Multi Parameter SHM System for Damage Detection in Real Scale Composite Wing for Next Generation Green Regional Aircraft

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ABSTRACT

This paper presents the validation of a multi-parameter and multi-fidelity structural health monitoring-methodology based on guided waves. An accurate design is carried out to define a comprehensive system capable of identify impact loads and characterize the consequent damage in complex aerostructures. The design is based on several technologies to offer multi-level diagnosis. In addition, different excitation and sensing techniques are applied using transducers deployed all over the structure. The conceived appoach is applied on a 9m long composite wing box for next generation regional aircraft, with the main aim of detecting barely visible impact damage via integrated sensors data. Both delamination and debonding of stiffened components are experienced via an extensive experimental campaign. The first results obtained in detecting and localization damage are discussed, showing the effectiveness of this approach.

INTRODUCTION

Lightweight airframe design requires massive adoption of composite materials in load bearing components to achieve highest performance possible. To this end, optimized design is combined with proper maintenance, optimized operations and accurate end of life prediction [1]. In this context Structural Health Monitoring (SHM) is considered the key technology as it can provide in-service monitoring as: (i) an alternative method of compliance to non-destructive inspection, (ii) input for condition based maintenance, and (iii) drive new design concepts. The main source of innovation relies into the inherent capability to timely detect a damage which is prone to lead to a catastrophic failure. This concept perfectly fits into the damage tolerance design philosophy, directly benefiting aircraft design with an overall decrease of direct operating cost of the whole aircraft [2].

SHM is specifically crucial for composite structures where accidental damage can likely in form of barely Visible Impact Damage (BVID). This type of defect is difficult to detect visually as it occurs as a combination of interlaminar fracture (delamination),

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intralaminar fracture (transverse matrix cracking and debonding between fibre and matrix) and fibre fracture. As a consequence, damage mostly occur at the inner side and through the thickness, with a very limited visibility on the front surface. When coming to damage tolerance approach, impact composite mechanics is accomodated by decreasing material allowables as to prevents damage growth until critical size in the time elapsing between three main inspection tasks. Another advantage of SHM is the presence of and different methods that can be applied simultaneously to gather complementary information and achieve multi-level diagnosis and prognosis. Among the approaches extensively tested during the last decades, fiber optic-based ones have the advantage of being characterized of quite massless sensory systems. In addition, they can be used with relatively good reliability in strain monitoring (distributed fiber optics) and impact detection (fiber Bragg grating). For instance, they can be successfully used to monitoring damage onset and growth in stiffened composite structures [3].

However, damage sensitivity strongly depends upon the vicinity of the fiber sensors to the damage. This is overcome by Guided Ultrasonic Waves (GUWs), which can propagate over long distances and interact with emerging defects. When excited and sensed by lightweight piezoelectric (PZT) transducers, they can be adopted for SHM and can be used even to estimate location and size of BVID [4]. Different methodologies based on GUWs are discussed in the literature where they resort to detection metrics established comparing a signal feature from different inspections (baseline based approach). The idea relies on the evident differences emerging in the GUW signals between (current) inspection carried out where damage is actually present and the (baseline) inspection carried out on the same structure in pristine condition. Different metrics sensitive to the damage can therefore be calculated (e.g.: energy of the incident wave, wave speed, statistical correlations) and used for diagnosis. However, this approach is often too costly to be operated in any specific point of a coplex real-scale aerostructure. An alternative solution consists in combining different technologies (e.g.: fiber optics and PZT) according to the level of inspection to achieve, for multi-level damage diagnosis. This can benefit from the advantages of both approaches and even provide more detailed information. However, a major challenge relies on replicating conditions of in-service operation during testing, characterizing the system [5] and assessing the reliability [6].

This is a fundamental step towards SHM industrial deployment and it has been addressed by CleanSky2 project AIRGREEN 2, where the maturity of different SHM approaches has been tested and verified from coupons to subsystems. As a further effort, this paper introduces the design of a multi-parameter and multi-level SHM specifically conceived for a real scale wing box fully manufactured in composite materials for new generation regional aircraft and subject to realistic damage. In particular, GUW based approaches have been tested and validated achieving technology readiness level equal to 5. The paper is organized as follows: the methodology of GUW based SHM approach is briefly described, the experimental setup is discussed in the way to define testing campaign and integration of sensors. Finally, preliminary results are shown at the industrial test level, which is a real scale and 10 m long wing box fully made in carbon epoxy material. Concluding remarks close the discussion.

METHODOLOGY

To monitor the real scale aerostructure a multi-parameter and multi-fidelity approach is put in place resorting to distributed sensing, where different information are retrieved to diagnose structural health. To achieve multi-level capability, several technologies are specifically envisioned to achieve different fidelity:

- Event classification, to detect and eventually localize an impact occurring on the structure. FBG based technology is adopted to catch waves excited by the impact and warn the presence and location of the adverse event. Despite the impact force can be predicted, no direct information is obtained whether the damage is present or not.

- First level damage classification to detect and eventually localize damage arising into the structure. PZT is exploited to excite and sense guided ultrasonic waves by sparse transducer array and global monitoring. The level of information include damage presence and location. However, severity of damage is not directly assessed.

- Second level damage classification, to assess the characteristic dimension of the damage arising into the structure. PZT is exploited to excite and sense guided ultrasonic waves by aligned transducer array and local monitoring. The level of accuracy dramatically increases. However this requires higher sensor deployment and inspection complexity, limiting the use to critical damage, e.g.: disbonding between stringers and skin.

- System fault classification to detect and eventually localize damage arising into the system. PZT is still exploited using electromechanical impedance to warn any damage at transducer and/or cabling level.

The combination thereof allows achieving a multi-level diagnosis pavying the way towards residual useful life assessment when damage growth characterization is available. The second level, essential for damage detection, is discussed in detail hereinafter and the results obtained on a real scale wing segment is reported in the following of the paper.

Guided Ultrasonic Waves (GUWs) are used in SHM by exploiting their inherent capability to interact with small damage arising through the thickness of the structure. Presence and characteristics of damage can be highlighted comparing historical database of inspections where the pristine and current state of the structure is included. Specifically, the dataset is obtained emplying the pitch catch approache to excite GUWs in a specific point (pitch) and sense propagation thereof in a different location (catch). Replicating the GUW interrogation within a network of piezoelectric transducers, different information can be retrieved through post processing data. The interrogation signal is burst using 4.5 Hann-windowed sine cycles having a central frequency in the range [20 300] kHz. The Damage is obtained loading the structure with energy controlled impact by pneumatic gun with 1-inch tip. this approach has the potential to correctly replicate real scenarios impact loads resulting in barely visible impact damage (BVID), which affects guided wave propagation. To build the experimental dataset, guided waves are acquired while traveling across pristine (before the impact) and damaged (after the impact) structure. To assess the condition of the structure, different damage indicators (DIs) can be defined by evaluating physics based metrics or statistical based metrics. Among the former ones, group velocity of propagating modes, based upon the time of flight, transmission factor, defined as the ratio between the sensed and excited energy of the wave modes, and energy of the wave modes are calculated. As to this last metrics, the calculation resorts to energy difference between two signals:

$$DI_E = \sum_{k=1}^{N} \left(x_C(k) - x_B(k)\right)^2 \tag{1}$$

where $x_B(k)$ represents the discrete signal response acquired on the pristine structure and $x_C(k)$ on the current structure at the time step k. Instead, N represents the sample number. In addition to that, to get to a statistical distribution of data samples, concurrent measurements are carried out on the pristine configuration and the baseline is recorded in the historical database after averaging all the signals. Then a statistically meaningful threshold is calculated [5] to discern healthy condition (DI close to zero and below the threshold) from damaged state (DI increased above the assigned threshold). Higher the DI bigger is the damage estimated by the system. Alternative metrics (belonging to the second group) consist in computing statistical features, such as root mean square deviation or cross-correlation among current and baseline signals. Exploiting the relation between damage severity and DI value, every damage indicator or combination thereof can be mapped over the structure through a meshless probabilistic imaging approach [7]. This allows localizing the damage.

Impact and inspection campaign

Five impacts of four different types have been loaded to the structure in different location to encompass all maintenance critical scenarios. They are mainly characterized by the location where the damage may occur (according to which a specific damage mechanics is triggered) and the severity of damage (category) which may lead to different consequences on the structure. The positions where the damage is simulated through impact testing are shown in Figure 1, schetching the outer wing box as well. The type of impact is then described in Table I. In particular, middle bay impact is characterized by extensive delamination through the thickness, while stringer impacts are usually followed by the disconnection of the stiffener from the skin, usually referred as to debonding. Instead, edge cut out is expected to be critical when the connection of the hole and the closing cap is not well secured at the nesting site. The latter classification depends on the outer visibility of the damage and the category depends upon whether the damage is visible (VID) or barely visible (BVID). In particular, the middle bay location is tested under BVID and VID conditions (see Table I). The impact is loaded by a pneumatic gun on the structures using 50 Joule energy for impacts no. 1-4 and 80 Joule energy for impact no. 5.

Overall, the experimental campaign consists of three different stages:

- Phase I: Baseline acquisition, where ultrasonic interrogation is carried out and data from piezoelectric transducers are recorded to build the baseline dataset.
- Phase II: Impact Testing, when impacts are carried out along with FBG based sensing to monitor the impact events.

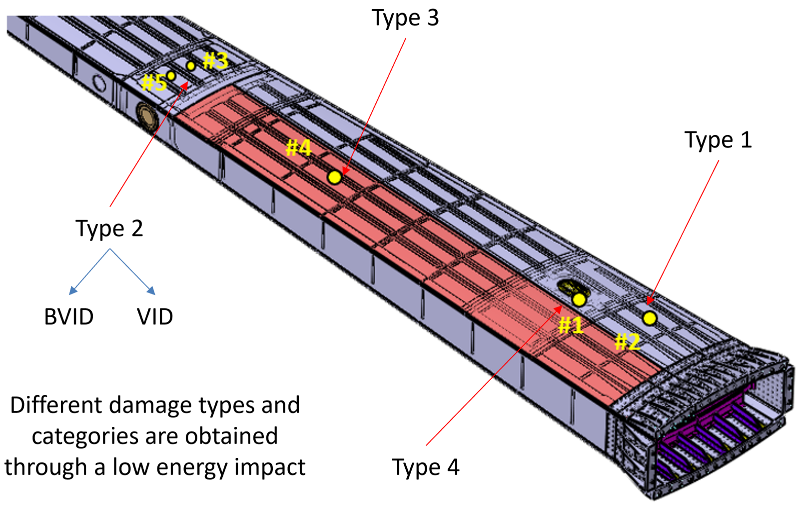


Figure 1. Different impact types according to position thereof on the final demonstrator

TABLE I. Impact description

Impact no.	Descritpion	Type	Category
1	Edge Cut-out	4	BVID
2	Stringer Core	1	BVID
3	Middle Bay cm	2	BVID
4	Stringer Foot	3	BVID
5	Middle Bay	2	VID

- Phase III: Current acquisition, where ultrasonic interrogation is carried out and data from piezoelectric transducers are recorded to build the current dataset.

It is worth noting the Phase II is carried out in two stages: (i) a preliminary impact testing to calibrate impact energies for BVID and VID and (ii) an execution impact testing when BVID and VID are generated on the prescribed locations.

RESULTS

The Experimental tests are performed on the real scale wingbox in Leonardo Aircraft premises, where the structure is assembled. To verify that impact campaign resulted in the expected damage, phased array ultrasonic testing (PAUT) is carried out. The inspection highlighted both BVID and VID damage with consistent through thickness damage even when the indentation is slightly visible [8]. In particular, when considering the stiffened panel (Impact no. 4), the BVID resulted in a disconnection between the foot of the stringer and the skin with an overall damage of 70x40 mm.

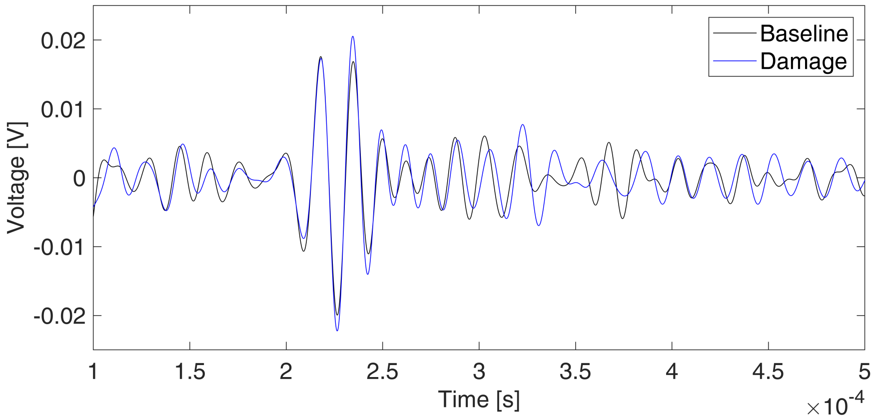
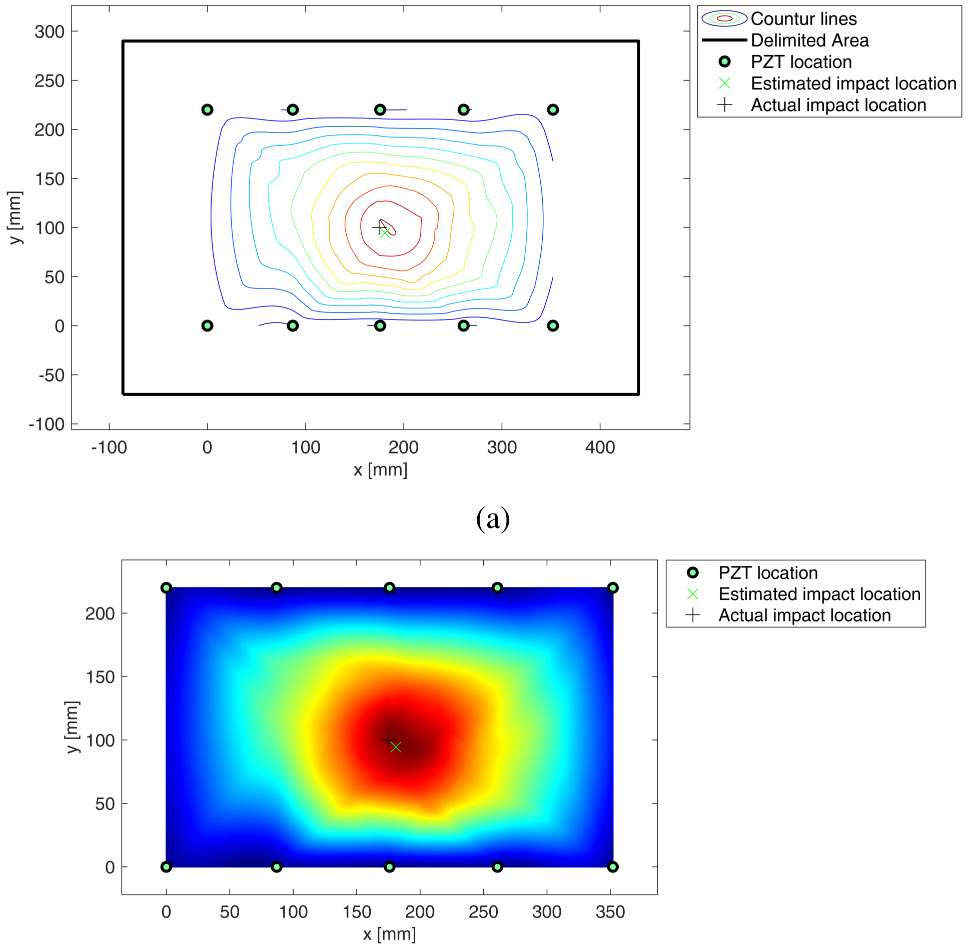


Figure 2. A-scan of current and baseline ultrasonic waves obtained in pitch catch mode among two transducers located alongside the stringer

After the characteristic of damage being validated through PAUT, the ultrasonic datasets are post processed to see the effect of damage on the wave propagation. The wavefield is strongly affected by the damage occurrence, being visible considering the A-scan from transducer couples placed alongside or opposite to stringer. An example of the former is reported in Figure 2. In particular, the debonding reduces the amplitude of the wave reflected back from the stringer. Windowing the signal when the reflection is expected, the debonding can be even highlighted. In the second case, not reported here for the sake of conciseness, the stringer damage strongly affects the transmitted energy, showing a severe change in the A-scan on the direct wave. Also in this case, windowing the signal when the arrival of the wave is expected, the debonding can be even highlighted.

A further processing is carried out implementing the reconstruction approach described in [7]. The concurrent measurements carried out on the baseline are used to define a statistical threshold for decision making. Different damage indicators are calculated and compared with the detection threshold. When the DI value overcomes that threshold, the path is selected as one crossing or delimiting the damage. Then, the nodes emerging from all intersecting paths selected during the decision making phase are highlighted and surface interpolated by using the DI value as weight. The resulting contour and imaging show the location of the damage as probabilistic function. In addition, the estimated impact location is also displayed calculating the center of gravity of the emerging nodes weighted by the DI. The results obtained when analysing the 60 kHz dataset of impact no.4 are reported in Figure 3, highlighting both the contour and the imaging of the probabilistic reconstruction. The estimated impact location clearly shows the accuracy of the damage localization, with an error of 14 mm (respect to the contour peak) and 7.5mm (respect to the center of gravity estimation) respectively. The accuracy is relatively high, considering that the debonding is found to be around 70 mm length by PAUT inspection, which is much larger than the error in estimating damage location- Other damage cases are omitted here for the sake of conciseness and shows similar accuracy in localizing damage.



(a)

(b)

Figure 3. Contour plot (a) and imaging (b) of the damage probabilistic reconstruction.

CONCLUDING REMARKS

The paper presents preliminary results obtained applying a multi-parameter and multi-level SHM approach specifically conceived for monitoring impact induced damage in real scale structures. To this end, several maintenance critical scenarios are considered and the structure is sensorized according to damage type and location. The non-desctructive inspection by PAUT highlights the critical nature of low energy impact due to complexity and assembly of the real scale wing box. Finally, first results obtained by guided ultrasonic waves inspection are also shown, highlighting the high accuracy in detecting and localizing damage occurring under the stringer foot of a stiffened bay of the wing.

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