Experimental investigation of damage detection on structures with friction stir welding (FSW) junctions

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Abstract. A Structural Health Monitoring system for damage detection is proposed in this paper. The Probability Ellipses method (PE) is a non-destructive method based on Guided waves. This method estimates a global index called Damage Index (DI), that represents a way to measure how much critical is the related sensing-path (actuator-sensor). The DI is high when the damage is closer to the sensing-path and it increases again when the damage severity grows. The work is being developed in the framework of the Clean Sky 2 specifically for More Affordable Small Aircraft Manufacturing (SAT-AM) project, whose main goal is the development of new technologies to be employed in the development of next generation of small aircrafts category responding to CS/FAR-23 certification specification Rules. The Friction Stir Welding (FSW) is one of key technologies to reduce cost, time and manufacturing costs. Conversely, the low historical data on structural degradation of FSW joints require a conservative approach during design stage. A possible answer to the lack of structural knowledge behavior could be overpassed by using structural health monitoring system that periodically evaluates the born of any criticalities of the FSW structures. Preliminary experimental investigations of the ET method, applied to structures with Friction Stir Welding (FSW) junctions, are illustrated. Aluminum panels were joined with FSW technique and damage was produced in the junctions. The structures were instrumented with piezoelectric actuators and sensors. The Guided waves were acquired on both undamaged and damaged configurations and the PE method was applied to identify the damage position.

1. Introduction
In the past decades, the Structural Health Monitoring (SHM) has been the main research topic of many scientists worldwide in order to develop efficient damage detection techniques able to identify the inception and propagation of the damage. The Structural Health Monitoring aims to implement systems able to detect the damage in a non-destructive way [1][2][3].

Many technologies are investigated in order to explore mix of novel technologies for weight manufacturing of metallic and composite structures for envisaged family of small airplanes, that allows them to take part in the future European Integrated Multimodal Transport System; build innovation
potential via synergetic, trimmed supply chain; finding maximum affordability for combination of tested technologies. The Friction Stir Welding (FSW) is one on the technologies studied to reduce errors and manufacturing costs. The FSW technology can be used in the manufacturing of several items like cockpit window frames, floor and other elements. Past studies demonstrated [8] that, for aeronautical application, SHM is considered an enabling technology to reduce the conservative assumption for structures sensitive to high probability of damages (i.e. composite structures). The techniques for the damage detections of composite and metallic structures have been developed through extensive numerical-experimental analysis based on lamb-wave investigation by using piezoelectric sense-actuators [9],[10]. The system is based on Guided waves [7] to [10], able to catch the presence of failure in a not-conventional aluminum structures rivetless joined (i.e. FSW). Further, the whole system will be developed in order to be easily usable both on simple sub-component and on complex aeronautical component. SHM system will be used in order to evaluate the different structural behavior of different rivetless solutions near the failure events and, in the future, to be a system to support the flight clearance on such not-conventional structures. FSW is a solid-state joining process that reduces errors and manufacturing costs by eliminating fasteners. This process appears to be especially suitable for welding the fuselage aerostructures of high-strength aluminum alloys that can maintain the excellent properties in the weld seams. This has an impact on potential weight savings compared to the conventional riveting techniques for fuselage assembly. Implementation of Friction Stir Welding (FSW) technology will revolutionize the manufacture of aerostructures. Deployment of this technology will allow for obtaining high-quality, i.e. homogeneous and high-strength connections, whose production will not cause environmental degradation, and will be safe for personnel as well as definitely reduce production costs in category CS 23 aircraft.

2. Method Description

The Damage Index (DI) approach was used to characterize the degree of damage of the structure, while the Probability Ellipse (PE) method was used for damage detection [5][6][7]. Combining the damage index of all actuator-sensor patterns, this method is able to assess the damage position. The DI approach is designed to overcome the complexity and variability of the signals in the presence of damage as well as the geometric complexity of the structure. It relies on the fact that the dynamic properties of a structure change with the initiation of new damage or growth of existing damage [16][17][18]. Considering measurements performed on an undamaged structure as baseline, the DI was evaluated by comparing the changes in the Guided waves measured after the damage. The DI vanishes if there is no change in the structure while its value increases with the severity and proximity of damage to the sensor locations. The objective of the present paper is to apply the DI method to structures with Friction Stir Welding (FSW) junctions. The DI obtained comparing the measured time response of two successive states of the structure is introduced as a determinant of structural damage. The presence of damage modifies the modal properties of the structure as well as certain characteristics of the ultrasonic waves. The changes in the measured dynamic response of the structure are analyzed to reveal the location and degree of damage. Wave propagation are performed in the reference and damaged states of the structure. In the wave propagation test, elastic waves with known properties are launched by broadband transducers located on the surface of the structure. The motion produced by the source is acquired by multiple sensors located on the surface of the structural component. The damage index, DI, is then calculated as follows:

$$DI = \sqrt{\frac{\sum_i (C_p - C_d)^2}{\sum_i C_p^2}}$$

(1)

The Cp and Cd are respectively the amplitude of the guided wave, at same time, in configuration “pristine” and “damaged”, while “i” is the time sample. The DI defined in equation (1) returns non-zero values only if any change in the measured dynamical response of the structure occurs, and it will return
zeros if the experimental measurements are identical. The reliability of the damage detection procedure is strongly dependent on the reliability of the measured dynamic response of the structure in the reference and damaged states. Once defined the Damage Index, a Probability Ellipse method was used in this work for estimating the probability of the presence of damage in the monitoring area for FWS joint aluminum plates. In this study, the presence of damage is assumed to be the exclusive reason for the changes in Guided wave signals between the reference and present states. The changes induced by other factors in practical application, e.g. the environmental noise in other frequency range, could be filtered out by employing advanced signal processing methods. The degree of signal change for a particular sensing path before and after that the damage is introduced will clearly be increased if the sensing path is close to the damage and conversely will be decreased if the sensing path is distant from the damage. It is evident that the correlation coefficients for seriously damage-impaired sensing paths are lower than those for slightly damage-impaired sensing paths. As a result, the damaged zone in the monitoring area can be considered as the common area which is near most of the seriously damage-impaired sensing paths with low correlation coefficients. The complexity of structural geometry or boundary conditions would not affect the capability of the damage identification, since these influences are implicitly included in both the reference and present signals. The monitoring area is meshed into uniformly distributed grids and the probability of the presence of damage at each grid is estimated. For any grid, the Damage Index for each sensing path presents an estimation of the probability of the presence of damage at this position. Different weights, which are measured by the distances from the grid to the selected sensing paths, are included in the final decision fusion. The area consisting of the grids with probability values for the presence of damage above a specified threshold is defined as the damaged area. In particular, the grid with the highest probability value for the presence of damage indicates the center of the identified damage.

Assuming there are N sensing paths in total, the estimation at position (x, y) can be written as [19]:

\[
P(x, y) = \sum_{k=1}^{N} p_k(x,y) = \sum_{k=1}^{N} DI_k \left[ \frac{-R(x, y, x_{ak}, y_{ak}, x_{sk}, y_{sk})}{\beta} + \beta \right]
\]

(2)

where

\[
R(x, y, x_{ak}, y_{ak}, x_{sk}, y_{sk}) = \begin{cases} 
R_c(x, y, x_{ak}, y_{ak}, x_{sk}, y_{sk}), & R_c(x, y, x_{ak}, y_{ak}, x_{sk}, y_{sk}) < \beta \\
\beta, & R_c(x, y, x_{ak}, y_{ak}, x_{sk}, y_{sk}) \geq \beta
\end{cases}
\]

(3)

and

\[
R_c(x, y, x_{ak}, y_{ak}, x_{sk}, y_{sk}) = \frac{\sqrt{(x - x_{sk})^2 + (y - y_{sk})^2} + \sqrt{(x - x_{sk})^2 + (y - y_{sk})^2}}{\sqrt{(x_{ak} - x_{sk})^2 + (y_{ak} - y_{sk})^2}}
\]

(4)

is the ratio of the sum of the distances from the grid (x, y) to the actuator (x_a, y_a) and to the sensor (x_s, y_s) to the distance between the actuator and sensor; in equation (2) \( p_k(x,y) \) is the estimation of probability of the presence of damage from the k-th sensing path and \( \beta \) is a scaling parameter which controls the size of the affected zone of sensing paths. The affected zone can be elaborated by an ellipse encircling an actuator-sensor pair (sensing path), if it is assumed that the velocity of the wave signal is constant, Figure 1 [19]. The scaling parameter \( \beta \), assumed as the reciprocal of the eccentricity, has been fixed to 1.3. The equation (2) highlights how the probability to have damage at location (x,y) is directly connected with the damage index.

3. Numerical applications and results

FEM model of two flat aluminum panels with different thickness, overlapped and joined with FSW, was performed (Figure 2). Since the Guided waves propagate in both symmetric and antisymmetric ways
into the thickness, all FEM models were realized using 3D solid elements to correctly simulate the wave deformation inside the thickness.

**Figure 1:** Probability ellipse affected zone.

The modelling criterion, in terms of mesh size, is such to guarantee the correct representation of the guided waves into the structure. Along the thickness, the modelling is such to have more than one solid element. In order to simulate the FSW joint an elastic modulus knockdown of 20% respect to the plates Aluminum material was considered. The set-up is composed by four piezoelectric devices that work both as actuator and sensor. Each piezoelectric sensor was modeled in the FEM using 3D solid elements. The actuator feature was carried out using the thermal expansion analogy. This analogy takes advantage of the correspondence between the structural expansion of the piezo under the action of both electric potential and thermal gradient. Numerically was then applied a thermal gradient to the 3D elements of the piezoelectric sensors such to generate a 4.5 sine tone-burst signal at 150kHz. Artificial damages (wormhole type) were simulated by removing elements inside the FSW joint.

**Figure 2:** Flat aluminum panels scheme and dimensions.

Shape, volume and position were modified in order to have a wide database of damage scenario. In Figure 3 is shown an example of damage and a zoom of the damaged area. Considering the symmetry of the panel perpendicular to the FSW joint, the damages were placed only in one half of the panel (left side in Figure 4) and in particular in two zones referred as Position 1 and Position 2 (Figure 4).

**Figure 3:** Example of simulated wormhole type damage inside FSW joint.

**Figure 4:** Zones of possible damage (Pos1 and Pos2)
Simulations were performed on the undamaged and damaged structure and the Damage Indexes (DI) were evaluated for each simulated damage and for each sensing path. The Probabilistic Ellipse (PE) method was applied in order to identify the position of each damage. In Figure 5 are shown some of the results, in particular in the images the red circled symbolize the sensors and actuators, red full squares represent the damages, the blue area is the area in which the probability to find a damage is bigger than 95% while the green point is the point with biggest probability of the damage presence. The PE method has correctly identified with very good accuracy all the damage positions; the damage detected is always inside or very close to the blue area. In order to quantify the damage severity, its volume was considered. It was found that, for each damage, the mean value of Damage Indexes evaluated for all sensing-paths (DI_Mean) was related to the damage volume and in particular to its natural logarithm.

![Figure 5](image-url) Damage position identification results.

In order to quantify the damage severity, its volume was considered. It was found that, for each damage, the mean value of Damage Indexes evaluated for all sensing-paths (DI_Mean) was related to the damage volume and in particular to its natural logarithm. The graph in Figure 6 reports all the studied cases, in terms of DI_Mean vs Ln(volume). Different colors were used for damages in position 1 (blue points) and in position 2 (red points).

![Figure 6](image-url) DI_Mean vs Ln(Volume): Pos1 (blue points) and Pos2 (red points)

Each group of results (pos1 and 2) showed a specific trend, so fitting curves can be find. The data for each position were split in two part, some data were used to get the fitting curves while the others have been used as validation test. To have the best fitting, were treated separately the data obtained for small damages (Volume < 20mm³) and those for big volumes (Volume > 20mm³). The first were fitted using parabolic curves, one for each position. The others were fitted using two different curves: a logarithm one for the damage in position 1 and a second-order polynomial for the damage in position 2.

In Figure 7 is shown a graph with the curves obtained for each position. The PE method allows to identify the damage position (Figure 5) and the damage zone (pos1 or pos2), then using the fitting curve corresponding to the detected zone (Figure 7), the damage volume is evaluated. This procedure was applied for all the validation data and the percentage error has been evaluated by comparing the true and estimated value of volume. The data used for validation are also shown in Figure 7 (point blue and red).
Instead, in Figure 8 is reported the graph of the percentage error. The maximum error obtained in calculation of volume is equal to 29% while the mean error is of 12%. These results are very encouraging considering that the DI_mean is affected by damage position and only two damage zone (pos1 and pos2) were considered. The results are expected to improve if the panel is split in more zones. The presented PE method allows to identify the damage position using the Probabilistic Ellipses (Figure 5) and then evaluate the volume damage using the fitting curves (Figure 7).

4. Experimental set-up and results

Two aluminum panels were used for experimental activities. Their dimensions and set-up were similar to numeric panel. Each panel was made of two flat aluminum plates with different thickness, overlapped and joined with FSW as shown in Figure 9.

The panels were instrumented with 4 piezoelectric ceramic patch (DuraAct) (Figure 9), used as both actuators and sensors. NDI showed absence of damages or imperfections inside the FSW joints, so in this preliminary investigation, in order to obtain a damage, a hole has been made in the welded area (Figure 9). To have different damage dimensions, three holes with increasing diameter were considered (8, 10 and 13 mm). Furthermore the holes were placed in the same zones as the numerical analysis: in the panel 1 was considered the position1 and in panel 2 the position2.

The experimental set-up is pictured in Figure 10. The excitation of the actuators has been realized with tone-burst with frequency of 150 kHz. The phases of generation and recording of the Lamb wave signals were accomplished using the National Instruments NI-USB Xseries device. The controlling and analysis tools were written in Matlab environmental. Acquisitions were performed on the undamaged and damaged structure. The damage indexes (DI) were evaluated for each sensing path and the Probabilistic Ellipse (PE) method was applied. The position of each damage was identified in a very accurate way as shown in Figure 11.
As second step, the DI_Mean has been evaluated for all the experimental damages and the results were plotted together with numerical data (Figure 12). For both panels and positions the DI_Mean for experimental data is smaller than the numeric one. This result was predictable considering that the numerical data were obtained from a simplified model of the panel and in particular of the FSW joint.

**Figure 10:** Experimental set-up

**Figure 11:** Experimental results in terms of damage position identification

The most important result of this preliminary experimental investigation is that the experimental data (blue and red dotted lines) show the same trend of the numeric ones (blue and red full lines) as plotted in Figure 12.

**Figure 12:** Graph with numerical fitting points and curve (red and blue circles and lines) and experimental results and fitting curves (red and blue squares and dotted lines)
5. Conclusions
An application of the Probability Ellipse (PE) method, based on Damage Index calculation, to structures with Friction Stir Welding (FSW) junctions has been presented in this paper. The work is being developed in SAT-AM, Clean Sky 2 project. Aluminum panels with different thickness were joined with FSW technique. A damage was produced in the junctions and the PE method was applied. The results, in terms of both damage position identification and damage dimension evaluation are very encouraging. The position of damages have been identified accurately in all the analyzed items. In addition, the damage dimension has been detected again accurately with a percentage error of about the 12%. Experimental activities were performed on two aluminum panels with FSW joints. Acquisitions on the undamaged and damaged panels were made and the Probabilistic Ellipse (PE) method was applied. The damage position was always correctly identified and the experimental data highlight the same trend of the numeric ones in terms of damage dimension. A more accurate numeric model of the FSW joint is necessary to verify if the numerical results go towards to the experimental ones. Furthermore, experimental tests on FWS joint with realistic damage (worm hole) have to be performed in other to assess the method when applied to real damage.

References
[1] Rose J 2001 A vision of ultrasonic guided wave inspection potential Proceedings of the seventh ASME NDE topical conference NDE 20 pp 1–5
[2] Sohn H Farrar C Hemez F Shunk D Stinemates D Nadler B 2003 A review of structural health monitoring literature: 1996–2001 Los Alamos National Laboratory USA
[3] Wang D Ye L Lu Y Su Z 2009 Probability of the presence of damage estimated from an active sensor network in a composite panel of multiple stiffeners Composites Science and Technology 66(13) pp 2054–63
[4] Di Palma L, Sorrentino, A., Vitiello, P., Izzo, C, Composite structural health monitoring for MALE UAV application. SAE TECHNICAL PAPERS, 2013, vol. 7, ISSN: 1083-4958, doi: 10.4271/2013-01-2159
[5] Di Palma L, Romano F. Sorrentino A. (2014). Structural health monitoring for aerospace composite application. In: Proceedings of the 22nd International Conference on Computers in Education, ICCE 2014. vol. 2014., ISBN: 978-499080143-4, Malta, 13th July 2014
[6] De Luca, A., Lamanna, G., Soprano, A., Caputo, F., Modelling of interactions between Barely Visible Impact Damages and Lamb waves in CFRP laminates., (2018) Procedia Structural Integrity, 8, pp. 288-296
[7] Su Z Ye L Lu Y 2006 Guided Lamb waves for identification of damage in composite structures: a review Journal of Sound and Vibrations 295:753–80
[8] De Fenza A Sorrentino A Vitiello P 2015 Application of Artificial Neural Networks and Probability Ellipse methods for damage detection using Lamb waves Composite Structures, vol 133 pp 390–403
[9] Sorrentino A De Fenza A 2016 Improved elliptical triangulation method for damage detection in composite material structures Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science doi.org/10.1177/0954406216682053
[10] Sorrentino A Romano F De Fenza A Mercurio U 2019 Advanced non destructive technique for debonding inspection of aircraft composite structures 12th IWSHM - International Workshop on Structural Health Monitoring Stanford USA

[11] De Fenza A Petrone G Pecora R Barile M 2017 Post-impact damage detection on a winglet structure realized in composite material Composite Structures Vol.169 pp 129–137

[12] De Luca A Perfetto D De Fenza A Petrone G Caputo F 2020 Guided wave SHM system for damage detection in complex composite structure Theoretical and Applied Fracture Mechanics Vol.105

[13] De Luca A Perfetto D De Fenza A Petrone G Caputo F 2019 Guided waves in a composite winglet structure: Numerical and experimental investigations Composite Structures Vol.210 pp 96–108

[14] De Luca A Perfetto D Petrone G De Fenza A Caputo F 2018 Guided-waves in a low velocity impacted composite winglet Key Engineering Materials Vol.774 pp 343–348

[15] De Luca A Perfetto D De Fenza A Petrone G Caputo F 2018 A sensitivity analysis on the damage detection capability of a Lamb waves based SHM system for a composite winglet Procedia Structural Integrity Vol.12 pp 578–588

[16] Banerjee S Ricci F Monaco E Mal A 2009 A wave propagation and vibration-based approach for damage identification in structural components Journal of Sound and Vibration 322 pp 167–183

[17] Banerjee S Ricci F Shih F Mal A K 2007 Structural health monitoring using ultrasonic guided waves Advanced Ultrasonic Methods for Material and Structure Inspection ISTE 18 pp 43–86 London and Newport Beach, California.

[18] Mal A Ricci F Banerjee S Shih F 2005 A conceptual structural health monitoring system based on vibration and wave propagation Structural Health Monitoring 4 pp 283–293

[19] Zhao X Gao H Zhang G Ayhan B Yan F Kwan C 2007 Active health monitoring of an aircraft wing with embedded piezoelectric sensor/actuator network: I. defect detection, localization and growth monitoring Smart Material Structure 16 pp 1208–1217