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A spectrum-driven damage identification technique: Application and validation through the numerical simulation of the Z24 Bridge

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ABSTRACT

The present paper focuses on a damage identification method based on the use of the second order spectral properties of the nodal response processes. The explicit dependence on the frequency content of the outputs power spectral densities makes them suitable for damage detection and localization. The well-known case study of the Z24 Bridge in Switzerland is chosen to apply and further investigate this technique with the aim of validating its reliability. Numerical simulations of the dynamic response of the structure subjected to different types of excitation are carried out to assess the variability of the spectrum-driven method with respect to both type and position of the excitation sources. The simulated data obtained from random vibrations, impulse, ramp and shaking forces, allowed to build the power spectrum matrix from which the main eigenparameters of reference and damage scenarios are extracted. Afterwards, complex eigenvectors and real eigenvalues are properly weighed and combined and a damage index based on the difference between spectral modes is computed to pinpoint the damage. Finally, a group of vibration-based damage identification methods are selected from the literature to compare the results obtained and to evaluate the performance of the spectral index.

1. Introduction

Research activities in vibration-based damage identification methods (VBDIMs) have been increasing more and more within the engineering community over the last decades. The possibility of catching the occurrence of damage at the earliest stage by means of global non-invasive tools is the drive behind this trend. Conventional non-destructive techniques (NDT), such as computed tomography, laser scanning, ultrasonic and acoustic methods, are approaches mostly suitable for detecting local damage. When dealing with large and complicated structures in invisible or closed environments, the

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applicability of these techniques becomes very difficult [1]. Hence referring to dynamic-based methods as a global way to assess the structural condition of non-conventional systems becomes necessary.

Considering the explicit dependence of the modal parameters on the physical properties of the structure and vice versa, several methods have been addressed to damage detection and localization using changes in system dynamic characteristics [2]. Most of the emphasis has been put on the use of frequency losses as 'damage indicator', but the frequencies alone cannot provide spatial information about structural damage since they refer to global parameters, whereas damage is a local phenomenon that can yield the same amount of frequency change even if associated with different locations. Furthermore, the sensitivity to mass variation and environmental conditions introduces uncertainties in the measured frequencies [3,4], revealing their limited feasibility for the purpose of damage localization. Due to that, the focus of the research activity has turned towards more sensitive modal parameters, such as mode shapes and modal curvatures [5], which dependence on the nodal coordinates of the system makes them appropriate for locating the damage. However, exciting higher modes from vibration tests in order to capture local changes is not always feasible, especially in case of large and heavy structures. This fact, coupled with the loss of information due to the inevitable reduction of time-history measurements, can affect the outcome of the damage investigation procedure. Other approaches in detecting and locating the damage have been either the use of changes in structural parameters, such as stiffness and flexibility [6–8], or 'model-based approaches' like the FE model Updating [9], a method based on a sensitivity formulation aimed at selecting the most suitable parameters to be updated in order to minimize the difference between numerical and experimental responses and to identify the location of the damage. One of the major drawback in this case is the lack of measured degrees-of-freedom (DOFs) with respect to the analytical ones. Modern-type vibration-based approaches have also been addressed, i.e. methods based on wavelet analysis, neural network or genetic algorithm [1], but their efficiency in detecting damage must be further validate. It needs to remark that the identification of structural damage at the earliest possible stage is very important in all the engineering fields, since it allows to keep under control and assess the structural conditions, to manage the potential seismic risk of structures and to plan efficient repair works before the accumulation of damage over time becomes an irreversible condition. All above mentioned reasons clearly explain why VBDIMs are techniques still under development.

The methodology here presented investigates the second order spectral properties of nodal response processes with the purpose of defining a spectrum-driven method able to detect and localize the structural damage by means of a proper combination of the eigenparameters, namely eigenvalues and eigenvectors, extracted from the output Power Spectral Density (PSD) matrix. Appealing features of this method are: (1) the possibility of identifying the modal parameters using exclusively the acceleration time-histories of selected points, collected either from output-only or input–output techniques; (2) the capacity of identifying closely spaced modes; (3) the advantage of ranging over the whole frequency domain, without reducing the damage investigation procedure to a limited number of resonant frequencies; and (4) the possibility of catching the occurrence of damage even if not visible to human eyes. The theoretical background on which the proposed approach lies is concisely presented in the first part of the paper, while the second part of the work focuses on the application of this method to a numerical model simulating a pre-stressed concrete bridge, the Z24. Before being destroyed and replaced by a new one, in the framework of the Brite Euram project BE 96-3157 SIMCES (System Identification to Monitor Civil Engineering Structures), progressive damage tests were carried out to study the dynamic response of the bridge, located in Switzerland. Detailed information about the experimental campaign can be found in [10] and [40]. The selection of this well-known case study has been driven by the necessity of having a full-scale benchmark in order to analyze and validate the spectral method hereafter introduced. In detail, the next sections of the present paper are organized as follows: Section 2 presents a concise review of the most representative algorithm-based damage identification methods available in the literature, Section 3 deals with the theoretical aspects of the method and the definition of the spectral index; Section 4 presents the dynamic analyses performed on the case-study with the purpose of validating the spectral approach; Section 5 discusses the obtained results; Section 6 is dedicated to the comparison of the spectral damage index with a group of well-known damage indexes selected from the literature; and Section 7 summarizes the most important points of the work and presents the final conclusions that can be derived from the proposed method.

Based on the work presented by [11], new aspects are addressed in the present work. Besides a more scientifically detailed description of the theoretical framework necessary for a thorough understanding of the proposed formulation, the numerical damage simulation of the bridge has been reformulated and an in-depth study on the sensitivity of the spectral damage localization index with regard to both type and spatial distribution of the input force has been carried out as well. Additionally, the spectral results have been compared to the ones obtained from other vibration-based damage identification methods with the purpose of weighing the performance of the introduced approach. Finally, the paper has been enriched with the study of the influence of the number of DOFs on the outcome of the spectral damage analysis.

2. State of the art

The field of damage identification is very broad and encompasses several methods categorized depending on various criteria. Vibration-based damage identification methods (VBDIMs) supported by continuous structural health monitoring are probably the best tool available to evaluate the structural conditions and to catch the onset of damage at the earliest possible stage, especially when dealing with non-conventional systems. Such methods can be classified according to the effect of the damage on the structure or to the level of identification attempted. With respect to the effect of damage,