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Lamb Wave Ultrasonic System for Active Mode Damage Detection in Composite Materials

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The work describes a new approach for the development of a SHM system based on flexible piezopolymer transducers which have some advantages over the piezoceramic thin disk transducers in space applications. The flexible piezopolymer transducers made with thin 100 μm PVDF film were proposed by the authors in previous works (Capineri et al., 2002) (Bellan et al., 2005a) (Bellan et al., 2005b).
The proposed technology is based on a network of transducers arranged in array configuration, designed to excite particular types of ultrasonic Lamb waves in laminate materials (metallic or composite). This type of transducers are called interdigital transducers because the comb geometry of the electrodes. The finger to finger distance of interdigital electrode patterns determine the central wavelength of the transducer and then the corresponding Lamb wave's mode. The interest for this technology comes from the characteristics of this piezoelectric polymer film that can operate in a broader range of temperature (-80°C to +60°C) respect to piezoelectric ceramics transducers and its high mechanical compliance allows being adapted to curved surfaces. A laser based micro fabrication design process developed by the research group allows to "tune" for and efficient excitation and reception of selected Lamb waves, depending on the characteristics of laminate material and defect types; in our case we adopted 8mm and 16 mm fingers distance and four pairs of electrodes.
The piezopolymer interdigital transducers have been characterized at low temperature (-80°C) and high temperature (+60°C) showing no significant change of behaviour, confirming that they can operate in the temperature range required for space application.
Different artificial defects have been detected successfully by signal processing with the developed laboratory system: defects with area of about 3cm^2 made by an ultrasonic gel drop on the surface of an carbon overwrapped pressured vessel (COPV) has been detected successfully by using only two arrays of four transmitters and four receivers placed at distance 180 mm.
A search in the literature (Beard et al., 2005) (Champaigne and Sumners) (Chan) (Mańka et al.) (Moll J. et al., 2002) (Park et al., 2006) (Prosser et al.) (Ross) (Staszewski et al, 2008) (Zhang et al., 2008) for methods and instruments that implement passive and active mode for structural health monitoring with acoustic and ultrasonic wave has been done to compare the development system with the state of the art.

1. Piezopolymer transducer network for damage detection on a COPV test sample

Piezopolymer transducers have been designed for the wavelength λ=8 mm, assembled on PCBs connected to the receiving electronics via shielded cables terminating with Jack connectors. Adhesion of the sensors to the COPV surface is assured by smoothing with sandpaper and than degreasing with isopropyl alcohol the vessel surface. Then 8 Piezopolymer transducers (4 transmitters Tx and 4 receivers Rx) are installed on the vessel surface to investigate a portion of the cylindrical surface. The chosen area on the vessel for the investigation (180 mm x 180 mm) is covered by a network of 8 piezopolymer transducers (expandable up to 16 piezopolymer transducers or more) located in two parallel rows. A developed electronic system is programmed for the selection of multiple couples of pitch and catch PIEZOPOLYMER TRANSDUCERs and for the acquisition of relevant data. The developed software

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interface controls the experiment and evaluates the damage index (DI) both in no damaged and damaged conditions and finally shows a coloured scale image connected to the levels of probability of the presence of the damage. The chosen configuration (4+4 piezopolymer transducers at 180mm of distance spread along 180mm depending of defect characteristic and dimension) allows the acquisition of data along the paths between all possible pairs of transmitting and receiving transducers with a good signal-noise ratio and the calculation of DI in different conditions(no damage – damage).

2. Algorithm development for damaged area detection

This task includes:

- The definition of signal paths (short, medium, long) from transmitter to the receiver
- The definition of excitation signal parameters
- The definition of artificially induced damages (drops of gel of different sizes)
- The definition of Matlab routine managing the acquired signals of different paths before the DI calculation
- The calculation of DI based on the difference of both shape and amplitude of two acquired signals across the same path in undamaged and damaged conditions.
- Tests for damaged areas localization are carried out, without and with damages consisting in gel drops laid on the vessel surface within the investigated perimeter, pointing out in damage absence the propagation modes of injected signal.

Reference data across short, medium, long path have been acquired without damages and the same acquisitions have been carried out with damages. The corresponding signals are plotted in time and in power spectral density; finally all damage index values for all paths are calculated and inserted on a matrix whose elements are elaborated by graphic software which shows in colours the areas with highest probability of damage presence. More piezopolymers couples will be used for the size evaluation of damage in a full scale pressure vessel. However the present electronic unit can manage up to 8 transmitting elements and 8 receiving elements. The test with surface defects (gel drops) with diameter from 10 to 20 mm shown clearly the high sensitivity of the method by showing the detecting the damaged area with high signal to noise ratio (or high contrast in the coloured scale image). The defects have been detected for different positions inside the area covered uniformly by the layout of the network, including at the edges of the area. Some artefacts are present due to the limited number of transducers employed; the artefacts consist in an enlargement of the damage area to about the double of the defect area. The assumed transducer density is comparable to those previously adopted by Thales Alenia Space Italia with commercial piezopolymer transducers as number of sensors but the PVDF-IDT solution has the advantage of studying and optimizing the layout by changing sensors positions by exploiting the removable features. Finally no significant changes of the response have been recorded by variation of room temperature from 20°C to 30°C. Wider temperature ranges have to be evaluated.

Figure 1 Programmable acquisition system for active SHM on COPV with piezopolymer interdigital transducers.

3. Experimental results

The complete SHM laboratory system is shown in Figure 1. According to a preliminary characterization of Lamb wave modes of the cylindrical part of the COPV, has been decided to use the anti-symmetric A0 mode at 220 kHz with Vphase = 2200 m/s. The plan view of the cylindrical portion investigated is shown in Figure 2 .

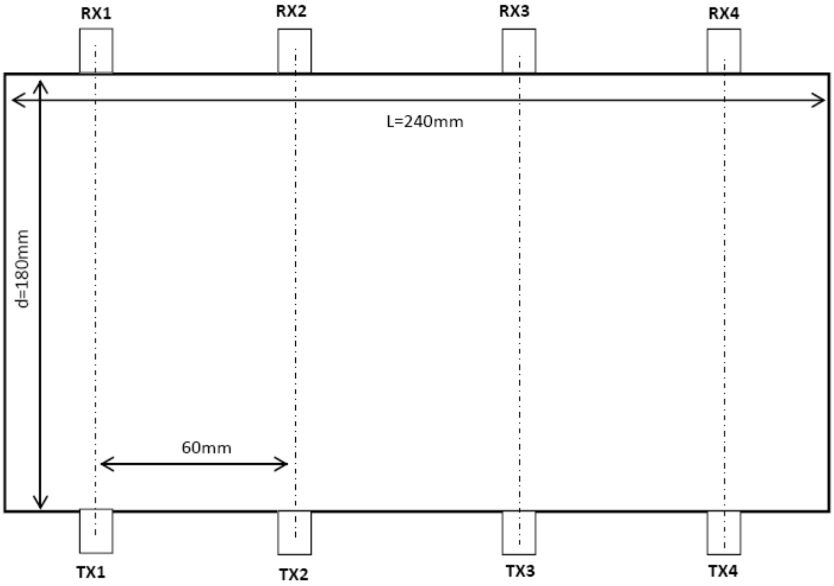

Figure 2 Set-up scheme for the experiments.

Among different experiments, here is reported the output of one experiments with the gel drop placed at the centre of the investigated area (Defect D4 in Figure 3). The data are obtained in real time and no averaging is used on single trace. In table 1 are reported the values of the DI index calculated for all possible paths between Tx and Rx transducers. The paths with a remarkable variation of the DI respect to the baseline are marked in red. The output of the SHM system can be chosen a 3-D plot of the average DI (see Figure 4) or as interpolated image with colour scale for DI (see Figure 5). We observe that the limited beam divergence of piezopolymer transducers decreases the number of available signals from angled paths: for example path Rx1-Tx4 and Rx4-Tx1 have not been available due to the low signal amplitude. However this problem can be overcome in two ways: by decreasing the piezopolymer transducers lateral length at the expenses of a decreased sensitivity or by using more piezopolymer transducers with finer pitch along the array. In the latter case the higher number of signal paths improve the spatial resolution and dynamic of the final image reconstruction

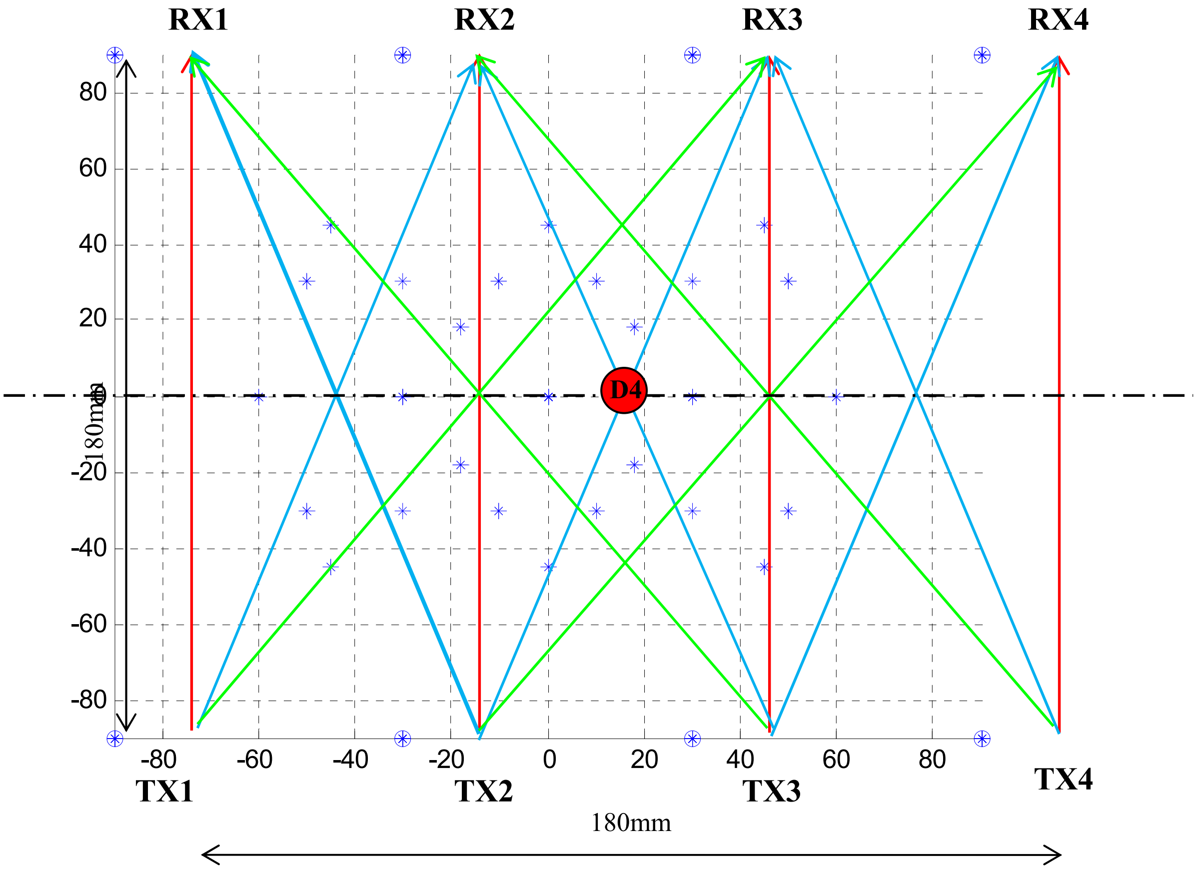

Figure 3 Set-up of the experiments. D4 are gel ultrasonic drops with diameter 20mm. The Image is produced in real time by MATLAB script.

Table 1: Calculated damage index (DI) for defect D4

TX\RX (T0+1)	TX1	TX2	TX3	TX4
RX1	0.93	0.91	0.79	1
RX2	0.90	0.93	0.52	0.75
RX3	0.71	0.58	0.92	0.93
RX4	1	0.88	0.93	0.91

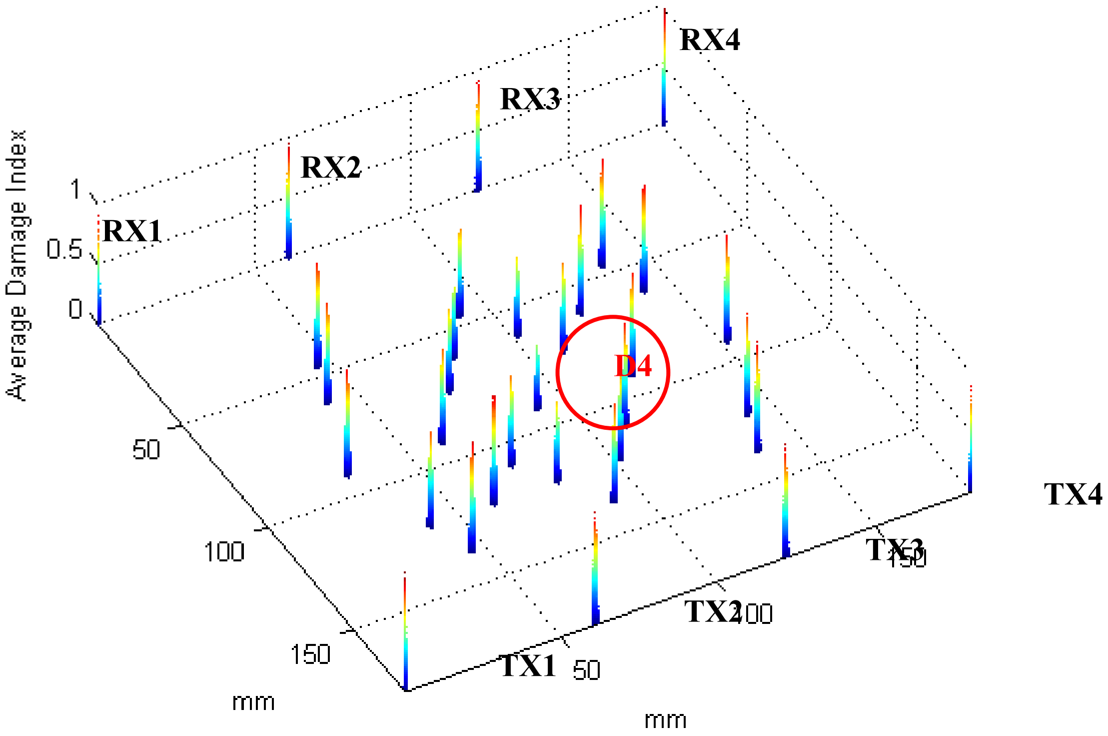

Figure 4 3D-plot of averaged DI for the investigated area with defect D4 in central position.

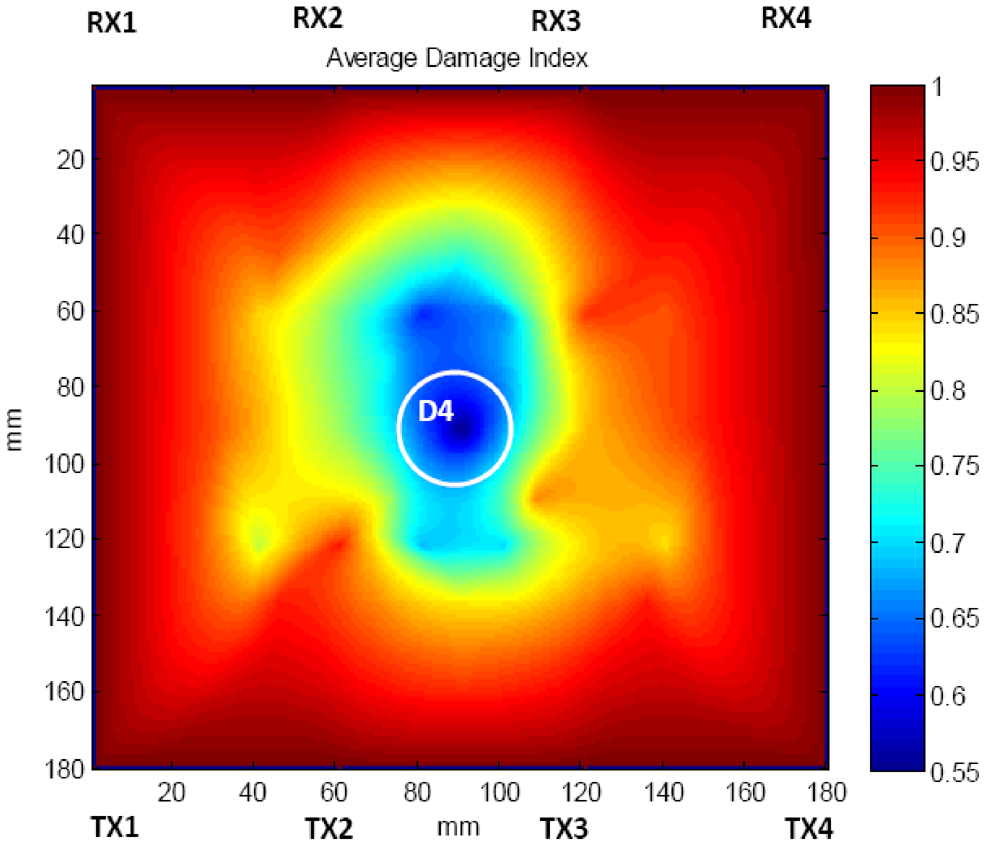

Figure 5 Colour map of averaged DI for the investigated area with defect D4 in central position.

4. Conclusions

A complete acquisition system with programmable parameters has been carried out. The electronic box is capable of 16 transducers with operation in pitch and catch mode.

A comparison of piezopolymer transducers with piezoceramic transducers of disk type (PWAS) have been carried out both for active and passive mode. In passive mode the piezopolymer transducers they have enough sensitivity to detect impacts and provide low frequency signals for impact location. In active mode the narrow band operation of piezopolymer transducers provide high sensitivity to surface defects that are detected by the damage index routine. The Damage Index compares signals of same paths before (pristine condition) and after damage, then can be classified as a baseline method. The method has been experimented at different temperature conditions (variations more than 5°C) without significant variations of performances. The experimental piezopolymer transducers divergence is about 40° and this allows to cover an area of 180 mm x 540 mm with 8 piezopolymer transducers and good signal to noise ratio. The entire cylindrical area (300mm x 540 mm) was monitored with 16 PZTs. Then the two systems have about the same transducers density.

An imaging algorithm based on the assignment of DI for each path is proposed: at the intersection of all possible paths is calculated the mean of the Damage Index for all intersecting path. Then a 3D plot of the averaged Damage Index intersection points is displayed. As shown in the images relative to experimental works the defect position is clearly identified by a lower Damage Index value. The area around the defect shows also a decrease of Damage Index.

The experience gained on this scale model of COPV provided the criterion for the design a new architecture of the passive-active acousto-ultrasonic system.

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