Online Damage Detection on Metal and Composite Space Structures by Active and Passive Acoustic Methods

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ABSTRACT

In the frame of ESA funded programme Future Launcher Preparatory Programme Period 1 "Preparatory Activities on M&S", Aerospace & Advanced Composites and Thales Alenia Space-Italia, have conceived and tested a structural health monitoring approach based on integrated Acoustic Emission – Active Ultrasound Damage Identification. The monitoring methods implemented in the study are both passive and active methods and the purpose is to cover large areas with a sufficient damage size detection capability. Two representative space sub-structures have been built and tested: a composite overwrapped pressure vessel (COPV) and a curved, stiffened Al-Li panel. In each structure, typical critical damages have been introduced: delaminations caused by impacts in the COPV and a crack in the stiffener of the Al-Li panel which was grown during a fatigue test campaign. The location and severity of both types of damages have been successfully assessed online using two commercially available systems: one 6 channel AE system from Vallen and one 64 channel AU system from Acellent.

INTRODUCTION

Health Monitoring is aimed at embedding diagnostic functions onto space infrastructures and transportation means, resulting in integrated on-board capabilities for 'self inspecting' either remote and not accessible spacecraft areas, producing real time health diagnostics (anomalies, ageing, integrity) of critical subsystems such as structure, thermal protection, propulsion and actuation, raising early warning flags either to mission and on ground proactive maintenance service.

Worldwide activities in the field of „Structural Health Monitoring" are continuously growing since more than two decades. An intensive overview of the various activities in the field of structural health monitoring can be found in [1] and [2]. It is possible to classify the different technologies by the used sensor principles or by the used SHM methodologies.

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The most promising sensor principles are based on piezoelectric materials, eddy current foils and fiber optic sensors like fiber Bragg grating sensors; for what concern methodology it is possible to distinguish between passive systems, i.e. the SHM system “listen” to structural changes, and active systems, i.e. the SHM system monitor the structural status in determined instants. Analyses show that mainly the acoustic methods either passive as acoustic emission (AE) or active as acousto ultrasonic (AU) are able to cover larger areas with a sufficient size of detectable damage [3, 4, and 5]. Within this study the authors present the latest result for online damage detection, localization and quantification in two different types of space structures: 1 COPV and 1 stiffened Al-Li panel – using a combined passive / active SHM approach based on AE and AU.

TEST ARTICLES

Two different types of test articles have been used in this study: 1 Composite Overwrapped Pressure Vessel (COPV) and 2 curved and stiffened Al-Li panels (1 undamaged and 1 pre-damaged one).

The COPV consist of a metallic inner bottle that is overwrapped by several layers of CFRP. For both online damage detection methods – passive Acoustic Emission (AE) and active Acousto Ultrasonic (AU) – the same type of sensors are used – smart layer single sensors from Acellent. The replacement of the bulky AE sensors is done to evaluate the behavior of non-conventional piezo disc sensors (smart layer) for AE, as such sensors are much cheaper and can be integrated much easier in future applications. The whole vessel is equipped with 15 smart layer sensors – 6 at the lower part and 6 at the upper part of the cylindrical portion and 3 close to the neck of the bottle. For AE measurements during the impact test campaign, totally 6 smart layer sensors will be used. In case the impact is introduced in the cylindrical part of the vessel, 3 sensors at the lower part and 3 sensors at the upper part of the cylindrical portion are active whereas for impacts around the neck region, 3 sensors at the upper part of the cylindrical part and 3 sensors close to the neck are active.

The Al-Li panels used in this study are curved panels with reinforcing stringers arranged in regular square pattern. In one panel a crack is introduced close to the centre of the panel at one stringer – 20 mm apart from the centre. For AE damage detection, 6 conventional AE sensors are attached to the corners and to two straight edges of the curved panel. The smart layer sensors for AU (totally 24 for one panel) are placed directly on the stringers in the middle between two crossing stringers. Fig. 1 shows the photos of both test articles with the sensors.

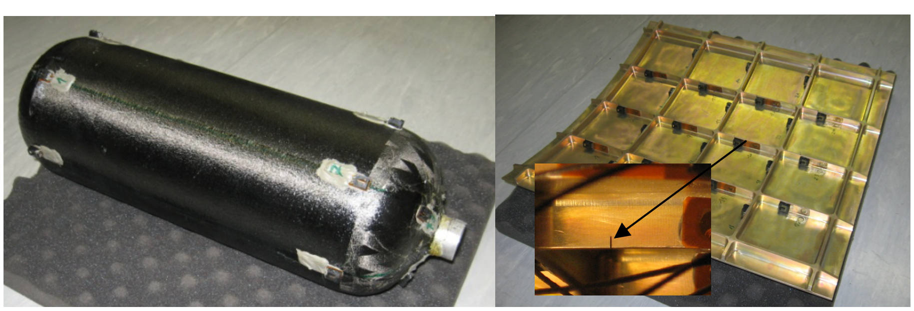

Figure 1. Photo of the COPV and AlLi panel with sensors and the position of the crack.

MONITORING SYSTEMS AND ALGORITHMS

Acoustic Emission System

Online Acoustic Emission Monitoring is performed with a laboratory based 6 channel Vallen AMSY-5 system with broadband pre-amplifiers AEP4 and AE sensors VS 900-M connected to a standard desktop PC. Prior to the individual tests, the AE system is calibrated. First the background noise is measured for a defined time of 180 s to assess its amplitude. The threshold for detection is set to a level of 2 dB above the background noise. Then all sensors and the quality of the gluing of all sensors are proven. Each sensor is excited by a series of short pulses to generate an acoustic wave in the COPV, in the meantime the other sensors are used to measure the arrival time differences and other AE features. In order to assess the damage status of the structures (location and severity of damages), the number and energy of located AE events over the structure is used. The most important step in damage assessment is the proper location of the AE sources. In case of simple geometries, as for the slightly curved Al-Li panel and the cylindrical part of the COPV, standard triangulation algorithms using the arrival time differences of the different sensors have been used. In case of complex geometries and un-isotropic wave propagation, as it is the case in the region of the neck of the COPV, a so called self-learning approach shall be used. The measured arrival time differences from the calibration are used to calculate virtual distances between the individual sensors based on the average wave velocity. The virtual distances between the 3 sensors that will be hit first by an AE event are used to construct a planar triangle with the sensors at the edges. This distorted triangle is used to locate the event by applying standard planar triangulation algorithms. Finally the position of the AE source in this distorted triangle is transferred back to the coordinates of the original structures. Once the source location is identified the number and energy of the located events around the position of the source locations are used to quantify the severity of the damage.

Acousto Ultrasonic System

The system used for acousto ultrasonic is an active 32 channel ultrasonic guided wave system type scan genie with single smart layer sensors from Acellent, using ACESS software for data acquisition. The system works in pitch – catch mode. That means that one of the transducers is activated whereas another (or the same) transducer acts as receiver (sensor) and the signal is measured for a predefined time with a pre-defined sample rate. The procedure is repeated for all defined combinations of actuators and sensors. In order to assess if a structure is damaged or not, first a baseline signal of the undamaged structure is measured and later on compared with a signal measured after usage (damage introduction). The severity of the difference between the signals – damage index – of the two measurements is calculated by the mean square root of the difference signal between the two measurements divided by the mean square root of the first signal in a predefined time interval. In order to locate and quantify the amount of damage several transducers are used as actuators and sensors leading to a lot of actuator – sensor paths which intersect each other on different points within the structure. At each intersection point the average damage index of all intersecting paths is determined and a color coded plot is generated to display a quasi C-scan of the structure.

RESULTS

COPV

Prior to the start of the impact test campaign all 15 smart layer sensors are glued to the COPV and baseline measures at different temperatures are taken, then three impacts are introduced in the COPV in an INSTRON Dynatup 9250 drop tower. To guarantee a perpendicular impact of the impactor on the COPV at different places (cylindrical part and around the neck), the COPV is mounted in an impact fixture and tilted to the preselected position by means of a tilt holder. Impact 1 is introduced at the cylindrical part of the COPV on the connection line between sensor 1 and sensor 7. Impact 2 is introduced in the spherical part of the COPV in the middle between sensor 7 and sensor 12 in direction to the neck. Impact 3 is introduced in the spherical part of the COPV in the middle between sensor 14 and sensor 15 on the connection line between sensor 14 and sensor 15. All impacts are performed with a spherical impactor of 20 mm in diameter and a total weight of 7.49 kg. Impacts 1 and 2 are introduced with incident energies of 7 J whereas impact 3 is introduced with incident energy of 15 J. During the introduction of the impacts the force and velocity of the impactor are measured to assess the absorbed energy in the COPV. After the introduction of the impacts the overall damage size is determined by conventional ultrasonic inspection. Table I summarizes the results of the impact testing campaign.

Table 1. Results of the impact testing campaign.

Impact No.	Absorbed Energy [J]	damage area [mm²]	Position: $\alpha1$[°] / z [mm] $\alpha1$[°] / $\alpha2$ [°]
1	7	2500	0 / 75
2	5	15	-30 / 40
3	7	225	180 / 80

The AE system is active during the introduction of the individual impacts continuously acquiring structural changes caused by the impact. The arrival time differences are used to determine the source location as described in chapter 3.1 and the energy of the located event on the COPV is used to display the assessed impact position (see Fig. 2). Impact 1 is detected at a position of [-2.9 / 78] that is very close to the actual position of impact 1 at [0 / 75]. Impact 2 is located between the sensors 7 and 13 with an average distance from the real impact position of 15 mm and impact 3 is located between the sensors 14 and 15 with an average distance from the real impact position of 10 mm.

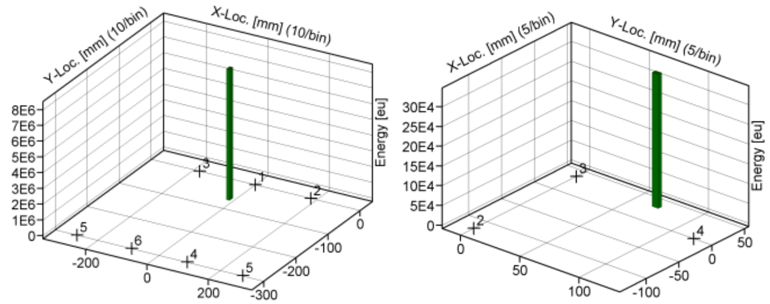

Figure 2. Located event measured by AE during the introduction of impact 1 and impact 2.

For damage detection with the active AU method, first the baseline of the acoustic response is measured and then the test campaign can start. All sensors (sensors S1 to S6 and sensors S13 to S15) are actuated by a 3-sin-burst signal (amplitude: 50 V) and the acoustic waves are measured by all remaining sensors (S7 to S12). The measured signals of all sensors are amplified by 40 dB. Data acquisition is repeated 6 times for each path for averaging and it is done with sampling rate of 24 MSamples / sec for a total length of 12 kSamples corresponding for a total time of 500 µs. Frequencies ranging from 50 kHz, up to 300 kHz in 25kHz steps are used. The measurements are done at different temperatures ranging from 15 °C up to 35 °C in 2 °C steps in order to evaluate the temperature influence on the measured acoustic signals. When comparing the measurements at different temperatures the following conclusions can be drawn: the higher the temperature difference, the larger the difference between the two signals; the wave velocities and the damping of the traveling lamb waves change with temperature – the higher the temperature, the lower the wave velocity and the higher the damping and the effect is larger when the actuation frequency is higher. The findings above are extremely important as they influence the results of damage detection, if the measurement of the baseline and the measurement after damage are done at different temperatures.

After the introduction of the individual impacts the procedure described above has been repeated at the actual temperature of 20°C. The transient signals for the baseline measurement and the measurement after the introduction of the individual impacts are used to located and quantify the individual damages by the algorithm described in chapter 3.2. It can be seen that the maximum of the damage index after the 1^{st} impact occur around the impact damage position [0° / 75 mm] for the 50 kHz, 100 kHz and 200 kHz measurement. For all frequencies ghost echoes exist mainly along the 0° coordinate. All of these ghost echoes are clearly smaller in amplitude and extension compared to the main echo (see Fig. 3 left side). In order to assess the influence of the temperature on the damage detection ability of the active method baselines taken at different temperatures compared to the measurement after impact 1 are used to calculate the damage index over the COPV. For a temperature difference of up to 15° between the baseline and after the introduction of the impact it is possible to detect and locate the impact damage when using 50 KHz for actuation (see Fig.3 middle). For the 100 kHz measurement the situation is different. Still the effect of the impact can be seen around position [0° / 90 mm] but several ghost echoes appear all over the cylindrical part when using a temperature difference of only 3 °C between the baseline and the measurement after impact 1. The ghost echoes have similar amplitude making a localization of the damage very difficult (see Fig. 3 right).

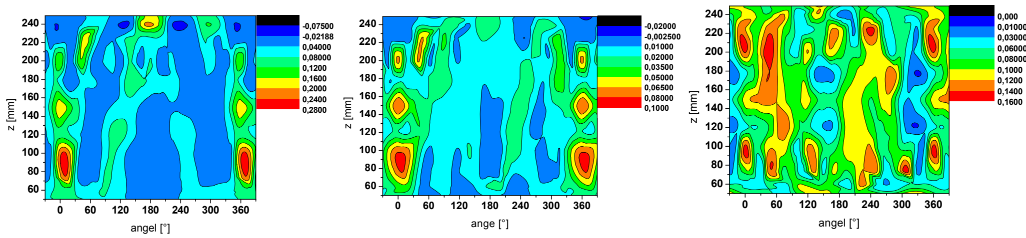

Figure 3. Distribution of the damage index using the best baseline and a baseline taken at a □T of 15°C after the first impact for 50 kHz and baseline taken at a DT of 3°C after the first impact for 100 kHz – over the COPV.

The same procedure is applied to the other impacts at the spherical part of the COPV. By using a frequency of 50 kHz impact 2 can be detected but the impact is located at position [90° / 42°] which clearly deviates from the position of the impact at [330° / 40°] and a second echo appears around position [240° / 30°] which also deviates clearly from that position. For impact 3 the angular 1 position [180° measurement] can be clearly located by using both frequencies of 50 kHz and 100 kHz whereas the angular 2 position [25° out of the AU measurement] cannot be correctly assessed.

AlLi Panel

In order to propagate a growing crack, the Al-Li panel is subjected to fatigue loads. Prior to the start of the fatigue test campaign all 24 smart layer sensors are glued and the 6 AE sensors are clamped to the Al-Li panel. For fatigue testing the flexible bending fixture is modified to a three point bending fixture with additional limiters in order to avoid a movement of the Al-Li panels in the bending fixture. The applied load cycles are between 400 N and 4000 N at a frequency of 0.5 Hz (based on analyses performed by TAS-I, the load cycles shall have a maximum force of 4000 N and a ratio of R = 0.1.). The following sequence is used: 1000 cycles – 1000 cycles – 2000 cycles – 2000 cycles. After each sequence the crack length is controlled and documented with a digital camera. Fig. 4 shows the crack length vs. load cycles together with a pictures made of the crack after 2000 load cycles.

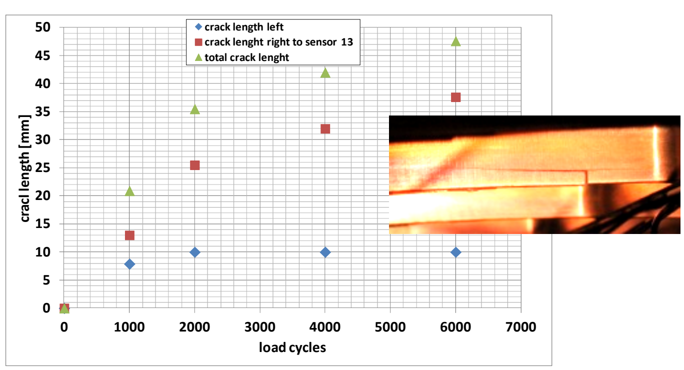

Figure 4. Crack length vs. load cycles together with a pictures made of the crack after 2000 cycles.

The AE system is active during the whole fatigue test campaign. This allows acquiring the AE hits at the individual sensors coming from the growing crack. As already described in chapter 3.1 the number and energy of the located events are used to locate and quantify the severity (length) of the crack. A lot of AE events arise from the friction of the support. In order to be able to limit the effects of friction from the support, the following filters are used: number of signals / event > 4, that means in minimum 5 of the sensor are used to locate an event and the location uncertainty < 100 mm. The located events coming from the friction of the supports can be largely reduced except around the places of the sensors and limiters. The remaining located events are concentrated on the panel near the position of the crack-starter which is located at x = 235 mm and y = 225 mm. From the analyses of the energy of located events (LEs), the position of the crack at the end of the individual load cycles are estimated by using the centre of gravity of the energy of the LEs around the region where a concentration of the LEs is detected. The position of the crack can be determined with an average distance to the real crack position of around 23 mm. When analyzing the cumulated energy and cumulated number of located events as function of time, different types of crack growth are observed. In the beginning the cumulative number of located events is continuous growing after the first small jump in the energy vs. time curve at around 800 s (225 cycles) and only very small jumps in the cumulative energy with time appear. Such behavior can be interpreted as a controlled crack growth after crack initiation as the crack continuously producing AE events of moderate energy. During the 2nd (1000 – 2000 load cycles) and 3rd (2000 – 4000 load cycles) test sequences the behavior is totally different. The cumulative number of located events increases only slowly but there are remarkable jumps in the cumulative energy versus time curves. Such behavior can be interpreted as an uncontrolled rapid crack growth at a defined time (or cycle number). During the 4th load sequence first a jump in the cumulative energy vs. time curve followed by a controlled crack growth is observed. Figure 5 shows a summary of the AE testing campaign.

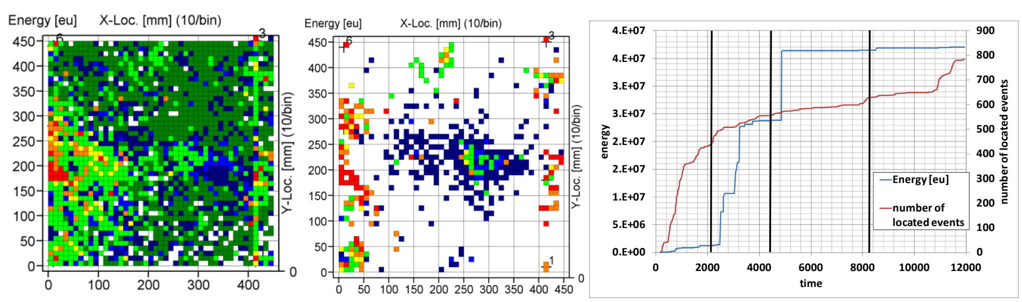

Figure 5. Energy of the located events over the first 100 load cycles over the panel before and after filtering (left and middle) and energy and number of the LE´s over time.

For damage detection with the active AU method, an approach similar to the COPV one is used. Prior to the test the baseline is measured and the damaged status is assessed after the different load cycle campaigns – after 1000, 2000, 4000 and 6000 load cycles using the same signals and frequencies as for the COPV. The transient signals for the baseline measurement and the measurement after the predefined number of load cycles is used to located and quantify the individual damages by the algorithm described in chapter 3.2. The maximum difference between the baseline measurement and the measurement after 1000 cycles occurs close to the crack at position [275 / 235] for the 50 kHz measurement (see right side of Fig. 6). The same procedure is applied to the other load sequences and the distribution of the relative average energy difference between the baseline measurement and the measurement after 2000, 4000 and 6000 cycles. For both frequencies the maximum relative average energy difference between the baseline measurement and the measurement after 1000, 2000, 4000 and 6000 cycles over the Al-Li panel is taken and evaluated for 50 KHz and 200 kHz and displayed versus the crack length. The crack length can be clearly correlated with the maximum relative average energy difference (left side of Fig. 6). This correlation is better for the 200 kHz measurement as there is no plateau between 20mm and 37mm crack length.

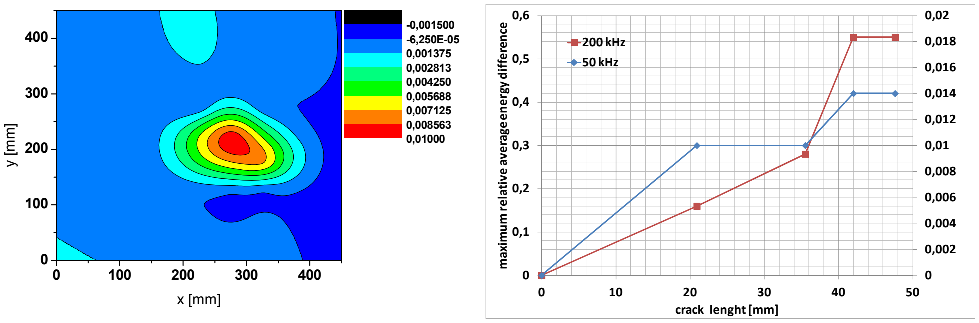

Figure 6. Distribution of the damage index after the first 1000 load cycles over the AlLi panel for 50 kHz (left) and damage index versus the crack length.

SUMMARY

All impacts can be detected and located on a COPV by using online AE and AU monitoring. For low frequencies such as 50 kHz, where the temperature influence is low, even baselines that were taken at a temperature differences up to 15° compared to the damage detection can be used for a proper detection and location of the impact in the cylindrical part. The impacts can be better located by using AE monitoring compared to the AU analyses. The maximum difference in the relative signal energy before and after the impact used in the analyses of the AU data can be correlated with the maximum impact damage area. Both methods AE and AU are able to locate the position of a growing crack in a curve stiffened Al-Li panel where more accurate results could be achieved by analyzing the data from online AE monitoring. Using the energy of the located AE events and the damage index of the AU analyses after a defined number of load cycles, a correlation between the crack length and the different energy measures is found. Combining together the passive AE technique, for exact damage localization, and the active AU technique, for assessing the severity (size) of the damage, the online damage detection is demonstrated.

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