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A Study on Effectiveness of an SHM Sensor System for Fatigue Damage Inspection

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Abstract

In this paper we present an elaborate testing study carried out at the IMA Dresden facility to demonstrate how we studied a new SHM sensor system design for its effectiveness in monitoring fatigue crack damage and its propagation over a varying load spectrum. This sensor system study was carried out to understand how it could complement, accelerate and become a possible NDE-SHM system in the future. We also present how an example simulation was carried out that drove our sensor system design. The activity carried out was an experimental validation of damage detection scheme in an integrated testing on a stiffened panel. A guided ultrasonic wave based sensor system was used to detect damage growth and strain gauge signals were used to understand the structural behaviour during fatigue damage growth in the panel. We then show a quantitative correlation on how to estimate fatigue damage location and size. Design approaches to arrive at most effective schemes of monitoring are illustrated with the help of signals collected from a number of sensors as part of an SHM sensor network.

1 INTRODUCTION

Damage tolerant aircraft structural design prescribes NDE inspection requirements. This in turn results in aircraft industry's one of the most critical and major activities with emphasis on quality control, cost optimization and developing new understanding that can become a driver for new designs and new technologies.

Structural Health Monitoring (SHM) technology is one of those, where in the primary role of NDE inspection has to be fulfilled in order to be effective for developing new structural design, new SHM sensors and electronics. The current challenges are to meet the scheduled inspection goals in fatigue damage monitoring while relying on the SHM system, in cases where we aim to reduce elaborate ground based NDE inspection. Another challenge is to improve the accuracy and reliability of the SHM sensor system in realistic conditions of loading and validate system design and schemes of monitoring that meets the NDE-SHM goals with minimal volume of data collected from sensors. Simulation plays an important role here in understanding SHM system design, various aspects involving the probabilistic nature of damage, accuracy of detection of damage and tracking its growth etc..

Experiments on fatigue behavior of complicated structural components are both time consuming and costly. Moreover, experiments are often only carried out for simplistic load cases such as under constant amplitude loading. But these load cases are not practically faced by the component in operation. While the experiments are time consuming, simulation of fatigue damage proves to be a viable alternative option to optimize a structural design process. When the cyclic loads are applied to a component with damage such as a crack, the crack tends to grow to a stage before critical failure results. Early detection of crack size and rate of crack growth are important to control the crack growth before it reaches allowable limits. Crack growth can be modelled using simulation to find out how the fatigue loads drive the crack growth. This information serves as the driver to inspection techniques, as the potential damage contours are visualized through simulation.

Simulation of the fatigue damage may not mimic exactly the behavior of the material owing to the restriction imposed on the finite elements used for modelling the component. Yet simulation offers greater insight to the problem and the flexibility of trying out different load cases and materials. It is only after finalizing the design requirements and understanding the behavior of a component through the simulation that testing is carried out. Also, simulation helps in optimizing the performance of a component as modifications are much easier to implement. Two approaches are generally utilized for fatigue simulation. The stress based SN method or the strain based ϵN method. While the former method is more suitable for the high cycle fatigue regime in the SN curve, the latter method is preferred for the low cycle fatigue regime as it incorporates plasticity effects. Both methods make use of the Palmgren-Miner's rule to evaluate damage having been accumulated [4-6]. However, these approximations indicated above in terms of fatigue loading and simulation approach introduce several uncertainties due to which scatter in the fatigue behavior is expected. To deal with this, probabilistic simulation is carried out to predict damage accumulation.

As a damage interrogation technique, the ultrasonic based inspection technique is one of the popular methods. In shell or plate like structures, guided wave based ultrasonic testing is a viable method for damage monitoring and is one of the popular methods in SHM system design. But, considering the complex geometries on which damages are monitored, one requires complex algorithms for damage identification and classification. This could be simplified by simulation which can aid in optimizing the different parameters required for damage monitoring. The authors have previously reported studies on the use of simulation to augment these tasks [1]–[3].Toward this research and development, we present here an elaborate testing study carried out at the IMA Dresden test facility, which demonstrates how we studied a new SHM sensor system design for their effectiveness to complement/accelerate and to possibly become a new NDE-SHM in future.

We show example simulation results that helped to evolve our SHM system design. We performed experimental validation of damage detection schemes in an integrated testing involving a stiffened panel, where strain gauge signals were used to understand structural behaviour during fatigue damage growth. The correlation between fatigue damage location and size is shown and an approach to monitor the damage grown is also illustrated using an SHM sensor network.

2 COMPONENT GEOMETRY AND SENSOR PLACEMENT

Damages such as cracks are most common in aircraft structures resulting from the variable loading scenarios in which an aircraft is operated. Simulations can be used to reliably predict the damage in a structure for a particular type of loading condition. We considered a representative example of a stiffened panel of 1300 x 1200 mm dimension with stiffeners mounted at equal intervals. The stiffened panel was loaded with a 3 Hz cycle rate with a mean load of 150 kN and a maximum load of 279 kN and a minimum load of 27.1 kN respectively as shown in Fig 1. Strain gauges, which were mounted on the sample were used to monitor the increasing crack size.

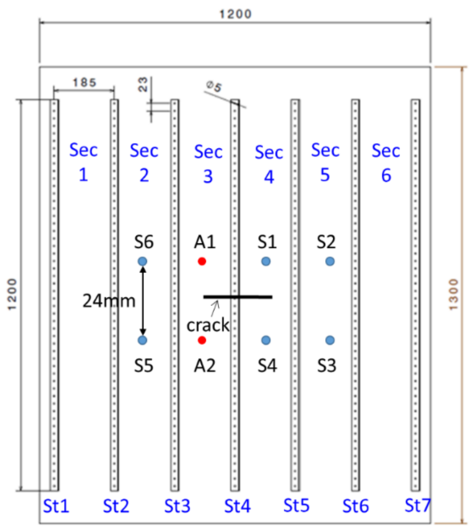

Fig 1. Schematic of test sample with actuator and sensor locations

Fatigue analysis was performed on the stiffened panel for the given load conditions. The finite element mesh was created using a commercial software Hypermesh. The fastener holes were modelled in the mesh. A crack of 200 mm was introduced in the center of the panel by disjointing the shell elements. The bottom side of the plate was constrained and the top side of the plate was subjected to load. The load transfer to the stiffener is through the fastener system which was also included in the mesh properties. Linear static analysis was then carried out with the stiffened panel using the NASTRAN solver. The finite element stress results was then subjected to the MSC fatigue simulation software [8]. The stresses were rescaled using the service load history. Von-Mises stress was used in the fatigue failure criterion, which was then used to identify the most probable damage location in the stiffened panel when subjected to service loads. Fig 2 (a) and (b) show the σ_y stress and von-Mises stress distribution in the stiffened panel. The load leads to a stress intensity around the crack tip as expected. Mode I crack growth is expected for this configuration as the stress perpendicular to the crack face is dominant over all other stresses likely to occur. The corners have artificial stresses due to the free-edge conditions which are not considered for identifying the most probable damage locations. Fig 2 (c) shows the log of damage contours for the stiffened panel. It is clear from the contour that the regions surrounding the crack tips and rivet locations are more probable locations for the crack to initiate or grow than any other regions.

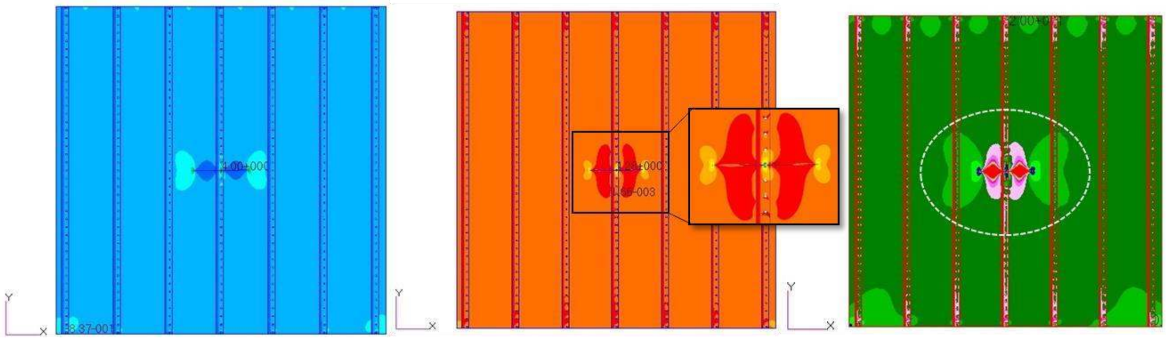

Fig 2. (a) σ_y, (b) von-Mises stress distribution & (c) log of damage contour on a stiffened panel with 200 mm crack length

The probable damage location is identified in this manner. These information are used to determine the placement of guided wave sensors on the panel. Guided wave propagation simulation in the panel was performed using the COMSOL software [9] to determine the difference in wave propagation characteristics of healthy and damaged panels. Simulation of guided waves in COMSOL software uses the structural mechanics module with the application of boundary load for the excitation frequency of 200 kHz. The excitation function used here is the Hanning window sine function with five cycles tone burst, which is shown in Eq. (1). The other important parameters in the FEM model are the element type, its size and the critical time steps. Ghose et al. [1] mentioned in their paper the specific aspect of optimum element size and critical time step for the numerical simulation of the guided waves. The maximum length of an element (Δx_{max}) is given in Eq. (2). In this model triangular mesh elements have been used.

$$F(t) = \begin{Bmatrix} F_0.\sin(\omega.t).\left(sin\left(\frac{\omega.t}{10}\right)\right)^2, t < \frac{10.\pi}{\omega} \\ 0 \qquad\qquad otherwise \end{Bmatrix} \tag{1}$$

where ω is the angular frequency and F_o is the initial amplitude of the excitation.

$$\Delta x_{max} = \frac{\lambda_L}{R} \quad (2)$$

where λ_L is the wavelength of the longitudinal ultrasonic wave and R is the ratio of wave-length to Δx_{max}. The value of $R \geq 8$ is recommended in this paper [1]. The requirement for the critical time step ($\Delta t_{critical}$) is as shown in Eq. 3.

$$\Delta t_{critical} = \frac{\Delta x_{max}}{C_L} \quad (3)$$

where C_L is the longitudinal ultrasonic wave in the material to be analyzed. In this simulation, the A_0 (anti-symmetric) mode is predominantly generated when compared to the S_0 (symmetric) mode. It can be seen that the signal packet gets reflected when the wave field is incident on the crack. This was validated by actual imaging of the wave field on the stiffened panel with damage, using a 3D Laser Doppler Vibrometer (LDV) as seen in Fig 4. Thus sensors mounted on the path of the packet reflected from the crack would help in capturing the reflected packet as the crack elongates and similarities between signals at other sensor locations could be used to detect the crack growth. The similarities between the FEM simulation and LDV measurements are evident as seen in Fig 3 & Fig 4.

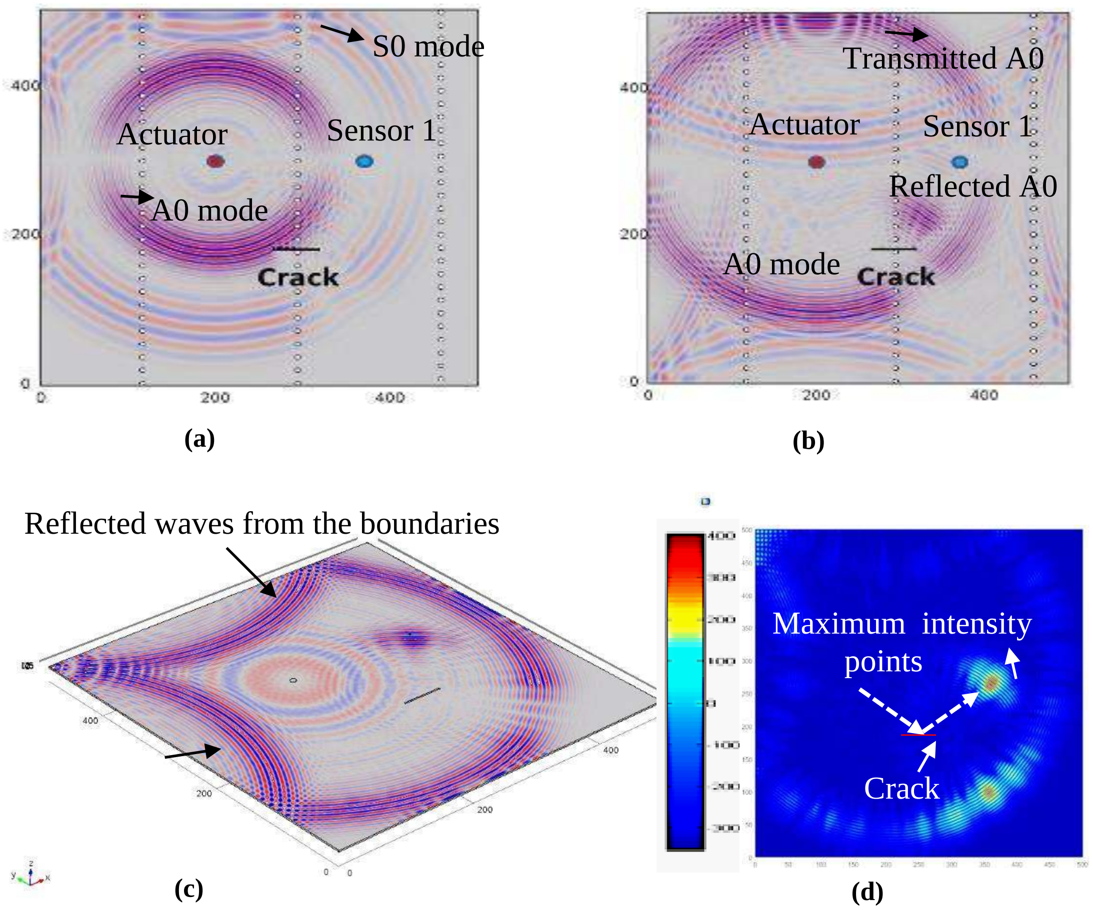

Fig 3. Snapshot of (a) 2D guided wave propagation at 80µs, 3(b) 2D guided wave propagation at 120µs 3(c) 3D guided wave propagation at 120µs, 3(d) image of difference signals (displacements) constructed from cracked and uncracked component

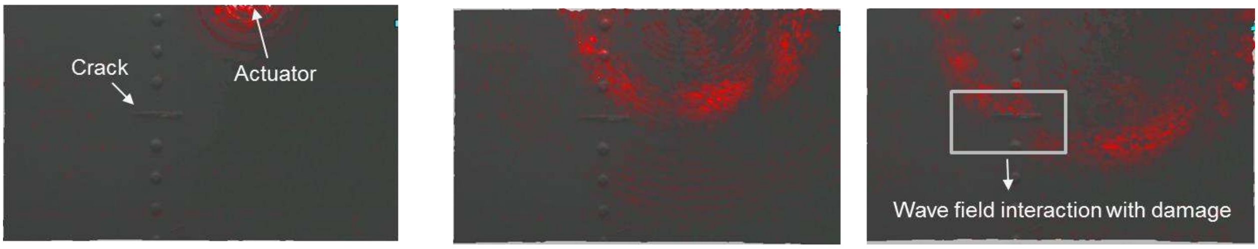

Fig 4. Wave field imaging using Laser Doppler Vibrometer

Based on the simulation and experimental validation to determine the sensor placement location, the sensors were mounted on the panel as shown in Fig 1. Two actuators A1 & A2 were placed at 120 mm from the crack location and six sensors (S1-S6) were mounted at the center of sections Sec 2- Sec 5 as shown seen in Fig 1. The sensors S1, S2 & S6 are in line with actuator A1 and sensors S3, S4 & S5 are in line with actuator A2.

3 TEST PROTOCOL

A test protocol has been defined such that when an actuator is excited, the sensor measurements were recorded at sensors S1-S6 mounted on the panel as seen in Fig 1. This was performed to monitor the extent of crack when the crack grew beyond the initial crack size and even beyond the stiffeners St 3 and St 5. An amplitude modulated 5 cycle chirp signal with 200 KHz center frequency, 20Vpeak-to-peak and 62.5 µsec initial delay to the signal packet was chosen as an excitation signal (Fig 5) applied to the piezo transmitter. Measurements were recorded at open crack condition the maximum load of a cycle was applied to the panel. A saw cut of 51mm in length was introduced as a crack starter in the experiment and signals measured for 51mm crack size were considered as the reference signal for subsequent measurements.

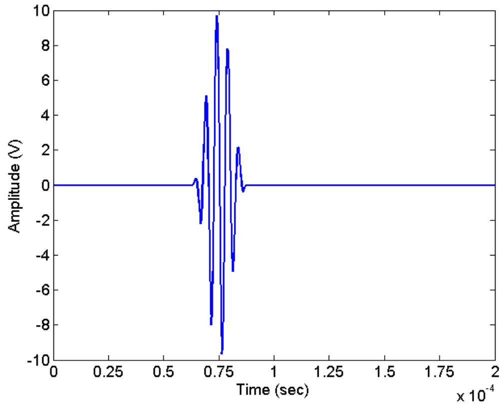

Fig 5. A 5-cycle 200 KHz amplitude modulated excitation signal used in the tests.

4 TEST SET-UP

The testing was performed at IMA Dresden. The testing machine was a 1kN standard testing machine as shown in Fig 6.

Fig 6. Test set-up at IMA Dresden. Instrumented stiffened panel under fatigue loading is shown

Prior to the fatigue test, a calibration of the panel was realized. During this calibration the minimum and maximum loads were determined to reach a stress in the skin near to 95MPa. After that, the artificial damage, which is a crack in skin over broken stringer, was introduced with an initial crack length of 50mm (See Fig 7). The initial crack lengths for crack A1 and A2 were determined with high-frequency eddy-current technique (HFEC).

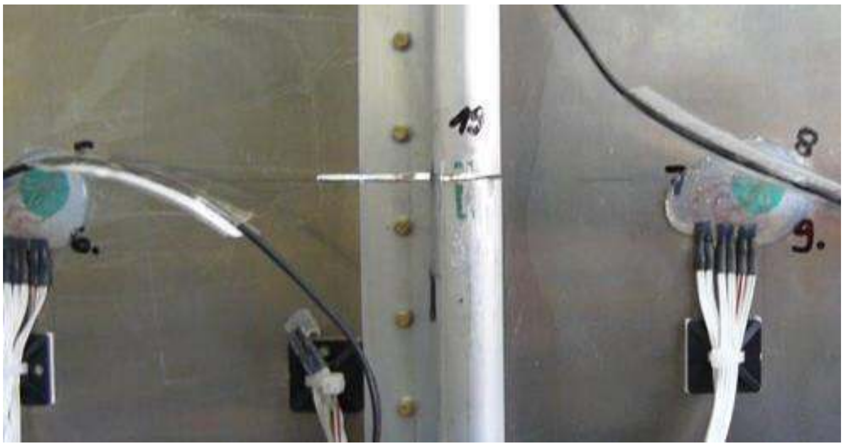

Fig 7. Introduction of initial crack of 50mm length

The dynamic test was performed in steps up to next damage event (broken stringer). The ultrasonic measurements were performed at maximum, minimum and mean load during the stops for the crack length measurements. The ultrasonic sensors are shown in Fig 8.

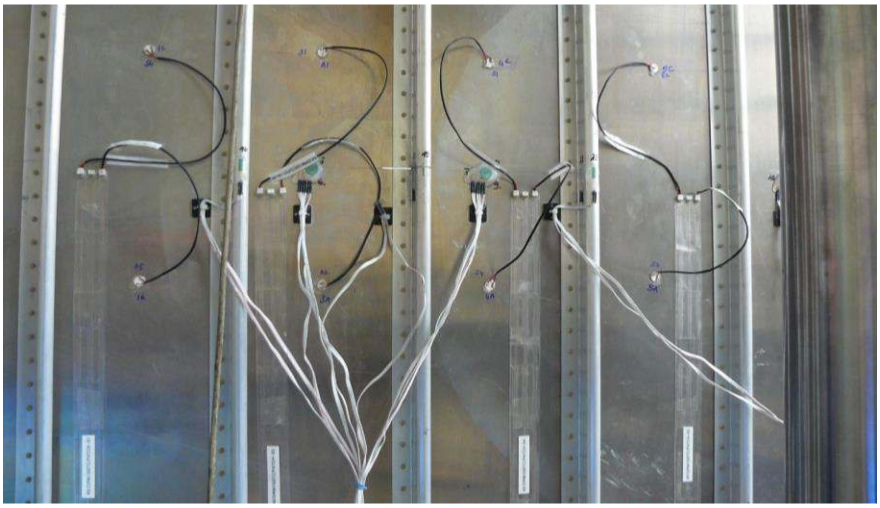

Fig 8. Piezo-electric sensors and strain gauges mounted on test panel

5 DAMAGE DETECTION AND MONITORING SCHEME

We define a correlation function J(t) given by

$$J(t) = Corr\big(X(t), X(t)\big) - Corr(X(t), Y(t)) \tag{4}$$

which is the difference between the auto and cross correlation of two signals X(t) and Y(t) where, X(t) is the reference signal and Y(t) is the signal measured for varying crack size over the consecutive loading cycles. The objective behind the use of this function is that, as crack size increases, the reflected signal packet from the crack will be uncorrelated with respect to the reference signal, since there is a packet spread over the increasing crack size. However, the correlation output will attain a constant value after a particular crack size since there is no additional packet spread due to the increasing crack length which has been defined as a zone of saturation.

6 RESULT S AND DISCUSSION

The crack size variation over the increasing load cycle number is as shown in Fig 9. It can be seen that the rate of increase of crack size increases towards the end of the loading cycle sequence.

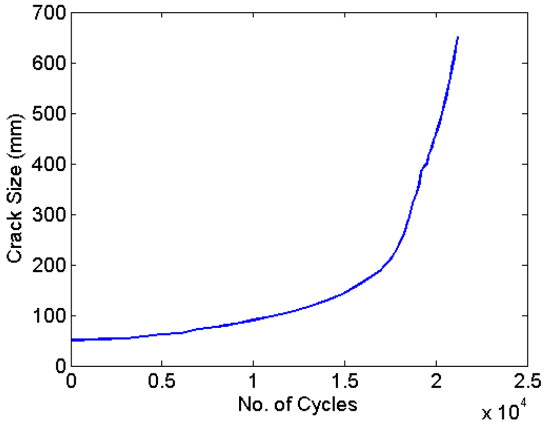

Fig 9. Variation of crack size over increasing load cycles

A typical packet at sensor S1 at the start of the cyclic loading sequence is shown in Fig 10.

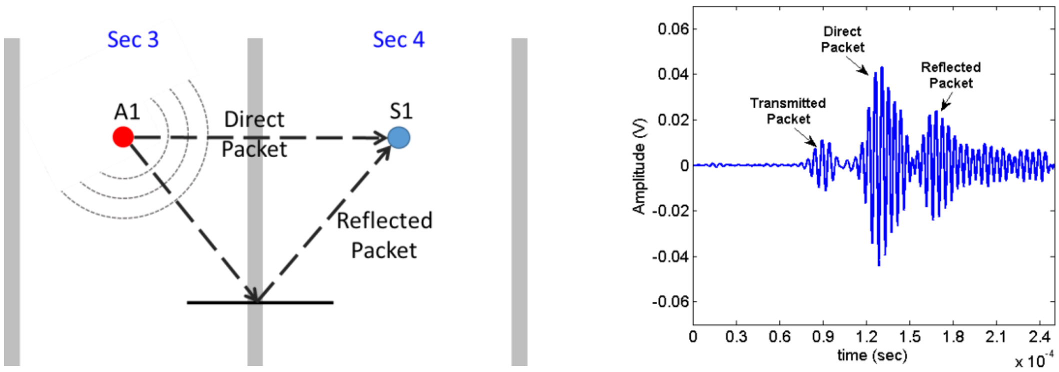

Fig 10. Sensor response at Sensor S1 when Actuator A1 is excited.

The signal variation over the increasing size of crack has been observed at Sensor S1 and is shown in Fig 11. It can be seen that the time of arrival of the wave packet travelling directly between actuator and sensor is independent of the crack size but the packet spread is increasing with increasing crack length. However, there is no drastic change in packet spread after the crack has attained a particular length.

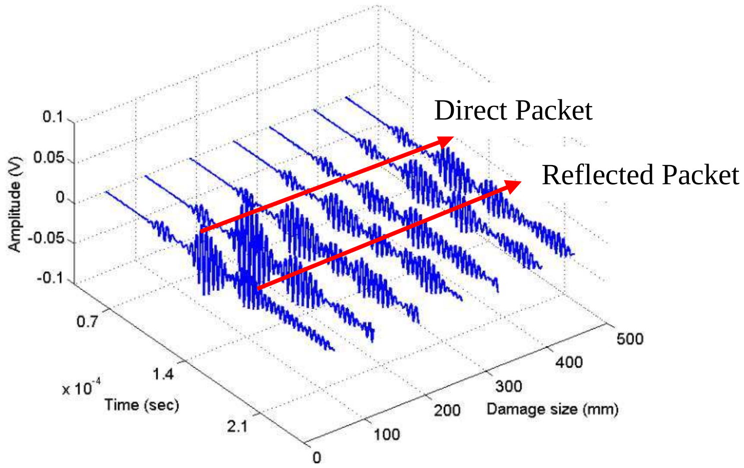

Fig 11. Signal recorded for various crack sizes at sensor S1 when actuator A1 is excited

A correlation function has been determined for zero lag and a window of approximately 120 μsec has been considered such that the window contains the packet reflected from the crack tip. Thus, as crack size increases, the signal is uncorrelated since the packet will be spread over time as crack length increases. However, the correlation value appears to not vary drastically after a particular size since there is no additional reflection anymore from the crack. This is what is defined as zone of saturation. The correlation curves for all the sensors for actuator A1 are shown in Fig 12.

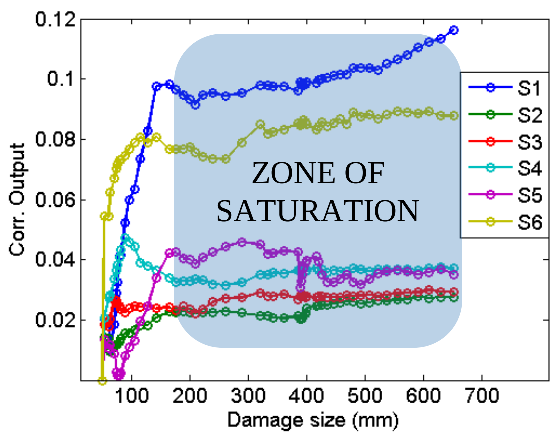

Fig 12. Correlation curves for all sensors when excited using actuator A1 for maximum load condition

7 CONCLUSIONS

We present an experimental validation of damage detection scheme in an integrated testing on a stiffened panel. A simulation based model was used to determine the most probable location of damage on a stiffened panel. Using this information of approximate damage location, simulations were used to optimize the sensor placement locations on the panel. A realistic test was performed for a loading condition where a damage was allowed to grow over the increasing number of load cycles from a detectable to a critical crack size. The guided wave sensors mounted on the sample were used to collect sensor signals and a correlation technique was established as a detection methodology to continuously monitor the crack growth. Thus a quantitative correlation scheme was established to estimate fatigue damage location and size. This approach is therefore proposed as an effective scheme to be used in guided wave based SHM systems.

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