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A simple damage detection indicator using operational deflection shapes

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ABSTRACT

Catastrophic structural failure of aircrafts, bridges, buildings and other structures in modern societies has always been of primary concern because of the loss of human lifes and of negative economic impact. The aging of the structures, the growing dependency on their role in our networks of transportation, energy and comunications, the smaller construction tolerances, the bigger power demanded and the media and society awardness to catastrophic events are sufficient motivations for the growing field of structural health monitoring, which aims at assessing the actual condition of a structure and to identify incipient damage. Damage identification can be considered as a two step process, the detection and the diagnosis. The former, and fundamental step, is the confirmation of an efective damage existence. When the response is affirmative, the latter step begins with the diagnosis, and then the questions are: where?, how much?, what type?, when will it fail? In this paper the authors propose a simple method to detect and relatively quantify structural damage by using measured vibrations data, specifically the operational deflections shapes. Numerical simulations and experimental tests are presented to validate the proposed method.

1. Introduction

Structural damage identification is a complex two-step process, detection and diagnostic. The former, and most important step, is to be sure that there exists damage. The sooner this is accomplished, more chances one has to avoid a catastrophic event or to refit the structure within an acceptable cost. The latter, also important but totally dependent on the former, is to know and to characterize the existent damage.

Damage detection is a complex challenge because of the difficulty to differentiate if a condition change is the consequence of a damage or the consequence of an operational or ambient change.

There are many technologies currently used to detect damage, namely classic non-destructive testing techniques, like the ones based on eddy-currents, thermal fields, dye penetrant liquids, ultrasounds, magnetic particles, X rays, acoustic emission and visual inspection [2]. These techniques are mostly very expensive, time consuming and often restrained to the observation of a limited area near the surface of the structure.

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In the last thirty years alternative technologies have been investigated, like fiber optics [20] and smart materials [9], which aim at assessing the global condition of the structures. Among them, the ones involving structural vibrations have been extensively investigated [7,34] because of their sensitivity to damage. In fact, modal properties, like natural frequencies, modes shapes, modal damping [14] and also operational mode shapes (ODS), change when damage occurs in the form of a mass, stiffness or damping change.

In 1969, Lifshitz and Rotem [12] presented an article proposing the detection of damage using vibration measurements. Since then many other methods have been proposed. Most of those methods are based on the comparison between a measurement set (one or several responses taken at different locations) of the actual state of the structure and a measurement set of a reference state of the structure, usually the healthy one. However, there are also methods that do not need a reference state [17,25,26].

There are methods that rely on an analytical or more often on a numerical model, usually a finite element model (FEM), to generate the measurement set of the reference state, and there are methods that rely on an initial measurement set of the structure to represent the reference state and do not need any model at all.

Some techniques use the variations observed between the damaged and healthy states, using parameters that are related to:

- the *spatial model*, using the mass, stiffness (or flexibility) and damping matrices;
- the *modal model*, using the natural frequencies [28], mode shapes [10,15,27,29,35] and modal damping [18,23] or quantities derived from these, such as the curvatures [3,8,22,26];
- the *response model*, i.e., the frequency response functions (FRFs) [11,15,24], the operational deflection shapes (ODS) [21,32,36], or the derived transmissibilities [1,4,13].

Some methods use the time domain [16,38], while others use the frequency domain. Some require only the response values [37,39] and others need the knowledge of the applied force too. Extensive surveys have been published, such as those given in Refs. [5–7,19,33,34].

The method presented in this paper is very simple and the indicator is based on the change of the ODSs to detect and quantify the damage in a relative way. The main advantages of the method are:

- it is not necessary to undertake a modal identification;
- there is no need for any analytic or numerical model of the structure;
- it uses all measured data, in the form of FRFs, without further treatment.

To illustrate the effectiveness of the method some numerical simulations and experimental tests are presented and the results compared with other, already published, methods.

2. Theoretical description

Assuming linear behavior, the dynamic equilibrium of a structure can be described by the following system of simultaneous equations [14]

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=\{f(t)\} \quad (1)$$

where $[M]$ is the mass matrix, $[C]$ the viscous damping matrix, $[K]$ the stiffness matrix, $\{x(t)\}$ the displacement vector, $\{\dot{x}(t)\}$ the velocity vector, $\{\ddot{x}(t)\}$ the aceleration vector and $\{f(t)\}$ the excitation vector.

For the case of harmonic excitation, the relation between the response and the excitation at each frequency of the analysis is given by

$$\{X\}=[H(\omega)]\{F\} \quad (2)$$

where $[H(\omega)]=\left([K]-\omega^2[M]+i\omega[C]\right)^{-1}$ is the system receptance complex matrix containing all the information about the dynamic characteristics of the system. Each element $H_{ij}(\omega)$ of the matrix corresponds to an individual FRF describing the relation between the response at a particular coordinate i and a single force excitation applied at coordinate j

$$H_{ij}(\omega)=\frac{X_i}{F_j};F_k=0,k=1..N;k\neq j \quad (3)$$

The column vector, j, of the receptance matrix, $\{H_j(\omega)\}$, is the ODS in the frequency domain when a force is applied at coordinate j. Therefore, the ODS describes the shape (in space) exhibited by the structure at each excitation frequency ω, given by the responses normalized by the applied force.

When a structure is measured the receptance matrix is given by

$$\left[{}^mH(\omega)\right]=\left(\left[{}^mK\right]-\omega^2\left[{}^mM\right]+i\omega\left[{}^mC\right]\right)^{-1} \quad (4)$$