Simulation Tools for a Fiber-Optic Based Structural Health Monitoring System

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Abstract: Probability of detection (POD) graphics allow for a change from qualitative to quantitative assessment for every damage detection system, and as such it is a main request for conventional non-destructive testing (NDT) techniques. Its availability can greatly help towards the industrialization of the corresponding Structural health monitoring (SHM) system. But having in mind that for SHM systems the sensors are at fixed positions, and the location of a potential damage would change its detectability. Consequently robust simulation tools are required to obtain the model assisted probability of detection (MAPOD) which is needed to validate the SHM system. This tool may also help for the optimization of the sensor distribution, and finally will allow a probabilistic risk management. INDEUS, simulation of ultrasonic waves SHM system, was a main milestone in this direction. This article deals with the simulation tools for a strain based SHM system, using fiber optic sensors (FOS). FOS are essentially strain/temperature sensors, either with multi-point or with distributed sensing. The simulation tool includes the finite element model (FEM) for the original and damaged structure, and algorithms to compare the strain data at the pre-established sensors locations, and from this comparison to extract information about damage occurrence and location.

The study has been applied to the structure of an all-composite unmanned aircraft vehicle (UAV) now under construction, designed at Universidad Politecnica de Madrid for the inspection of electrical utilities networks. Distributed sensing optical fibers were internally bonded at the fuselage and wing. Routine inspection is planned to be done with the aircraft at the test bench by imposing known loads. From the acquired strain data, damage occurrence may be calculated as slight deviations from the baselines. This is a fast inspection procedure without requiring trained specialists, and it would allow for detection of hidden damages. Simulation indicates that stringer partial debondings are detected before they become critical, while small delaminations as those produced by barely visible impact damages would require a prohibited number of sensing lines. These simulation tools may easily be applied to any other complex structure, just by changing the FEM models. From these results it is shown how a fiber optic based SHM system may be used as a reliable damage detection procedure.

Key words: damage detection; fiber optics distributed sensing; finite element models; probability of detection (POD); principal component analysis (PCA); fibre bragg gratings (FBG)

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0 Introduction

Structural health monitoring (SHM) is defined[1] as "the process of acquiring and analyzing data from on-board sensors to evaluate the health of a structure". The three elements of an SHM system are listed as follows.

(1) A network of sensors, permanently attached to the structure. which is a main differentiation with conventional non-destructive testing (NDT) procedures.

(2) On-board data handling and computing facilities. Due to the high number of sensors, da-

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ta have to be processed on real time. SHM was feasible when large capacity portable computers were available in the mid-1980′s.

(3) Algorithms that collect data from sensors, clean data from environmental effects, compare to former data from the pristine structure and inform about occurrence, localization and damage type.

The concept of including sensors to detect failures in mechanical systems was applied with great success during the 1990′s to the power transmission mechanisms of the main and tail rotor of helicopters, significantly reducing the number of incidents and accidents. The helicopter drive train is a complex system operating in highly variable and adverse conditions; and any imperfections in gears and bearings are quickly amplified, threatening the safety of the helicopter. But it was enough to place accelerometers at the bearing supports, and to perform the fast Fourier transform(FFT) of the acquired signals, to obtain a reliable early warning system. The signal is very intense at the rotation frequency, any imperfection is manifested as a distortion of the frequency spectrum. Thresholds have to be set to warn for the anomaly before it becomes a threat. The same concept works equally well in any other rotating machinery, such as power plants, wind turbines, and it is a mature technology widely applied today, known as ″condition monitoring″. Why it was so easy for rotating machines and so difficult for conventional structures is an enlightening discussion but out of the scope of this paper. Nevertheless, technologies for conventional structures are quickly maturing, and as pointed out by, ″the SHM market is estimated to grow from \$ 701.4 million in 2015 to \$ 3 407.7 million by 2022, at a growth rate of 25% between 2016 and 2022″[2]. It looks like we may witness new developments and many commercial SHM systems in the near future.

The comparison of similarities and differences between NDT and SHM gives some insight into SHM main characteristics (Table 1). Both are aiming to check the structural integrity, by alerting of the occurrence of imperfections that may jeopardize the strength of the structure.

Table 1 Comparison of NDT and SHM photonic system

NDT	SHM
Inspection is done by external probes and equipments	Sensors are permanently attached at fixed locations in the structure
Off line monitoring, parts need to be disassembled for inspection	On line monitoring, aircraft inspection may be done in flight or during overnight stops
Detect discontinuities in the solids, either at the surface or internal cracks, which are identified as damages. Serves to do ″first article″ inspection	Detect local changes in the structure or boundary conditions, which are identified by comparing the response of the structure to a stimuli against to the response of the pristine structure
Time based maintenance, checks must be regularly spaced	Condition based maintenance. Disassembly only when required for repair
Labour intensive	Evaluation done without human intervention
Mature technologies are available	Still under development for real aircraft structures

An aspect of common interest, widely developed for NDT and recently recognized for SHM, is the need for each technology to quantify the damage detection capability, expressed as the POD curve (probability of detection vs crack size). It is the most basic information supplied by the NDE equipment manufacturers, and required by the structural engineers to calculate the damage tolerance of each structure, and the schedule of maintenance tasks. POD was initially obtained through tests in 1973, when the concept was established, but since 2004 the interest has shifted to model assisted POD(MAPOD). The advantage of using simulation tools is that they are easy to use, and faster and cheaper for running tests. Simulation becomes even more essential in the case of SHM, because sensors are permanently fixed to the structure[3]. Several software tools were available for ultrasonic/guided waves systems, but none for fiber optic sensors (FOS)-based SHM systems, to our knowledge.

1 Fiber Optic Sensors

Fiber optic sensors offer a very low size, the standard optical fiber has a diameter of 125 mm, so it can be embedded within a ply into the composite material during manufacturing. Other benefits for FOS are electromagnetic interference/radio frequencies interference (EMI/RFI) immunity, wide temperature range, very long cabling if needed, because of the low attenuation, and the multiplexing capability (several sensors on the same optical fiber). As sketched in Fig. 1, three topologies are possible.

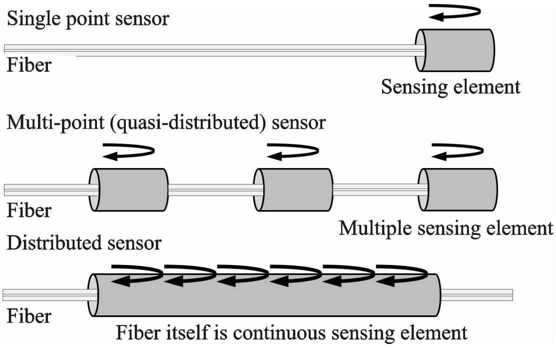


Fig. 1 Fiber optic sensor morphology

(1) Point sensor: Detect measurand variation only in the vicinity of the sensor. Example: Micromirror at fiber tip. This is mostly used for chemical sensors

(2) Multiplexed sensor: Multiple localized sensors are placed at intervals along the fiber length, i. e . FBG (sensor length 10 mm typical). About 10 sensors/fiber if multiplexed by wavelength, to 1 000 sensors by using OFDR. Ref. [4] provides a wide discussion about fiber optic sensors, and particularly FBGs.

(3) Distributed sensor: Sensing is distributed along the length of the fiber, the optical fiber works simultaneously for transmitting the information and for sensing the local external variables (temperature, strain)[5].

Fiber optic sensors have built a confidence at their performances as strain/temperature sensors, equaling conventional sensors, and their reliability is now fully proven and accepted. As damage sensors, the following considerations must be taken into account:

(1) Strain changes caused by damage are very small a few centimeters away from the crack tip, and may be masked by temperature drifting, load changes or any other environmental factor.

(2) Getting information about damage occurrence from strain measurements is then a difficult task. The larger the damage and the proximity to some sensor, the higher the probability to be detected. It drives to the need to include a large number of sensors into the structure, which is feasible when using optical fiber sensors.

SHM techniques are classified as ″local″ or ″global″, according to the area under surveillance. comparative vacuum monitoring (CVM) is the most classical example of a local technique, only the area under the elastic patch is monitored. It is also the only SHM system currently certified by aeronautic authorities. Vibration monitoring, or operational modal analysis, is the best example of a global technique, the most widely used for civil engineering. The only issue is that damage size needs to be large enough to be detectable, larger than detection thresholds needed for aeronautics applications.

The usage of distributed fiber optic sensing as a local damage detection method to detect cracks and delaminations that occur at the path of the optical fiber has already been reported[6]. The method is based on detecting the residual strains caused by the damage, and it has a high sensitivity, of a few micrometers. , the same resolution as the optical interrogation equipment. It may be useful to survey high-risk areas, like the doors surroundings and laminate edges, but it is unfeasible to cover large surfaces because it would require optical fibers closely spaced.

The method proposed at this article is a ″global method″, able to detect damage anywhere in the structure.

It is based on submitting the structure to known loads, register the strain at different positions, and compare the data with those obtained formerly on the pristine structure. Any local damage must change the local stiffness, and consequently promote different load paths, like the strain field changes, even when sensors are non-coincident with damages. Changes will be very slight, but detectable with appropriate algorithms, as will be demonstrated.

2 Algorithm for Strain-Based SHM System

The algorithm is sketched in Fig. 2. By using a proven finite element model (FEM) code (we used NASTRAN) on a model of the structure. The strains map is obtained, and data may be reduced to simulate the readings at the sensors positions. Same analysis is done on the structure with a predefined crack. A detailed FEM analysis at the crack tip is not needed, and we are only interested in the far-field. The numerical results will be always different, but after adding simulated noise (typically four microstrains of standard deviation, with a normal distribution), the differences may be faded out, at least under a bare-sight comparison. Multivariate analysis techniques are able of extracting relevant information from confusing data sets, revealing some hidden patterns. Many mathematical techniques are available, and we were using the simplest one, principal component analysis (PCA). Usually PCA is used for reducing the dimensionality of large data sets, by re-expressing the original data in a new orthogonal basis where the data are arranged along directions of maximal variance and minimal redundancy. For SHM purposes, it is enough to calculate how new data set fits inside original data baseline, which is done by the Q-index, or Damage Index.

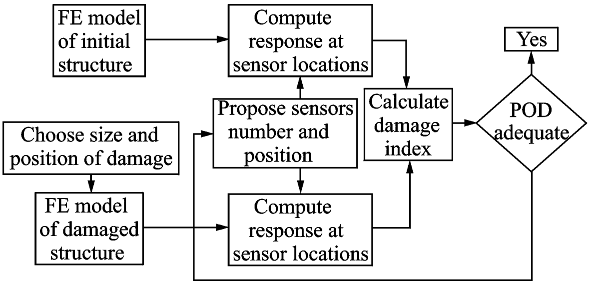


Fig. 2 Algorithm for a strain-based SHM

These calculations may be repeated as many times as needed, by changing the damage position and size, and also the sensors positions, until a desired damage detection capability is attained.

3 Application to Structure of a UAV

Fig. 3 is a picture of LIBIS, an all-composite UAV designed at UPM, with VTOL and hovering capabilities, combining the benefits of fixed and rotary wings. Its main mission is the surveillance of utilities networks.

Fig. 3 LIBIS UAV view

Due to its rugged operating conditions, impacts may occur to the vehicle, potentially damaging the structure. It is required to have tools able to locate and quantify the damages, so the residual strength of the structure can be calculated and compared to the mission requirements (prognosis). Conventional NDE methods, like ultrasonic inspections (US), may afford this information, but are time consuming and require trained personnel. It is said that more than 90% of the inspections are done just to verify the good condition of the structure, without any other significant findings, so it would be highly desirable to have some faster procedure that may reliably ascertain about the damage occurrence, and in case of positive risk, proceed with the full US inspection. This fast first check may be done by the Fiber-Optic SHM method.

Each half-wing has been done in graphite/epoxy tape material by out of autoclave(OoA) procedures. As two skins for extrados and intrados, its lay up is changing to optimize weight, which is slightly less than 1 kg. Wing is clamped at the root, and design requirements establish a max tip displacement of 5 mm under a tip load of 100 kg, with an adequate margin for static strength and buckling. A FEM model of nearly 4 000 elements was built, and it has been used for the purpose of this paper.

Optical fibers are integrated with the structure, either embedded into the laminate or during assembly, as sketched in Fig. 4 (red lines). An optical fiber is running at the top and bottom of the main spar, and along the bonding line of the first rib. The simulated damages (blue lines) are:

(1) Debonding at the leading edge, of increasing length, from 20 to 100 mm (D1).

(2) Debonding of the lower skin from the main spar; again several lengths are simulated (D2).

(3) Partial debonding of the first rib (D3).

(4) Crack at the lower skin, starting at the trailing edge and perpendicular to it (D4).

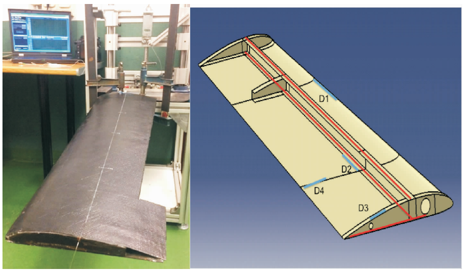


Fig. 4 Test set up (left) and damage positions (right)

In Fig. 5, the strains on the skin along the optical fibers lines are represented, for both the pristine structure and after the damage case 2, with a debonding length of 40 mm (from the wing span 360 to 400 mm). It is worthy to comment.

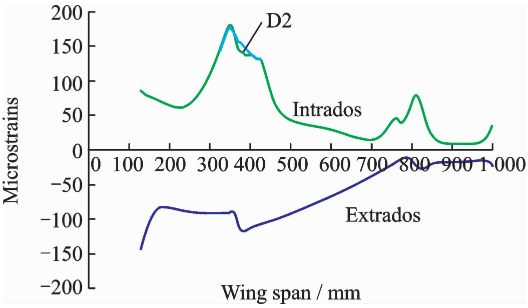


Fig. 5 Strains on the skin along one optical fibers

(1) The strain at the intrados and extrados are not symmetrical because the layup of the skins is not identical (layup at the extrados includes some local reinforcements to avoid some early buckling conditions). Also it is worthy to mention that strains are rather low for the design loads, because buckling is critical due to the low thickness of the skins.

(2) A local debonding does not change the global pattern of the strains. Only just when the sensor is coincident with the damage (for the D2 case, at the intrados skin, at the wing span 360—400 mm), distinguishable changes can be seen. Even for this case, the change is small, from 142 to 154 microstrains (roughly 10%). At the extrados, for the same damage the numerical change was less than 1%, as a maximum. For the other damages cases, the numerical changes are also quite low.

(3) To simulate the experimental conditions, noise has to be added to these numerical results, because the opto-electronic equipment always introduces noise on the measurements. Noise is dependent from many factors, like the length of the optical fibers, time for measurements, and other setting parameters, but typically is about 5 microstrains.

From the former comments, it looks like damage detection from strain measurements would not be a feasible task, unless the sensors were located coincident to damage, or damage size is large enough to promote larger changes, or higher proof loads may be applied to improve the signal/noise ratio. Nevertheless, by using multivariate data analysis procedures, a noise reduction is achieved, and a distinction may be obtained from apparently similar data sets.

4 Principal Component Analysis

As mentioned at the introduction, PCA is a statistical tool to analyze large experimental data sets, reduce all the redundant information and identify which are the independent factors influencing on the problem. Also, it can identify if a new set of data follows the general data trends. Very briefly, the steps follows below list:

(1) Organize the data set as matrix $\boldsymbol{X}=[n\ x\ m]$, where n is the number of experiments and m the number of measured variables (strains points).

(2) Normalize the data to get zero mean and unity variance.

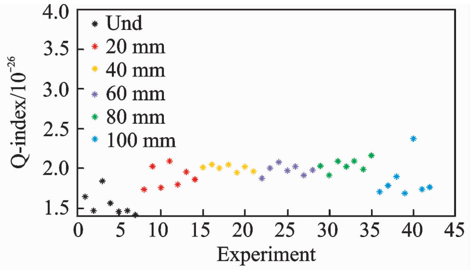
(3) Calculate the eigenvectors-eigenvalues of the covariance matrix: $\boldsymbol{C}=\boldsymbol{X}\boldsymbol{X}^{\mathrm{T}}$.

(4) Keep only the first eigenvectors as the principal components baseline.

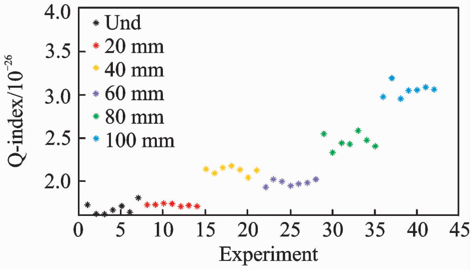
(5) Project any new collected data into the former baseline.

(6) Identify if new data follow global trends (Calculate damage index) $\boldsymbol{Q}_i=\boldsymbol{x}_i^{\mathrm{T}}(\boldsymbol{I}-\boldsymbol{P}\boldsymbol{P}^{\mathrm{T}})\boldsymbol{x}_i$.

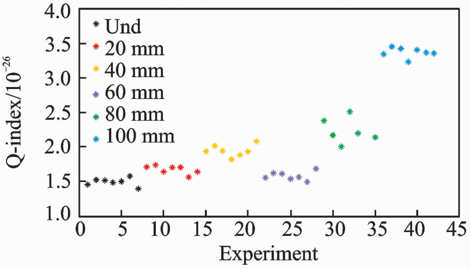
Fig. 6 represents the Q-index for the four damages cases under increasing crack lengths. Once the baseline was obtained on the undamaged structure, new sets of data were generated by adding random noise to the numerical results of the strains afforded by the FEM, and each of these set of data is a new experiment. To get a statistical significance, we repeat the process 8 times for each damage case and crack length, so 8 experiments are calculated for each condition. From these graphics, the following conclusion may be drawn:



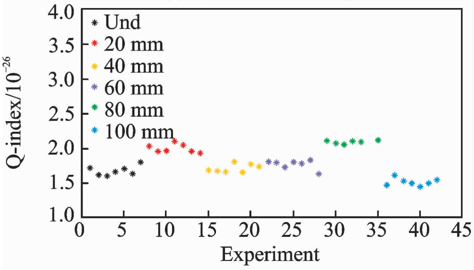
(a) Q-index for damage 1



(b) Q-index for damage 2



(c) Q-index for damage 3



(d) Q-index for damage 4

Fig. 6 Q-Index for different debonding lengths

(1) Even for the undamaged structure, the Q value (damage index) is not null, but a number ranging from 1.4 to 1.9. It is a consequence of the random noise introduced on the signals.

(2) As expected, the case more easily identified is Damage 2, debonding of the skin from the main spar, because the sensors were located coincident with damage, even for the shorter length of the crack (20 mm).

(3) The debonding of shells at the leading edge (D1) are also well identified. This is not the case of D4 (damage at the trailing edge), suggesting that another sensor line running by the trailing edge would be needed to detect reliably this damage.

5 Conclusions

A simulation tool for a SHM system based on fiber optic sensors have been proposed and demonstrated. By using proven software packages, like FEM codes, it is able to reproduce and compare the strain data that would be obtained experimentally from a fiber optic sensor network, and to calculate the damage detectability, as expressed by the damage index, for each damage condition.

The damage detectability is dependent on the distance of the damage to the closest sensor, and also on the damage size and loading conditions. The highest detectability is achieved when the damage crosses the optical fiber path, but even when damage occurs at some distance, and the change in the strain data is quite small, in the order of the measurement noise, PCA is able to resolve it and afford information about damage occurrence.

The computational tool serves not only to define the sensor network, according to the damage detection requirements, but also to compare different multivariate analysis algorithms, which that will later be used with the real experimental data.

This approach affords only information about damage occurrence, that is, SHM level 1. Once the damage is detected, the position (Level 2) may be identified by a careful analysis of the strain deviations. It has been fund that damage index is not directly proportional to damage size, so Level 3 information is not straightforward.

Acknowledgement

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