambient vibrations

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A B S T R A C T

The motivation of the paper is to develop a fully automated data-based technique for damage localization using in-service ambient vibrations. The idea is an extension of the modal filtering technique previously developed for damage detection. A very large network of dynamic strain sensors is deployed on the structure to be monitored and split into several independent local sensor networks. Simple and fast signal processing techniques are coupled to statistical control charts for efficient and fully automated damage localization. The efficiency of the method is demonstrated using time-domain simulated data on a simply supported beam and a three-dimensional bridge structure. The method is able to detect and locate very small damages (2% stiffness reduction in an area corresponding to 1/100th of the length of the structure) even in the presence of noise on the measurements and variability of the baseline structure.

1. Introduction

In many domains of engineering such as civil, mechanical and aerospace, assessing the integrity of the structures in (near) real time is a very important topic for which many methods have been developed in the last decades. Today, structural health monitoring (SHM) is gaining increasing attention: in the case of bridges for example, the maximum loads tend to increase (increase of the vehicle weights) while most of the structures are coming to the end of their theoretical lifetime (due to corrosion, fatigue loading, etc.). In [8], a broad overview of the problems which occurred on the East River Bridges in New York City due to their aging is given. Those phenomena as well as exceptional events such as collisions or earthquakes will possibly be responsible for a damage growth in the structures. Optimal maintenance calls for an early detection of small damages in structures, as it is well known that small and frequent repairs are much less costly than major repairs or total rebuilding after collapse. Current monitoring practice consists in scheduled maintenances including visual inspections, ultrasounds, eddy current, magnetic field or radiography techniques to name but a few [14]. All these experimental methods require however that the vicinity of the flaw is known, and that the proximity to be inspected is accessible. Moreover, these local inspections are tedious, expensive (the biennal inspection of the Brooklyn Bridge in New York lasts for more than three months and costs about one million US dollars [8]), subjective and not automated. In [8,21], the authors describe some of the difficulties encountered with the scheduled maintenance of long-span bridges. A major problem is that traditional monitoring is non-continuous which means that if a critical damage occurs between two

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inspections, it might lead to catastrophic structural failure. One of the most relevant examples is the I-35W Mississippi River Bridge case [28]: this bridge collapsed in August 2007 killing 13 people and injuring 145, despite annual inspection.

A general trend for new structures and bridges is a lighter and more slender design, which tends to increase the levels of vibrations under ambient excitation. While these levels of vibrations need to be controlled as they could be detrimental to the lifetime of the structure, they can also be used for the continuous monitoring of the structure without disruption or decrease of functionality. The basic idea is that the occurrence of damage alters the structural parameters (i.e. corrosion of steel reinforcement decreases the stiffness in concrete structures, cracks create new surfaces which increase the damping [1] and alter the stiffness, etc.) which in turn affect the vibration characteristics. Based on this basic concept, many vibration based SHM techniques have been developed in the last decades using mainly eigenfrequencies, damping ratios or mode shapes [7]. The reason of this popularity is the ease of measuring modal parameters or frequency responses on real structures thanks to recent advances in sensing systems (increase of cost-effective computing memory and speed [16,33,35]).

The general SHM methodology can be decomposed in four levels [30], targeting the detection (level 1), the location (level 2) and the quantification (level 3) of the damage, as well as the prediction of the remaining service life of the damaged structure (level 4). As the level increases, the knowledge about the damage increases and, usually, the complexity of the method increases as well. The simplest methods are data-based methods. These methods present the important advantage of avoiding the need to construct a detailed numerical model of the structure to be monitored. A distinction must be made between unsupervised methods in which only data from the undamaged structure is available, and supervised methods for which data in different damage conditions is available as well. Generally, unsupervised methods are able to tackle the first level of SHM only, while supervised techniques can reach up to level 3. More complicated methods use model updating techniques and can reach up to level 4 [23,27,12]. Despite the huge scientific literature on the subject [34,7], SHM technologies for civil engineering structures have not yet been successful in real industrial applications, due to major difficulties. The first one is that the damage is typically a local phenomenon, which means that only important damage levels will be detected if one looks at global dynamic properties such as the eigenfrequencies [31]. The second one is that the structures are subjected to ambient excitation such as traffic or wind (which is changing and cannot be measured) as well as environmental changes (temperature, humidity). The vibration levels are rather low and instrumentation has to be very sensitive in order to measure them with a good accuracy. The third one is the problem of automation and robustness of the SHM system against sensor failure and variability (environment, loading, etc.) [15]. In addition, non-technical issues such as economic benefits that can be expected from SHM systems have to be further investigated in order to convince structure owners of the interest of such approaches.

In this paper, the authors propose an automated output-only method for the localization of small damages which fits particularly well to civil engineering applications. The method is divided into four steps, following the statistical pattern recognition paradigm proposed in [10]. Because the technique exploits only sensor responses, it falls in the category of data-based or non-model-based methods, therefore avoiding the need to build an accurate numerical model of the structure to be monitored, and relies on output-only in-service vibration data. This is motivated by the fact that, on one hand, many studies have shown that output-only measurements are representative of the dynamic behavior of the structure and can be used for modal identification [24,25], and that, on the other hand, the complexity of bridges and buildings is such that when constructing numerical models, the modeling errors are usually of an order of magnitude larger than the effect of damage on the dynamic properties (except if the damage is really severe). The method is based on a very simple and automated feature extraction process based on the so-called modal filters [4]. These features have been shown to be relatively robust to environmental changes [5] which can cause significant changes in modal properties [11]. Control charts [18,29] are used to detect automatically a change from the normal healthy condition, based on the extracted features. The automation of the process is a key point for a successful implementation of continuous monitoring systems.

This paper is organized as follows: Section 2 describes the method proposed for automated damage localization using output-only measurements. The theory of modal filters is briefly recalled, and the extension of the method proposed earlier for damage detection in [4] to damage localization is presented. Feature extraction and novelty detection using control charts are also detailed. Section 3 presents two numerical applications of the method: the first example is a simply supported beam. A comparison of damage localization possibilities using accelerations or dynamic strain measurements is presented, showing much better performances with dynamic strains. A second example of a more realistic bridge-like structure in which fiber optics FBGs (Fiber Bragg Grating sensors) are embedded is presented. Both examples exploit numerically simulated time-domain data (polluted with noise) obtained from finite element models, and show the very good potential performances of the proposed method.

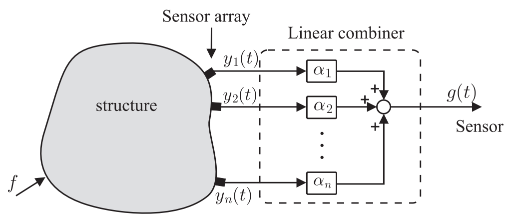

Fig. 1. Principle of spatial filtering on a network of n sensors.