Probability-Based Damage Assessment on a Composite Door Surrounding Structure

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Abstract

A Structural Health Monitoring (SHM) system based on Acousto Ultrasonics (AU) is installed and used to inspect a full scale Door Surround Structure (DSS). A generic DSS is manufactured with an integrated SHM Network conform of 584 piezoelectric. Afterwards, the DSS undergoes an impact campaign with a total of 112 impacts, inducing skin delaminations and debondings of various structural features. The purpose of the impact campaign is the development and validation of the SHM system applied to the DSS. A probability-based damage identification algorithm is developed within the project and its performance detecting the damages of the DSS is evaluated. Traditional non-destructive inspection (NDI) serves as a reference for the evaluation of the damage assessment. The results show a good correlation between SHM and NDI in identification as well as location of damages. The SHM system is sensitive to all damage types occurred in the DSS.

Keywords: Piezoelectric sensors, feature extraction, guided ultrasonic waves, composite, aerospace, SARISTU

1. INTRODUCTION

The activities around an aircraft Door Surround Structure (DSS) during in-service can lead to Barely Visible Impact Damages (BVID) in the CFRP structure. The potential presence of BVID in a structure implies increased maintenance efforts to assure the structure performance. Structural Health Monitoring (SHM) aims to be used as a complement of traditional non-destructive inspection (NDI) techniques, enabling a decrease in maintenance efforts. Acousto Ultrasonics, a SHM technique, is based on a permanently installed piezoelectric transducer network, which actuates and receives ultrasonic guided waves to provide information concerning the structural integrity [1]. A reliable damage detection procedure is under development so that AU represents a feasible alternative to the currently used NDI in aircraft structures.

A probability-based damage identification algorithm has been developed within the project. The probabilistic approach has been reported to be effective in detecting damage in structures with complex geometries. Zhao et al. [2] detected and localized rivet cracks and corrosion on an aircraft aluminum wing, Wu et al.[3] used the RAPID (reconstruction algorithm for probabilistic inspection of defects) with a composite panel with bonded T-stringers, combining several frequencies for an improved damage assessment, and Wang et al. [4] identified a through-thickness hole in a composite stiffened panel. The current approach introduces modifications to adapt the probability-based algorithm to the proposed structure geometry, damage types and SHM-Network.
2. EXPERIMENTAL SETUP

2.1 Integration of a SHM Network in the Structure

A full scale DSS has been manufactured with the focus set on the SHM network integration and the subsequent evaluation of the SHM system. The structure has therefore a representative design without sizing and generic structural components. The dimensions of the structure are 5.1 x 3.5 m² with a curvature radius of 3 m. The DSS features include a skin with two thicknesses (2mm and 8mm), 44 omega stringers, 4 normal frames, a ladder structure and 16 intercoastals. A SHM Network consisting of 584 piezoelectric transducers with their corresponding cabling and connectors has been installed during the manufacturing of the DSS. An exhaustive explanation of the manufacturing and integration process can be found in [5].

2.2 Impacting Campaign

An impacting campaign was carried out in order to introduce realistic BVID. A total of 112 impacts from the outer skin of the structure were performed. The symmetry of the structure allowed the repetition of the test for each quadrant. The first quadrant with its corresponding impacts is depicted in Figure 1.

The impacting campaign has introduced the planned delaminations and minor debondings near the impacted area. Additionally, the impacts have caused unpredicted damages in the structure, such as large stringer debondings in the stringer run-out area, clip detachments and alterations in the frame region. Non-destructive inspection (NDI) has been carried out after every impact and used as a reference for the evaluation of the SHM damage assessment.

3. DAMAGE IDENTIFICATION APPROACH

The damage assessment is performed by means of a probability-based methodology with the help of an imaging algorithm. The core of the employed algorithm is based on [2] although several aspects have been modified. The alterations have been described in detail in [6] and [7].

The damage assessment is performed comparing a baseline, acquired with the structure in a pristine state, and the current signal, acquired in a normally unknown state of the structure. A change in the structure characteristics translates into a variation in the acquired signal, which
has to be interpreted properly. The comparison between the two signals is quantified with a Damage Index (DI). Finally, the damage identification is made combining the information of each actuator-sensor pair in an imaging algorithm. The damage detection algorithm is defined as detailed below.

A grid representing the surface of the monitored structure is first defined. The damage intensity \( I(x,y) \) at each grid point \((x,y)\) is calculated, by assuming a certain area of influence of the actuator-sensor paths. The damage intensity indicates the probability of damage presence and is defined as:

\[
I(x,y) = \sum_{k=1}^{N_p} \left( 1 - \rho_k \right) \left( \frac{\beta - R(x,y)}{\beta - 1} \right)
\]  

(1)

with \( \rho_k \) being the damage index of the \( k \)th actuator-sensor path, \( N_p \) the number of paths, \( \beta \) the scaling factor determining the area of influence and \( R(x,y) \) defined as:

\[
R(x,y) = \begin{cases} 
\sqrt{(x-x_i + a(x_i-x_j))^2 + (y-y_i + a(y_i-y_j))^2} + \sqrt{(x-x_j + a(x_j-x_i))^2 + (y-y_j + a(y_j-y_i))^2} & \text{for } R(x,y) < \beta \\
\sqrt{(x_i-x_j - 2a(x_i-x_j))^2 + (y_i-y_j - 2a(y_i-y_j))^2} & \text{for } R(x,y) \geq \beta
\end{cases}
\]

where \((x_i,y_i)\) and \((x_j,y_j)\) indicate the locations of transducer \( i \) and \( j \) respectively. The coefficient \( \alpha \) is introduced to modify the location of the probability distribution function. The effects of \( \alpha \) and \( \beta \) on the distribution function for a single actuator-sensor pair are depicted in Figure 2.

Figure 2: Elliptical distribution function for a single path with effects of \( \alpha \) and \( \beta \)

The comparison between the two signals is quantified with a Damage Index (DI). In the developed damage identification tool fourteen DI are implemented. The DI suitability to detect damage applied to the current structure and damage type has been previously investigated in [6]. The selected DIs are based on the correlation coefficient, the signal amplitude, the coefficients of the signal wavelet transform and the covariance matrix and are presented in Table 1.
The combination of the information provided by each actuator-sensor pair of the SHM network generates a damage probability indicator. Finally, an imaging algorithm depicts the monitored structure indicating the damage probability with a color scale.

4. RESULTS

This study focuses on the evaluation of the algorithm performance in the presence of the encountered damage situations. The impacting campaign of the door surrounding structure has introduced the planned delaminations and small de-bondings near the impacted area. Additionally, the impacts have caused indirect modifications in the structure. Therefore, the analysis has been divided in two damage scenarios: damage assessment of the isolated effects of the delaminations at the impact locations and multi-damage assessment. The additional damages consist of large de-bondings of the stringer run-outs, frames and clips.

The reference used to evaluate the performance is the location and size of the damages obtained with traditional NDI. The error is defined as the distance between the center of the damage measured with NDI and the damage location given by the SHM damage identification algorithm. The location of the single or multiple damages with SHM is obtained with the local maxima in the damage probability imaging.

4.1 Single Delamination

The algorithm is conceived to find delaminations and de-bondings with an approximate diameter of 1 inch [2]. Therefore, the algorithm reaches its best performance where the impacting campaign has mostly introduced one damage with the desired damage size (310 to 2311 mm²) per impact.

The maximal allowed localization error to consider a damage as found has been set to 100mm. In a first analysis, 45 of the 47 single damage scenarios have been successfully located. A typical damage assessment analysis is plotted in Figure 3, overlaying the NDI results to the SHM plot with a white rectangle. The location error has been plotted in Figure 3 (right) ignoring the two outlier values. The location error, indicated with a solid red line, has an average value of 27mm.
The two delaminations with low location accuracy are both caused by the lower path density on the edges of the monitored area. Since the algorithm is based on a cumulative principle, the damage is displaced towards the interior of the monitored zone, with a higher path density. The damage localization can be improved by including the paths between two adjacent transducers into the damage analysis, enhancing the path density on the edges. The damage assessment I68 is depicted in Figure 4.

### 4.2 Multiple Damage Detection

Most stringers are not attached to the skin with rivets on the run-out area. As a result large disbonds appear at the run-out zone when an impact takes place in the vicinity of the stringer run-out.

Two examples are depicted in Figure 5: both entail a stringer debonding away from the impact position. The first 5 local maxima are indicated with black crosses in the picture. In Figure 5 (left) the algorithm finds both the stringer debonding and the smaller delamination. The maximal damage probability is located on the debonding but another local maximum accurately detects the delamination. On the contrary, in the second example the effect of the debonding is highly dominant and the algorithm cannot locate the delamination within the first 5 local maxima. Nevertheless, the damage probability plot shows a damage indicator above noise level. A further analysis excluding the zone around the debonding will highlight the effect of the delamination.
A large debonding of the stringer run-out can also occur near the impact position, where the delamination is located. The same actuator-sensor pairs shall be then employed to detect both damages. Given/In this situation, represented in Figure 6, the algorithm cannot distinguish between damages. Since the delamination has a lower effect on the propagating waves, the detection algorithm concentrates the highest damage probability on the areas around the disbonds.

The impacts within the immediate door surrounding area often induce clip debonding along with the planned delaminations. From a total of 18, 56% damage situations including delamination and clip debonding successfully locate both damages in a single damage assessment. This situation is illustrated in Figure 7 (left), where the delamination is located with the first maximum and the clip detachment with the second local maximum. However, in 44% of the cases the effects of the clip debonding dominate the damage indexes and the effects of the delamination go unnoticed. The example displayed in Figure 8 (right) belongs to this category, where the algorithm solely detects the clip debondings, larger than the delamination. The delamination area has nevertheless a higher probability of detection than noise level. With the omission of the clip detachment areas the delamination can be detected.
The frame areas undergo alterations when impacting close to the area. In Figure 8 (left) the impact has caused a delamination in the impact position and damage to the frame nearby. The algorithm shows a high damage probability in the frame area, but the delaminated area goes unnoticed. In a more detailed analysis, the damage detection analysis shows also a certain damage probability on the delamination area. The delamination can be located after filtering the effect of the frame modification. The damage on the frame zone has a large effect on the propagating guided ultrasonic waves. As a consequence, only in 22% of the cases the algorithm is able to locate both the frame debonding and the delaminations, such as in Figure 8 (right).

Since frame debonding was not expected, NDI was not performed during the impacting campaign for the area. After evaluating the SHM results and observing the damage indications on the frame area, posterior NDI was performed. The NDI results revealed that the frame indicated as damaged by the SHM damage assessment had indeed suffered damages. However, no statement can be made about the moment those modifications occurred.

4.3 Damage size estimation

According to the SHM axioms, the detection and location of damage can be performed in an
unsupervised learning mode. However, a supervised learning mode is mandatory to carry out damage quantification. Thus, a threshold shall be set in order to calculate the damage area. In Figure 9 the damage size detected with the algorithm is plotted as a function of the damage size determined with traditional NDI. The green line indicates the optimal size estimation: The damages above the green line are overestimated and the ones under the line are underestimated. Two proposed thresholds are plotted in Figure 9. The 92% threshold produces more accurate damage sizing for the damages located in the stringer foot area (S-type). The 95% limit is suitable for damages located on the skin, between sensors (B-type) and under the stringer head (H-type). A threshold of 92% means that the zone with probability values between the maximum probability and the 92% of this maximum is considered the damaged area.

![Figure 9: Detected vs. NDI damage size for single damage detection](image)

The determination of the damage size depends on the location of the damage and cannot be generalized for every damage type. The dependency between both parameters in Figure 9 shows that the method relies on the correct signal features to quantify damage. However, the high dispersion of the results indicates that the method still needs to improve in robustness and reliability.

5. CONCLUSION

A total of 108 impacts on a door surrounding structure have introduced various realistic damages. The acquired data has been employed to evaluate the performance of a damage identification algorithm. The algorithm shows a good performance when it is challenged with one skin delamination pro analysis, with a 27 mm average localization error. The results are very positive, since the detection of a single damage pro analysis is the goal of the damage identification algorithm within the project. The additional challenges arise with the unexpected effects of the impacts on different structural elements of the door surrounding structure. The acquired data shows a good correlation between the physical changes undergone by the structure and the changes in the propagated waves. The features extracted from the signal have proved to be sensitive to each encountered structure alteration: delaminations, stringer debondings, clip detachments and modifications in the frame zone.
The evaluation of the damage identification algorithm regarding the visualization of multiple modifications in the structure is a promising result. Nevertheless, some figures have illustrated the limitations of the current algorithm regarding multi-damage detection. On the one hand, since the damage assessment relies on the relative effect of the DI, a larger damage can hide a smaller one: small clip and stringer debondings do not generally mask the initial delamination, but large stringer debondings and damage on the frame tend to hide the presence of the common BVID. On the other hand, a DI offers one piece information for each actuator-sensor pair. The employed approach is therefore unable to determine which region around the actuator-sensor pair is affected, hindering the multiple-damage detection with nearby damages. Future work focuses on overcoming some of the algorithm limitations.

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REFERENCES