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TOWARDS REAL-TIME STRUCTURAL HEALTH MONITORING DAMAGE DETECTION WITHOUT USER INPUT

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Abstract. *In this work a real-time damage detection platform is presented, requiring little to no user input after initial installation and set-up. Diagnostic ultrasonic signals are generated using attached piezoelectric transducers, which also serve to capture the structural response. This paper shows real-time detection in a flat CFRP panel. The necessary data acquisition and signal processing is carried out in an automated manner. A visualization of the damage map is then given as the primary output highlighting the predicted damage location. The developed system is flexible in allowing scalable deployment to cater for an increased number of transducers. The detection platform is experimentally demonstrated by real-time localization of artificial damages at various locations on a CFRP panel. This was also done under operational environment vibration loading, yielding accurate damage localization.*

1 INTRODUCTION

There has been an increase in the use of Carbon fiber reinforced polymer (CFRP) composites for aerospace applications due to their superior properties in comparison to metallic structures. However, stringent requirements on damage tolerance are a major factor in preventing greater adoption of composites in this sector. Barely visible impact damage (BVID) is a damage type of huge concern. As the name suggests these damages may not be readily detectable with visual inspections. Non-destructive testing (NDT) methods can locate and characterize damage. However, these often require operational downtime, are labor intensive and performed by highly trained specialists. With a spars network of permanently attached transducers, guided wave structural health monitoring (SHM) can be used for effective inspection of large plate like structures. In contrast to other NDT methods SHM approaches offer in-situ diagnostics with minimal intrusion to the operation schedule.

With low mass and small overall size piezoelectric patches are often used both actuators and sensors in SHM. These allow for excitation of Lamb wave guided wave signal within the structure and measurement of the response. Propagation of Lamb waves are highly sensitive to geometric features. Thus through analysis of wave features it is possible to detect and localize the damages. Many researchers have demonstrated the effectiveness of the baseline comparison approaches for detection of damage presence [1-3]. Delay and sum methods utilize key wave features in diagnostic signals; including time of flight (TOF), velocity and damage scatter, to predict the location of damage. Information from all transducers within the transducer network is fused to assemble a damage prediction map highlighting the location of damage. The delay and sum detection method adopted centers on comparison of the current or damaged signal with those recorded in a pristine condition. Through this baseline comparison, damage scatter features can be isolated. Assuming any residual between the baseline and current signal are due damage, the TOF and envelope of the damage can be manipulated to localize the damage.

In previous work diagnostic signal acquisition has been accomplished with manual channel switching and also with automated switching systems. These have suffered from deteriorated signal quality including signal crosstalk, low signal to noise ratio or repeatability when a signal amplifier was not used [4, 5]. In this work a real-time automated damage detection platform is presented, requiring little to no user input after initial installation and set-up. Diagnostic ultrasonic signals are generated using attached piezoelectric transducers. The damage detection approach used has previously been shown to be effective in detecting BVID in curved stiffened CFRP panels [6]. This paper shows real-time damage detection in a flat CFRP panel. Using a signal switching system integrated into a high performance acquisition platform, all the necessary data acquisition and signal processing is carried out in an automated manner. The tone burst actuation is applied to the transducers in turn and pitch-catch signals are obtained with minimal interference, by exploiting the switch architecture. A visualization of the damage map is then given as the primary output highlighting the prediction of damage location. The developed system is flexible in allowing scalable deployment to cater for an increased number of transducers.

The SHM system developed must be demonstrated under the environmental and operational conditions, in ordered to be deployed on aircraft. The RTCA DO-160 and MIL-STD 810 [7, 8] provide testing conditions and procedures that must be tailored to the relevant operational environment. The operational environments that are relevant for SHM systems include humidity, temperature, lightning strike, altitude, shock, ice formation and vibration. The main novelty in this work is demonstration of the integrity and performance of the developed real-time damage detection system under operational vibration loading.

The detection platform is first verified using experimental results to detect a softening area in a CFRP panel. It is then experimentally demonstrated by real-time detection and localization of artificial damages at various locations on a CFRP panel. Finally, the vibration tests are performed and the results are reported.

2 FINITE ELEMENT SIMULALTION

Computational methods have been used for simulation of wave propagation and finite element (FE) methods have proven as an effective development tool [2, 9]. The Abaqus explicit FE package was used to simulate diagnostic signals in a composite plate shown in Figure 1. The layup was modeled as $[0,45,-45,90]_{2s}$ with an overall size of 300 x 225 x 2 mm. Only the PZT part of the six DurAct transducers were modeled using 3D solid elements. These were attached to the plate with surface tie constraints. The composite plate was modeled with S4R shell elements. It has been previously suggested that an element size of at least 20 nodes per wavelengths (NPW) are required to ensure a converged solutions [2, 9]. A NPW of 30 was used by setting an element sizes to 3.42 E-4 and 1.98 E-4 for the plate and PZTs respectively. Damage was modeled as a circular softening area of radius 5 mm with a 50% reduction in in in the local stiffness.

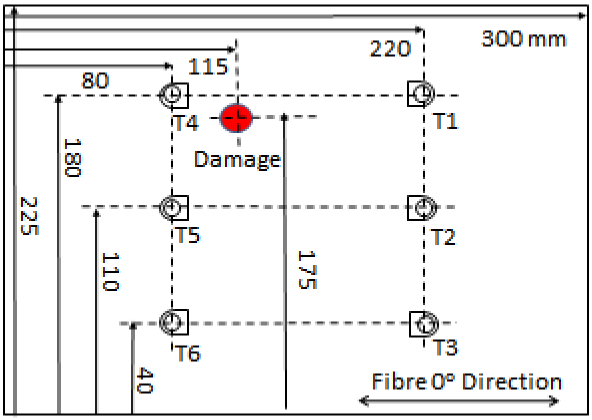

Figure 1: Schematic of composite plate used for damage detection.

A five cycled tone burst signal of central frequency 300 kHz was used as the actuation signal V :

$$V = \left(1 - cos\left(2\frac{\pi f t}{n}\right)\right) sin(2\pi f t) H(\tau) \tag{1}$$

Where f is the central frequency, n is the number of cycles, t is the time and H is the Heaviside function.

The actuation was applied as a radial displacement to the top circumference of the PZTs, Figure 2. Each transducers was excited in turn as the actuator, while the response at the other transducers were recorded at a 1000 time points over the simulation time of 200 μs.

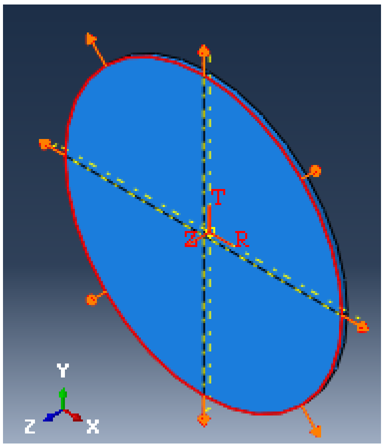

Figure 2: Actuation of piezoelectric patches with radial displacement.

3 EXPERIMENTAL SETUP

The developed real time detection system was built around a National Instrument (NI) instrumentation and software. Utilizing the available hardware, as outlined below, it was possible to collect all the necessary diagnostic signals from the structure under interrogation in under a minute. Immediately after the data was collected the damage detection algorithm was performed, providing a visualization of the predicted damage location.

3.1 Signal Generation and Acquisition

The data acquisition system was built around the NI PCI eXtensions for Instrumentation (PXI) system. For purposes of generating ultrasonic signals, a PXIe 5412 single channel arbitrary voltage generator card was used. This was operated, without the need for a standalone amplifier, at an amplitude of 12 volts. The voltage response of the PZTs were then captured and digitized using a PXIe 5105 digital oscilloscope card. To allow for time efficient and automated acquisition of the required signals, a Pickering 40-726A switch was used. This facilitated channeling of the actuation voltage to the correct transducer and capture of the voltage responses of the rest of the transducer network. Each transducer was excited with a tone burst signal of central frequency 300 kHz with voltage defined in equation 1. The response of the plate was recorded as the voltage output of the transducers.

3.2 Cross-Talk and Switch Architecture

The actuation voltage was in the order of tens of volts while the voltage response of the transducers in the order of tens to a hundreds of millivolts. This disparity in the voltage scales of the input and the output exacerbates the effects of electromagnetic interference between these two sets of signals. This so called crosstalk can be mitigated by wire shielding, but typically the close physical proximity of the circuitry within switch card brings about significant signal crosstalk as shown in Figure 3a.

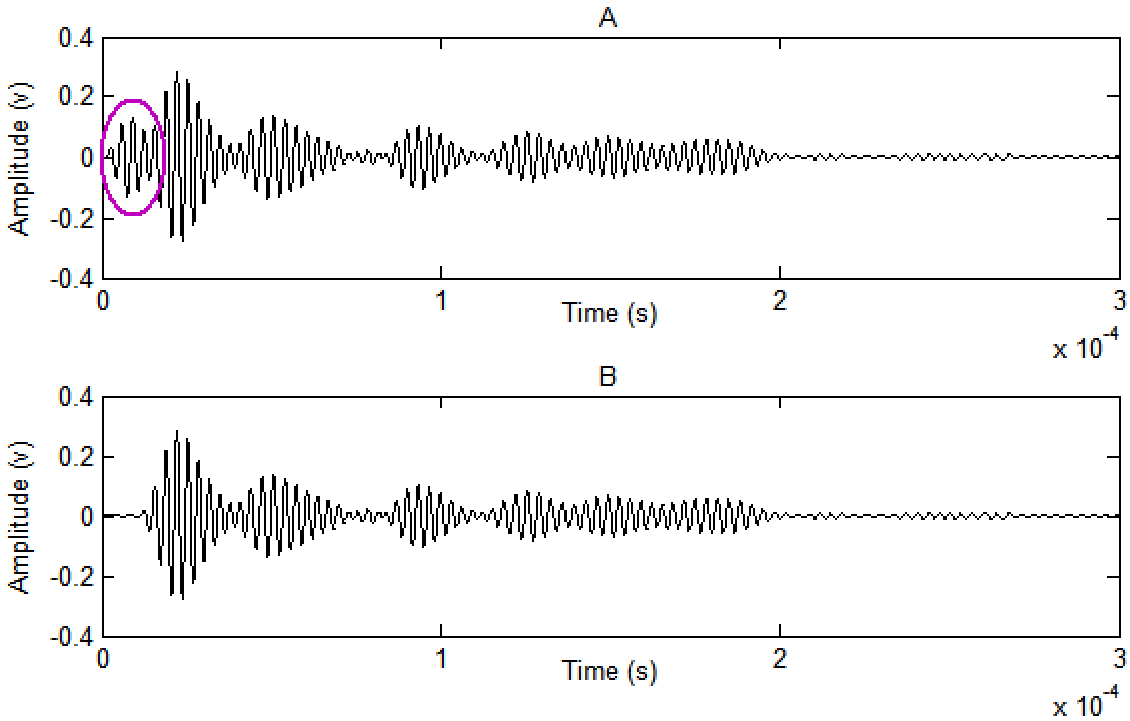

Figure 3: (A) Sensor voltage response with significant crosstalk (highlighted in purple ellipse), (B) signal without crosstalk obtained by exploiting switch architechture.

The Pickering 12 x 8 RF switch caters for the interconnection of 8 Y (instrument) channels with 12 X (PZT) channels as illustrated in Figure 4. The internal architecture actually consisted of four smaller sub-switches, allowing for decoupling of the relatively high voltage input from weaker output signal. Thus sub-switch two was used exclusively for sensing, with sub-switch three reserved for actuation. This interference free signal could be obtained at the cost of a reduced number of instrument channels, meaning that four oscilloscope channels can be used at any one time. This would not result in a reduced overall PZT count, but rather an increase in the overall time to record all the voltages, as PZTs signals can be recorded in sets of four. It thould be noted that separate switching cards can be interconnected. Hence the number of PZTs in the network is limited by the the avaliable number of switch cards.

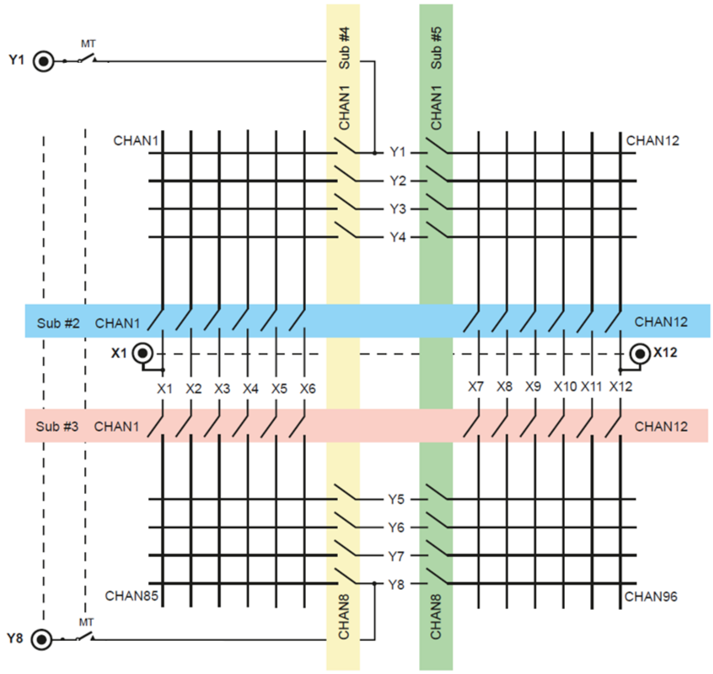

Figure 4: Schematic of switch architecture, adapted from [10].

3.3 Plate Definitions

The structure under interrogation was a composite panel of size 300 x 225 mm shown in Figure 1. The CFRP panel consisted of 16 unidirectional Fiberdux 914 TS 5 plies with layup $[0,45,-45,90]_{2s}$ and cured thickness of 2 mm. A total of six DurAct transducers were permanently bonded to the plate with Hexcel Redux film adhesive.

Researchers [11, 12] have used intuitive methods of simulating damage, including mastic. Though artificial damage does not fully represent actual damage, it provides a means by which to cause scattering of waves at a particular location. This allows for development of methods for finding the location of the source of this additional wave scatter. In this work BluTak mastic with a nominal diameter of 10 mm was used as artificial damage.

3.4 Operational Environment: Vibration Test Setup

The vibration profile applied during this test was selected from the RTCA DO-160 certification requirements. This profile corresponded to that of the operational environment of an electronic components attached to the fuselage of a fixed wing aircraft with a turbofan propulsion system. The setup consisted of a TMS shaker with power amplifier, ICP high sensitivity accelerometer used as control accelerometer mounted on the fixture and a four channel control unit as shown in Figure 5.

The vibration acceleration power spectral density (APSD) was set as per the requirements with slopes of 6 dB/octave and a grms value of 4.12. The plate was mounted into a fixture representative of a fuselage panel spaced within structural ribs. The tests were performed for one hour in the z-axis. The tests were set to abort if the APSD deviated from the set profile by more than 3 dB. Diagnostic signal was recorded with under no vibration before and after the tests. While the plate was subjected to vibrational loading signals were recorded with and without the simulated damage.

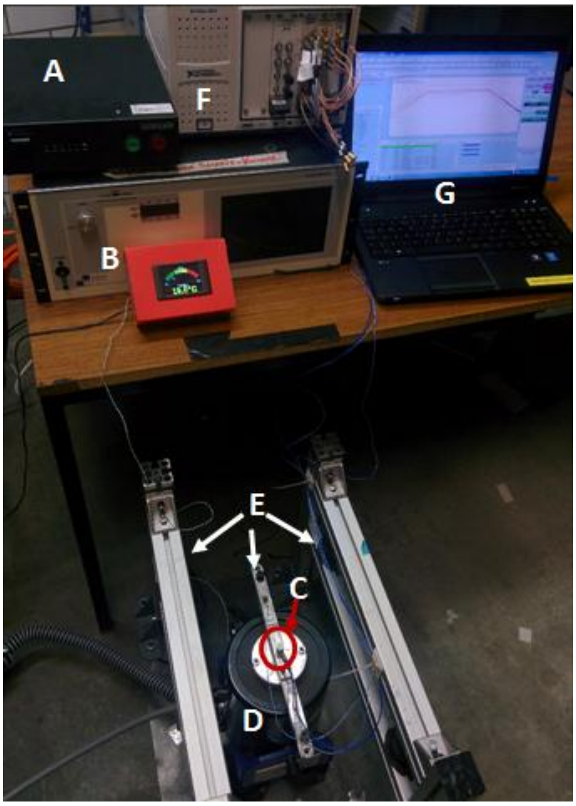

Figure 5: Setup used for vibration tests, (A) controller, (B) shaker power amplifier, (C) control accelerometer, (D) shaker, (E) fixture, (F) real-time detection platform and (G) workstation.

4 RESULTS

4.1 Computational Results

The obtained FE results were used as inputs to the detection system, mimicking the data acquisition system for the initial verification. The location of the 5 mm radius softening damage was accurately predicted with a localization error of less than 9 mm. The damage prediction map has been normalized to its peak value with a range of 0 to 1. It should be noted that the region with peak index is localized to an area around the actual damage location.

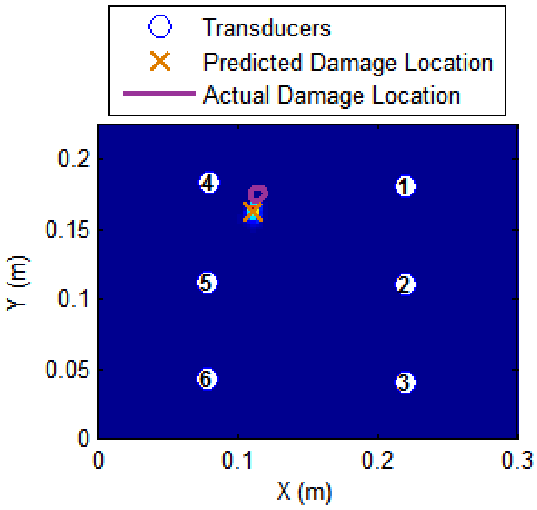

Figure 6: Damage location prediction of a softening region with FE simulated results.

4.2 Experimental Results

The artificial damage was located at different locations and localization predictions shown below. For damage located outside the transducer area the location prediction as not accurate. It should be added that the peak index values did provide a coarse indication of the general location of the simulated damage.

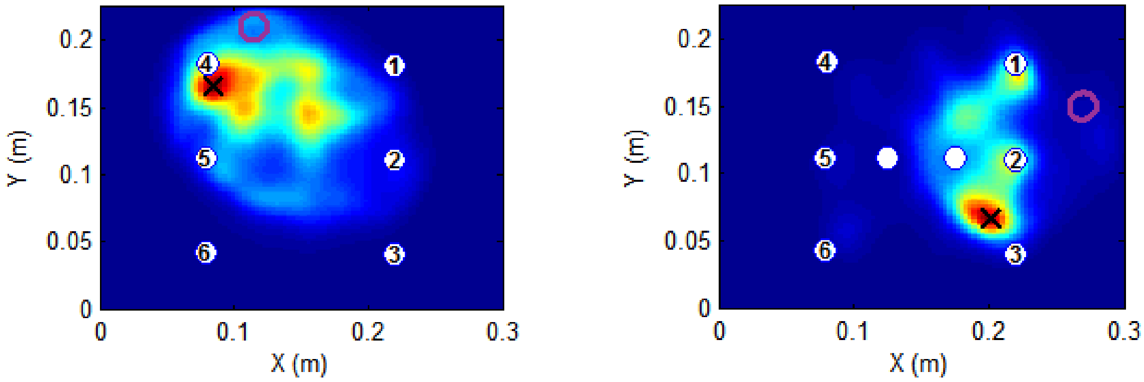

Figure 7: Real time damage location prediction maps for simulated damage outside the transducer area on a composite panel.

It was found that for the positions within the enclosed transducer area the localization was very accurate as shown in Figure 8. Furthermore, areas with highest index were confined to locations near the actual damage position.

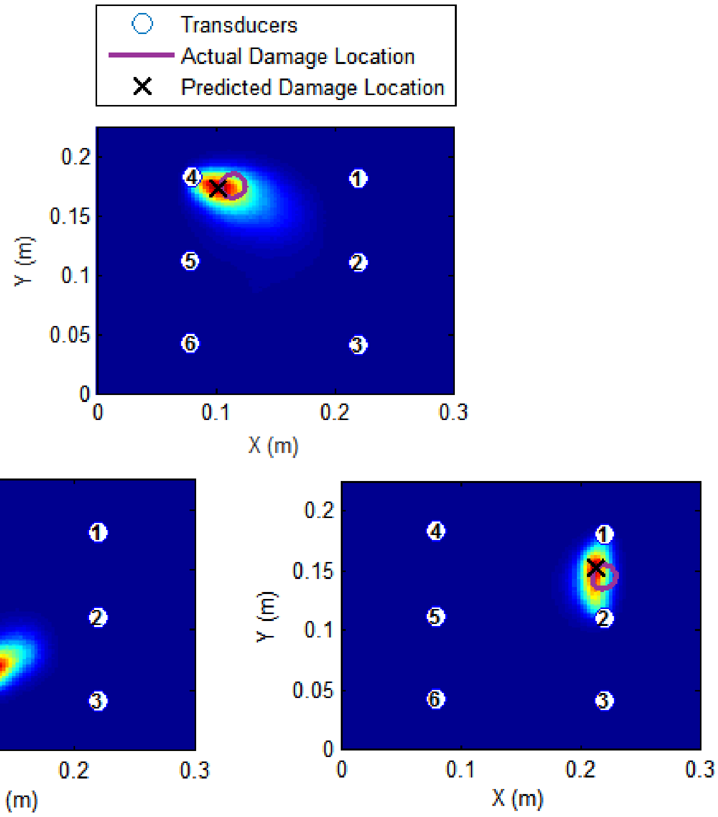

Figure 8: Real time damage location prediction maps for simulated damage within the transducer area on a composite panel.

4.3 Vibration Tests

The plate was subjected to the vibration profile for the full duration without the APSD abort limit being exceed. Real-time damage detection was performed at various intervals during the vibration test. The final results obtained at nearly 59 minutes of vibration, highlighted accurate damage location prediction with localization of error of 7 mm, as depicted in Figure 9. It should be noted that after the vibration test a similar level of detection accuracy could be attained. Also, visual and electro-mechanical impedance inspections did not highlight any loss in integrity of the transducers or wiring.

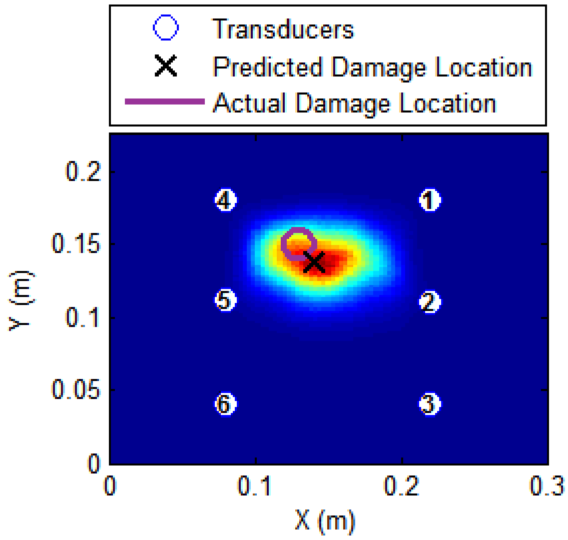

Figure 9: Real-time damage detection under vibration loading

5 CONCLUSIONS

It was shown that the developed real-time damage detection system is able to record the all the diagnostic signal required and perform the necessary calculation for damage detection in a matter of minutes. The system was first verified using FE simulated results to localize a softening region in CFRP plate. The real-rime detection system was applied to six transducer plate to localize artificial damage. It was able to accurate predict the location of artificial damages within the area enclosed by the transducers.

It was also shown that the permanently attached transducer network was able to maintain its integrity throughout the vibration tests specified for a fixed wing aircraft with a turbofan propulsion system. There was also no significant reduction in performance of the damage location prediction during or after the test. Additional tests will be performed with actual BVID cases under other operation and environmental conditions including temperature and humidity, temperature shock, altitude and icing.

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