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Modal identification and damage detection in beam-like structures using the power spectrum and time–frequency analysis

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ABSTRACT

This paper presents a new method, based on natural frequency changes, able to detect damages in beam-like structures and to assess their location and severity, considering the particular manner in which the natural frequencies of the weak-axis bending vibration modes change due to the occurrence of discontinuities. The problem is to accurately determine frequencies, because their changes present low sensitivity to damage; moreover, in some modes the damping effect is significant, and thus the analyzed signal has to be precisely identified in time. To overcome these difficulties, we propose a three-step approach. In the first stage a time–frequency analysis is performed, to roughly determine the frequency range for the first ten weak-axis bending vibration modes and to locate in time the relevant signal segment for each of the harmonics. Afterwards, filters are applied to the signal, in order to visualize the individual components corresponding to these ten vibration modes. Finally, the power spectrum of each signal component is calculated for the relevant signal segment and for integer periods of the respective harmonic. Having the precise frequencies for the healthy and damaged structure, one can calculate the frequency shifts, and thus damage location and assessment become a pattern recognition problem. It consists in comparing the measured frequency changes with values obtained analytically, using a relation which defines these changes contrived by the authors. The method's performance was experimentally proven on steel beams, for various damage scenarios and boundary conditions.

1. Introduction

Regular inspection and control of engineering structures is necessary to detect damages in real time and determine the safety and reliability of the structure. Early damage identification allows properly programmed maintenance with impact on exploitation costs diminution, or the putting out of operation and replacement to avoid accidents. A large series of non-destructive testing methods can be used to detect damages. The conventional ones permit a precise characterization of the damage(s), but their local nature requires good preliminary knowledge about the position of the area where the damage is located. On the other hand, dynamic methods, due to their global perspective, are able to indicate the appearance of possible damages even in large structures, to locate the damaged area, but provide little information regarding the characteristics of the damage(s). An important advantage of the dynamic methods is linked to the fact that these techniques do not require access to the damaged area. The two methods do not exclude each other; they can be used complementarily [1].

Damages influence the dynamic behavior of structures, changing their mechanical and dynamic characteristics such as natural frequencies, mode shapes, damping ratio,

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and stiffness or flexibility. These most common features that are used in damage detection are identified from measured response time-histories (most often accelerations or strains) or spectra of these time-histories.

Damage detection using natural frequency shifts is largely presented in literature [2,3] and [4]. The methods based on frequency change can be classified in two categories: methods limited to damage detection and methods destined to detect, locate and quantify damages [5]. Literature reviews, [3] and [6], affirm that all methods based on natural frequency changes belonging to the second category are model-based, typically relying on the use of finite element models. Due to low sensitivity of frequencies shifts to damage, very precise measurements are required. Often the changes in the frequency caused by structural damage are smaller than those observed between the undamaged structure and the mathematical model. This makes almost impossible to discern between inadequate modeling and changes due to damage, consequently the use of models is difficult to use, [7] and [8]. Other problems in using natural frequency shifts to detect damages reside in the fact that natural frequencies are sensitive to changes in temperature and loads applied on the structure.

Methods based on change of mode shapes compare differences between the measured modal shapes before and after damage. A single-number measure of mode shape changes, used to detect damages, is the Modal Assurance Criterion (MAC) [9], which compares a mode shape in the undamaged and damaged states, respectively. The Co-ordinate Modal Assurance Criterion (COMAC) combines information from different modes and is able to indicate the probable location of damage [10]. Curvatures, as second order derivatives of mode shapes in respect to position, are sensitive to damage and can also be used [11]. The use of change in modal strain energy (MSE) to detect structural damages, introduced in [12], is based on the decrease in modal strain energy caused by damage and is known in the literature as the damage index method. In all cases the mode shape vectors must be one-to-one associated to the measurement points coordinates. The main disadvantage of this class of methods is the large number of measurement locations required to accurately characterize mode shape vectors and to provide sufficient resolution for determining the damage location. A possible solution is the use of markers and bespoke computer vision algorithms for the contactless acquisition of modal shapes [13]. But, because the COMAC and MSE use finite elements models with multiple degrees of freedom, the sensor/marker locations must be carefully matched to these finite element degrees of freedom.

Methods based on flexibility of the structure constitute another class of damage identification methods. They make use of dynamically measured flexibility matrix to estimate changes in the static behavior of a structure, in most cases completed with static measurements. Several variants of this method are known, e.g. the change in flexibility method, the change in uniform flexibility curvature method and other methods having the same principle but different procedures, largely described in [14].

Another class of damage identification methods is based on fitting the behavior of analytical models as closely as possible with that of the real structure by adjusting some elements of the model. Both direct methods, among the first of this class used in damage detection, as well as sensitivity-based methods are discussed in detail in [15]. Direct methods use finite elements models, where certain elements in stiffness, mass or damping matrices are changed in order to tune the models with the real structure. In most cases a large number of elements in the matrices may be changed; this is a major problem for damage location. Sensitivity-based methods use continuous or finite elements models, allowing a wide choice of physically meaningful parameters. The idea is to fit the parameters in order to minimize the difference between modal quantities like natural frequencies or mode shapes of the measured data and model predictions. One of the problems in model-based vibration-based damage detection is the need for a very accurate mathematical model, differences between the real structure and the model should be significantly lower than changes occurring due to damages in the structure. Other methods are of course available; a comprehensive classification and description is made in [3].

Each method, due to its specific advantages, fits a particular application, although no method meets all the requirements imposed by the high variety of analyzed structures and the diverse conditions imposed.

In this paper a new method to detect, locate and evaluate damages in a beam is presented. The method is based on an extensive study regarding the behavior of damaged beams, which allowed us to establish how the natural frequency varies depending on the position of the damage on the beam for a high number of frequency modes. Consequently, unlike other authors who analyzed the behavior of damaged beams considering a low number of frequency modes (generally one or two), we could involve in this analysis the first ten vibration modes. Our research showed that the shift in natural frequency for a certain vibration mode depends on the position of the damage on the beam, being influenced by the mode shape vector for a given location, while the defect depth only amplifies this phenomenon. Based on these observations, it was possible to identify sets of values characterizing uniquely the behavior of the beam with a given damage. Distinctive from the other methods presented in the literature, e.g. [3] for an overview, the proposed method is easy to apply and requires a single accelerometer for the detection, location and evaluation of the damage; the precision is at least comparable with other vibration-based methods presented in the signal processing literature, while it makes use of a large number of vibration modes. Additionally, it is valid for any support types and beam cross-section shape. The method is implemented in a procedure that does not imply human action, allowing the remote monitoring of structures.

2. Preliminary considerations

Analyzing the above presented methods a series of problems can be identified, likely to be grouped in four categories. The first category includes *data acquisition and processing*. We may highlight two types of problems here. The first is related to the data used in the detection of defects. Usually time-history of accelerations or displacements is acquired; afterwards natural frequencies or mode shapes are extracted.