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ASSESSMENT OF A MODEL-UPDATE METHOD FOR DAMAGE CHARACTERIZATION OF CRITICAL STRUCTURES

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ABSTRACT

A damage characterization approach is developed adopting a model-update method. A derivative-free global optimization based on the Particle Swarm method was adopted, combining data computed from a FEM model and experimental signals retrieved from accelerometers in order to estimate degradation of the material´s properties. The method is able of simultaneously locating, determining the type of damage (changes on the stiffness, mass, damping) and outputting its severity (size and variation in material properties) using a vibrational approach. The procedure is fully automated (using pre/post-processing operations, scripting capabilities, data exchange) and implemented into PRODDIA® - Structural Systems Health Management platform. The proposed approach results in a closed loop optimization process driven by an objective function that considers appropriate damage metrics. The damage assessment capability is validated in a sensorised CFRP plate, 1x1 m and 3 mm thick, with two Z-shape stringers. A data acquisition system with low number of sensors (4 accelerometers, 1 temperature sensor) is deployed. Several experimental signals are obtained by simulating damage through the placement of a mass at 25 different locations on the plate. Different damages metrics are also evaluated. The proposed approach is able of characterizing damage in complex composite plates at different locations.

KEYWORDS : *Structural health monitoring, damage diagnostics, model-update methods, particle swarming optimisation method*

1 INTRODUCTION

An early detection of structural damage in critical structures is essential for the control of its performance and damage progression with time, thus supporting decision making actions (e.g., inspection and maintenance, mission planning, logistics). Structural health monitoring, SHM, techniques are based on the continuous monitoring of the condition of the structure with damage diagnosis (detection/location/severity) in mind. The structure is instrumented with a monitoring system, typically a sensor network that continuous assess prescribed physical variables, such as acceleration, displacement, strain, which are sensitive to damage states of the structure and allow inferring about its structural health state. SHM involves the integration of sensors and actuators; data acquisition, transmission and processing; computational power; data analysis and algorithms; and tools supporting decision making actions.

Damage diagnostic systems based on physical models use a mathematical description of the physical behaviour of the component, generally using a FEM model, to describe the response of a reference component that is continuously updated based on new experimental data (real data) in order to identify damage [1]. The material properties of the model (e.g., density, modulus) are updated to better describe the behaviour of this current real data. FEM model updating techniques are, intrinsically, iterative processes driven by optimization techniques whose final goal is the minimization (or maximization) of an objective function formulated to increase numerical agreement between experimental and simulation results. The algorithms based on FEM data take advantage of the discretized domain that allows localized variations of material and structural properties, improving the capacity of damage diagnostic algorithms to detect and localize damage and, also, estimate its severity [2]. This approach requires a platform that integrates experimental data from sensors, computed data from model update calculations, efficient reasoning algorithms, business intelligence tools and expedient human-computer interfaces. PRODDIA® is such a software platform that allows the continuous evaluation of the structural integrity of critical components [3], supporting effective decision-making actions for: a) inspection and maintenance operations (condition-based maintenance); b) condition-based mission planning; c) extended airworthiness; and d) logistics planning. PRODDIA® is an advanced Structural Systems Health Management solution allowing an integrated critical asset health management, supporting component damage diagnostic, structural health status prognostic and interface with other systems. PRODDIA® deals with any type of damage diagnostic method, being agnostic in terms of sensing technologies and methodologies. In this work a model update approach is developed using a vibrational method, implemented in PRODDIA® and evaluated.

2 MODEL-BASED SHM

2.1 Sensor positioning and data matching

The importance of sensor locations is crucial for a correct assessment of the dynamic response of structures and of damage. To reduced weight, the probability of sensor failure, the complexity and costs of the sensing system, a minimum number of sensors must be judiciously positioned in order to extract adequate information from the monitored structure, whilst maximising the probability of detection, PoD. Optimal sensor positioning is a problem of optimisation and/or selection [4]. Viana et al [2] developed a sensor placement method that places the sensors (accelerometers, strain-gauges) where they can capture the entire set of vibration modes of the system response. Worden [5] used a blend of combinatorial optimization methods, such as Genetic Algorithms, GA, and Simulated Annealing in order to optimize sensor placement for fault detection using a model-based approach. Beal et al [6] proposed a method of sensor positioning that enhances the sensitivity to structural stiffness changes, where an inverse problem is solved numerically using a generalized mixed variable pattern search algorithm. SHM driven sensor positioning methodologies optimise sensor locations to increase the sensitivity to induced structural damage.

Model-based SHM approaches require a good and coherent definition of the FEM models, namely, loading conditions and material constitutive modelling and properties. The FEM model should take into account all the mechanical behaviour features (e.g., elastic and dissipative properties, anisotropy) of the material and the type of loading (deterministic or non-deterministic) that is being applied to the structure, allowing for a coherent comparison between real and simulated dynamic results. Data matching allows tuning the material properties in order to get a better agreement between experimental and computed frequency responses of the structure. An optimization method can be used to minimise this objective function.

2.2 Optimization method, PS

Model-based inverse problem’s formulations can be effective for simultaneous locate damage and estimate its severity through the introduction, in the problem’s formulation, of both spatial and material information. However, the complexity of the problem demands the implementation of robust optimization techniques that leads to a global optimal solution and consequently to an effective damage assessment. Meo et al [7] developed a damage assessment method based on a global optimization approach. Meruane et al [8] solved the inverse problem by applying a parallel genetic algorithm, GA, optimization procedure. Sandesh et al [9] presented a hybrid of particle swarm and GA optimization procedure for structural damage assessment.

2.3 Adopted approach

The adopted strategy (Figure 1) was to develop a new SHM approach based on global optimization techniques, combining data retrieved from FEM models and experimental from sensors, which is able of simultaneously locating, determining the type of damage (stiffness, density, damping) and outputting its severity (size and variation in material properties) [10]. The proposed approach results in a closed loop optimization process with automated local variation of material and structural properties, driven through the considered objective function: the best agreement between simulated and experimental vibrational spectra. Improved damage diagnostic can be fostered by the development of software tools that support this data integration. PRODDIA® is such a software platform, focused on the continuous evaluation of material condition and structural integrity of critical components through the integration of physical-computed data. Several sensing technologies and types of sensors can be used to monitor different physical variables, for complementarity or redundancy. The platform is a scalable, with the ability to incorporate information from several monitored components and systems. PRODDIA® is an open and modular SHM platform, promoting software integration, flexibility and customization to different application contexts.

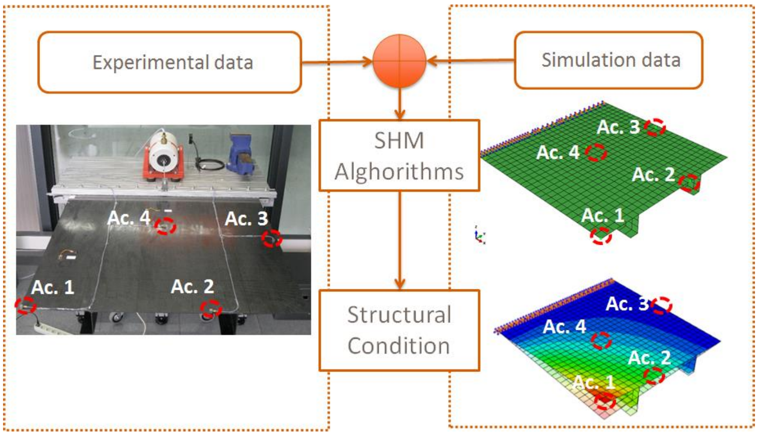

Figure 1: Combining experimental and simulated data in a model-based SHM using vibrational technique.

3 NUMERICAL AND EXPERIMENTAL PROCEDURES

The proposed SHM method was tested in a CFRP plate reinforced with two Z-shaped longitudinal reinforcement ribs, clamped in one side (Figure 2). The composite structure was fixed to a heavy table and the vibration induced with a suspended mechanical exciter. Structural damage was induced by placing cylindrical rubber pads (weighing approximately 90 g) in specific zones of the structure.

3.1 Numerical model

The model was discretized using quadratic shell elements (S8) with quadrilateral topology in a total of 2904 elements (Figure 3). In order to reproduce the experimental fixation conditions the nodal displacements were constrained in the top edge of the plate. The vibration imposed by the electromechanical shaker was simulated through unitary load with constant amplitude in the considered frequency range.

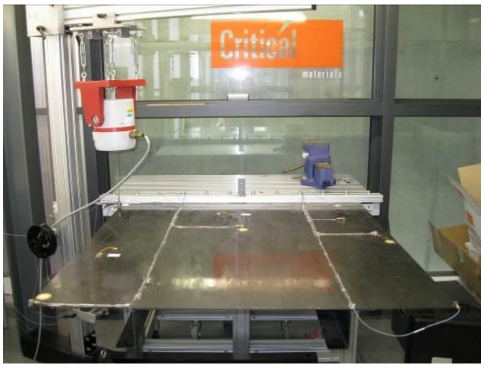

Figure 2: Experimental setup.

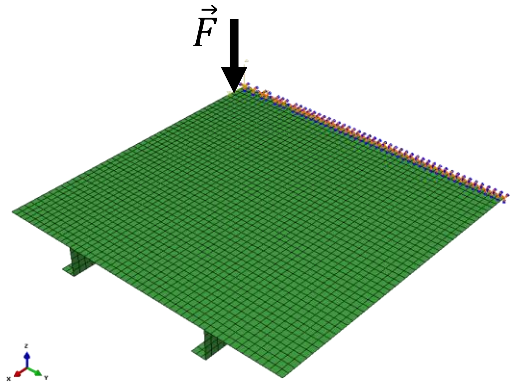

Figure 3: Discretized FE model.

A mode-base steady-state dynamic analysis procedure was considered for the current FE model in the frequency range [0, 1000] Hz, a frequency resolution of 1Hz and a damping (modal) of 0.1%. Also, a natural frequency extraction step in the range [0, 1500] Hz, based on the Lanczos eigensolver, precedes the modal analysis step in order to extract structural Eigenmodes and Eigenvalues. In order to account for the self-weight of the component (and stress-stiffening effects), a gravity static step was also considered. Material behaviour was assumed as being orthotropic with initial material properties given in Table 1. It should be noticed that these material properties serve as input for data matching operations that will be explained later in more detail in this section.

Table 1. Initial material properties.

E1=E2 (GPa)	G12 (GPa)	G13=G23 (GPa)	υ	ρ (ton.mm^{-3})	damping
54	5	2.5	0.10	1.380x10^{-9}	0.001

3.1.1 Sensor positioning optimization

Sensor positioning algorithms developed were applied in order to better positioning uniaxial accelerometers, thus augmenting its signal-to-noise ratio. The WMDCr-Weighted Modal Displacement Criteria [11] was computed for a frequency range between [0, 2000] Hz. As displayed in Figure 4, an optimal sensor positioning is indicated by the red colour (WMDCr=1.0) while blue coloured zones indicate zones more susceptible to low signal-to-noise ratios. Four uniaxial accelerometers were available and its respective positions in the structure are displayed in Figure 4.

3.2 Experimental procedures

The experimental setup is shown in Figure 5, where is also highlighted the insertion of damage (via an added punctual mass). Also, the division of the plate in several damaged zones is represented with the longitudinal and transversal arrows representing a total of 25 damaged areas. The mass is positioned at the geometrical centre of each squared area. Output-only transfer functions were measured for the four considered accelerometers in a total of six frequency response functions, FRF. In Figure 6 is plotted the frequency response functions (between accelerometers 1 and 2) for the baseline conditions and when a mass is positioned in the 5-5 zone (as indicated by the red circle in Figure 5). For coherency with the FEM model, the edge along the table is aligned with the YY axis while the edge perpendicular to the fixation table is aligned with the XX-axis (as in Figure 8 and Figure 9).

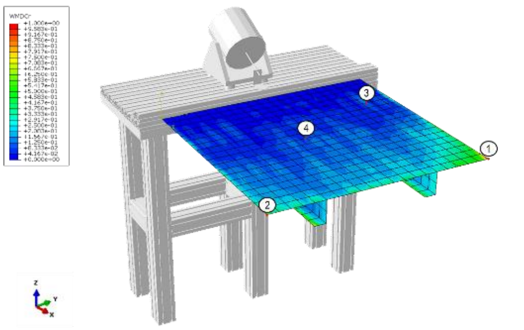

Figure 4: WMDCr sensor positioning field.

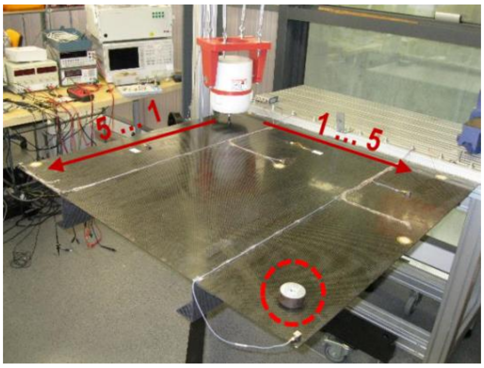

Figure 5: Experimental setup and insertion of damage (5-5 zone).

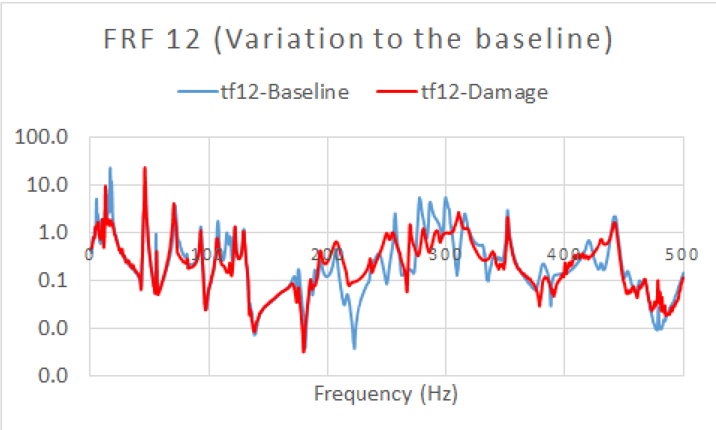

Figure 6 – Comparison between baseline and damaged FRF.

4 RESULTS

4.1 Data matching

As already abovementioned, data matching operations (based on global optimization procedures) were conducted in order to optimize material baseline properties and to better predict the real behaviour of the structure. Optimized material properties are summarized in Table 2. In Figure 7 is plotted the comparison between simulation and experimental accelerance FRF data for the [0, 500] Hz frequency range considering, as an example, the accelerometer number 2.

Table 2: Optimised material (baseline) properties (after data matching).

E1=E2 (GPa)	G12 (GPa)	G13=G23 (GPa)	υ	ρ (ton.mm^{-3})	damping
40.99	2.25	1.97	0.08	1.18×10^{-9}	0.008

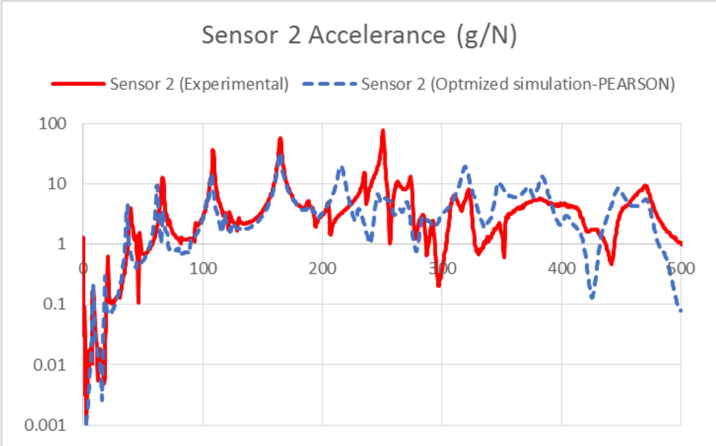

Figure 7 – Simulation/experimental data correlation (after data matching).

4.2 Damage assessment

Several damage scenarios were considered in order to test the effectiveness of the proposed method in terms of damage location and estimation of damage severity (size of damage and change on material properties). The frequency range considered, for damage assessment procedures was on the range of [0, 200] Hz, as for this frequency range the correlation experimental/simulation data is the best (Figure 7). For this case, the Pearson correlation criteria obtained was approximately of 0.50. Damage assessment results are plotted in a 3D model of the component, highlighting the damage position and its severity in terms of element density variation. In Figure 8 are plotted two cases corresponding to damages 1-5 and 5-5 on the plate. In these cases, the density variation (increase in local weight) obtained is equal to a factor of 14.7 and 10.6, respectively.

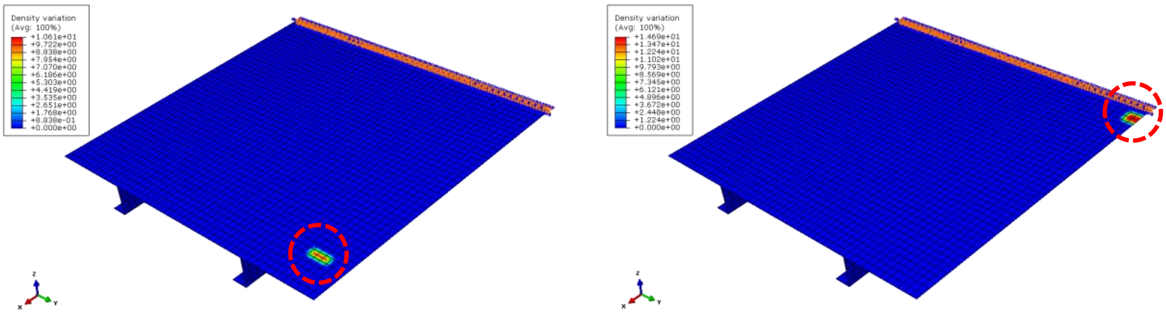

Figure 8 – Damage assessment map for damage located in zone 5-5 (left) and zone 1-5 (right).

In Figure 9 are plotted in matrix format the results obtained for the 25 considered damage cases, where it is indicated per zone of the plate the successful/unsuccessful location of damage. A correct damage location was found for 60% of all the considered cases.

4.3 Results discussion

The proposed SHM method was able of successfully detecting and localizing damage for the majority (60%) of the considered damage cases. Although the acceptable percentage of damage assessment success, some results inconsistency was found for a considerable number of damage cases. Aspects like the frequency range considered (a small range was considered in order to reduce computation time), numerical parameters intrinsic to the optimization method adopted (that need further investigations), the low induced damage (90 g mass) and the experimental/simulation correlation levels can contribute to the unsuccessfully damage assessment for some of the cases. In fact, the unsuccessful damage detection should, in a near future, be reduced to 10%, what could be achieved by increasing the analysis frequency range (e.g., double it). Although the correlation levels between experimental and simulated data in the [0,200] Hz frequency range are optimal (Figure 7) for all the considered accelerometers, the response spectra mismatch between baseline and damage case is not pronounced for the same frequency range (Figure 5). This fact may lead to greater difficulty in the convergence process and inconsistency in the damage assessment process. The quality of the FEM model may also be improved, including more physical aspects of the modelled Z-plate behaviour (e.g., improved material constitutive model, matrix-fibre interactions, enhanced damping law). However, this may not be desirable as it may increase considerably the computation times, and a compromise solution needs always to be defined. Also, it is intended to perform a sensitivity analysis on the variables intrinsic to the global optimization method in order to increase the effectiveness of the proposed method in terms of damage assessment.

XX-Axis \ YY- Axis	1	2	3	4	5
1	✗	✓	✓	✗	✓
2	✗	✗	✓	✓	✗
3	✓	✓	✓	✓	✓
4	✗	✓	✓	✗	✗
5	✗	✓	✗	✓	✓

Figure 9 – Compilation of results for damage assessment (25 cases).

CONCLUSIONS

This work focused on a SHM method based on the combination of experimental and simulation results driven by a global numerical optimization procedure. The effectiveness of the method was tested with experimental data gathered from 25 different damage cases (positions). Several techniques, including sensor positioning optimization and experimental/simulation data matching were applied in order to assure a more effective damage assessment procedure. Although a successful location for the majority of the cases was achieved (60%), a new damage assessment procedure should be defined in order to, based on systematic approach, optimize several inputs of the method in order to increase the capacity of damage location to at least 90%.

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