DAMAGE DETECTION USING PROPER ORTHOGONAL DECOMPOSITION

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__Summary__ Structural damage detection based on proper orthogonal decomposition is reviewed in all its aspects. The method is easily understood when applied to numerical models of beams and plates. The experimental verification has been carried out using homogeneous beams and plates and has revealed possible pitfalls. Finally an alternative version of the method that does not require the comparison between damaged and undamaged structure is presented.

INTRODUCTION

Structural safety and residual life evaluation are becoming key factors for many engineering applications. Structures often are in continuum use and a real-time monitoring system would be very convenient to locate possible damages which can compromise the structure [1-3]. In this work a damage detection technique based on Proper Orthogonal Decomposition (POD) is revised [4-9]. Numerical and experimental examples conducted on beam and plate structures are described. The first provided useful information on the effect of the grid size of the sensors on the reliability of the damage detection technique for various levels of the damage severity and for different types of excitation (sine, random) and noise levels. The experimental verification using the POD method on the acceleration data show that it is possible to locate some defects in beams and plates, however, the analysis of experimental data highlights the sensitivity of the method to the modification of boundary conditions. The application of this technique to the detection of delamination in composite materials is conducted numerically on a cantilever beam. A three-dimensional model allows to investigate how the position of the damage along the length and the thickness of the beam is detected, as well as the sensitivity of the method to the location of the sensors with respect to the position of the damage. Finally a version of the method that does not make use of a comparison between damaged and undamaged structure will be described and its weak points discussed.

POD based damage detection method

Often the application of POD to structures requires the acquisition of accelerations at N locations of a vibrating system. The recorded values of the accelerations at a given time t are labelled $a_1(t)$, $a_2(t)$, é $a_N(t)$. If the accelerations are sampled for M times simultaneously at the N locations, one can form acceleration-history arrays, such that $\boldsymbol{a}_i=(a_i(t_1), a_i(t_2), é\ a_i(t_M))^T$ for i=1, 2, é N. When performing the proper orthogonal decomposition these acceleration histories are shifted by subtracting the mean value. The vectors $\boldsymbol{A}_\mathrm{i}$ are then formed as

$$\boldsymbol{A}_\mathrm{i} = \boldsymbol{a}_i - \overline{a_i}\ \mathbf{1} \tag{1}$$

where $\mathbf{1}$ is a vector of dimension M whose components are all equal to unity. The vectors $\boldsymbol{A}_\mathrm{i}$, which therefore have zero mean, are then used to form an $M\times N$ matrix:

$$\boldsymbol{A}=[\boldsymbol{A}_1, \boldsymbol{A}_2, é\ \boldsymbol{A}_N] \tag{2}$$

Matrix $\boldsymbol{A}$ is used to form the correlation matrix $\boldsymbol{R}$:

$$\boldsymbol{R}=(1/M)\boldsymbol{A}^\mathrm{T}\boldsymbol{A} \tag{3}$$

$\boldsymbol{R}$ is real and symmetric, therefore its eigenvectors form an orthogonal basis. The eigenvectors of $\boldsymbol{R}$ are a finite dimensional approximation of the Proper Orthogonal Modes (POMs) and its eigenvalues a similar approximation of the Proper Orthogonal Values (POVs) of the system. POMs can be drawn as a function defined on the area occupied by the structure and the damage indicators can be the maximum values of the difference between POMs of the damaged structure and those of the undamaged one or the maximum changes in the slope of such a difference [10].

COMPUTATIONAL EXAMPLES

Several different numerical models have been generated with different types of finite elements: models of beams made of beam elements or continuum elements and models of homogeneous plates made of shell elements [10]. Damage in this case is represented with elements characterised by lower mechanical properties than the rest of the structure. Different types of external forcing have been used such as harmonic, random, impulsive ... In all cases computations have shown that the POD based method is capable of locating the damaged area and distinguishing damages of different magnitude. Multiple damage locations and noisy signals can be dealt with by the method.

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EXPERIMENTAL VERIFICATION

The method has been tested in the lab, applied to both beams and plates. Experimental sensors were accelerometers and in the beam case sinusoidal forcing close to resonance were used, while in the bidimensional case the input was a flat PSD applied to one of the shorter edges. Results were encouraging with beams whereas the success of the method was more limited with plates.

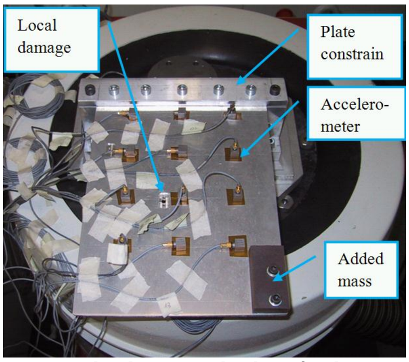

Figure 1: Plate mounted on the shaker for vibration test. On the plate corner has been fixed a mass in order to increase the three-dimensionality of the dynamic behaviour of the plate. The damage has been introduced with a local plate thickness reduction.

APPLICATION TO COMPOSITES

A cantilever beam made up of several layers has been modeled in two ways: a two-dimensional plane stress model and a fully three dimensional model. Each layer is discretised by at least an element in the thickness direction, and different mechanical properties are given to the different layers. Delamination is introduced by decoupling two adjacent layers of elements through the thickness and connecting the corresponding nodes with gap elements. The use of continuum elements did not provide only the possibility to introduce delamination in the beam, but also to investigate possible variations in the effectiveness of the method according to the position of the sensors.

SMOOTHED PROPER ORTHOGONAL MODES

If the considered beam is undamaged, the fundamental POM is a regular curve and can be fitted well by means of a polynomial function. However, if the POM of the undamaged structure are not available, it is possible to replace them with the ones obtained smoothing the irregular POM of the damaged structure. The polynomial function used for this purpose can be of the following type è [11]:

$$POM(x_i)=b_0+b_1x+b_2x^2+b_3x^3 \tag{4}$$

where the b_i coefficients relative to the coordinate x_i have been calculated by means of the measurements acquired in correspondence of the adjacent coordinates $x_{i-2}, x_{i-1}, x_{i+1}, x_{i+2}$. The method called Gapped Smoothing Method (GSM) proposed by Ratciffe was developed for the curvature of the mode shape. Numerical simulations showed how the damage localisation can be achieved by considering the difference between measured and smoothed POMsô curvatures.

CONCLUSIONS

Proper Orthogonal Decomposition is used as a mathematical technique applied to data generated by structural vibrations to locate damaged zones in the vibrating structure. Several numerical models and experimental tests have been presented to illustrate strengths and weaknesses of the proposed damage detection method. Great sensitivity to environmental conditions and variations seem to be the major drawback of the newly proposed methodology.

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