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FATIGUE CRACK DETECTION IN AEROSPACE STRUCTURES REVISITED – SOME LESSONS LEARNT FROM ULTRASONIC GUIDED WAVE APPLICATIONS

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Abstract. Ultrasonic guided waves have been considered for fatigue crack detection applications for decades. However, reliable implementations and applications have not been demonstrated up to the level that is required from aircraft maintenance authorities. This paper revisits some experimental research tests performed and guided wave ultrasonic data gathered, to show lessons learnt from these tests and to indicate avenues for potential future developments in this field. Cases studies presented relate to civil and military aircraft components.

Key words: Fatigue Crack Detection, Guided Ultrasonic Waves, Smart Structures, Aerospace Components, Piezoceramic Transducers.

1 INTRODUCTION

Fatigue crack detection is one of the major concerns with respect to the integrity of aerospace structures [1]. Various non-destructive testing (NDT) techniques have been developed to get this concern to be addressed and alleviated. These techniques include visual inspection, eddy current, acoustic emission, ultrasonic testing and many other successfully developed and implemented for crack detection. Application of those techniques to damage critical locations may become laborious and costly due to the locations' difficult access. Consequently, integration of the different NDT techniques' respective sensors into the structures to be monitored has been considered and discussed for decades in the sense of structural health monitoring (SHM). This has been mainly triggered due to the ageing aircraft problem but also considered for new aircraft designs. Crack detection based on low-profile piezoceramic transducers and ultrasonic guided wave propagation - that is one of the most

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widely studied approaches - falls into the category of integrated monitoring systems, that could be potentially used for aerospace and maybe also space applications. Technologies for hardware, data processing algorithms, monitoring strategies and various methods developed are available. However, despite three decades of research and validation experience in this area, reliable implementations and applications have not been demonstrated up to the level that is required from aircraft certification authorities. Furthermore, convincing business cases for the implementation of SHM have only been shown to a very limited extent. Various explanations could be given to explain why the progress achieved is still not satisfactory. Understanding problems and obstacles is essential for the success but success stories are also important to stimulate progress.

This paper revisits some experimental research tests performed and guided wave ultrasonic data gathered, to show lessons learnt from these tests and to indicate avenues for potential future developments in this field. The paper consists of three major parts. The method used for fatigue crack detection is briefly introduced in Section 2. Case studies related to civil and military aircraft components are presented in Section 3. Finally, conclusions are given in Section 4.

2 GUIDED ULTRASONIC WAVES FOR CRACK DETECTION

Various non-destructive methods have been developed for fatigue crack detection in metallic aerospace structures for the last few decades, as reviewed in [1-2]. Vibro-Acousto Ultrasonic (VAU) approach – that is of interest in this paper – is based on two major approaches. The first approach involves one High-Frequency (H-F) excitation that leads to guided ultrasonic wave propagation. Lamb waves are the most widely used ultrasonic guided waves in plate-like structures [3-9]. The second approach also involves guided ultrasonic wave propagation. In addition, extra Low-Frequency (L-F) excitation is used to perturb damage and enhance damage detection results [10-12]. Both approaches are illustrated graphically in Figure 1.

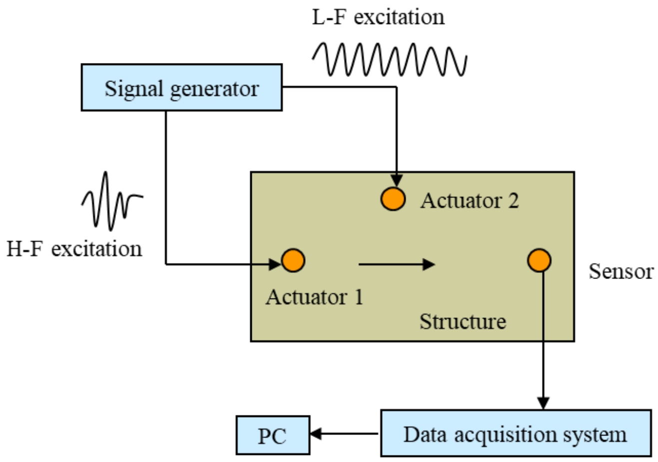

Figure 1: Vibro-acoustic ultrasonics used for structural damage detection

Most Structural Health Monitoring (SHM) applications in this area use low-profile, surface-bonded piezoceramic transducers for excitation and sensing, allowing for periodic and/or continuous monitoring for fatigue cracks. Experimental work described in this paper utilises *SMART Layer*^{TM} transducers [13-15]. *SMART Layer*^{TM} comprises small piezoceramic transducers (thickness – 0.254 mm, diameter 6.35 mm) on a thin dielectric Kapton layer. This layer can be manufactured to any shape and adhesively surface-bounded on a structure. For a given approach described above, H-F signal (and L-F signal if needed) is generated and passed to the bonded actuators and relevant responses captured by the sensor. It is important to note, that the damage detection strategy used in all presented case studies relied on the so-called diffuse Lamb wave field [16]. Wave dispersion characteristics were not used and multimodal responses that included all possible reflections from various geometrical features were analysed. In addition, the amplitude of the H-F excitation was relatively low – if compared to other reported applications – and did not exceed ±20 V in all cases investigated.

Ultrasonic responses from monitored structures can be processed using various signal processing methods. The work presented in this paper was based on the baseline approach and involves phase analysis through either cross-correlation [17] or instantaneous phase [1-2]. The former compares template ultrasonic responses (corresponding to undamaged condition) with monitored ultrasonic responses (representing various damage severities). The Hilbert transform is used in the later approach to extract the instantaneous phase and detect potential phase shifts due to structural damage.

3 CASE STUDIES - APPLICATIONS RELATED TO AEROSPACE STRUCTURES

This section presents case studies from fatigue crack detection in aerospace structures. The experimental work has been performed over a number of collaborative academic-industrial research projects performed in the early 2000s. Some results from these projects have been previously reported in [1,14-15,17-23]. Examples of successful fatigue crack detection in riveted lap joint panels and reinforcement structural elements are re-called from these projects and presented in this section.

3.1 Riveted aluminium fuselage panels with hidden cracks

The first case study demonstrates the application of the crack detection method in two civil aircraft fuselage aluminium lap joint panels shown in Figure 2. The dimensions of the smaller and larger panel were 150 x 230 and 462 x 936 mm, respectively. The thickness of the panels varied from 1.6 to 4.4 mm. Both panels were fatigue-tested to initiate and grow cracks around rivets. The cracks were hidden and therefore visual inspection was not possible due to the installed doublers at the joints. The *SMART Layer*^{TM} transducer strips were surface bonded between rivet rows for crack detection and monitoring. For the smaller panel two series of experimental tests (Test 1 and Test 2) were conducted one year apart, in two different laboratory locations, using different fatigue testing equipment. The experimental test of the larger panel involved one laboratory facility and was conducted over few days.

(a) (b)

Figure 2: Smaller (a) and larger (b) fuselage aluminium lap joint panels.

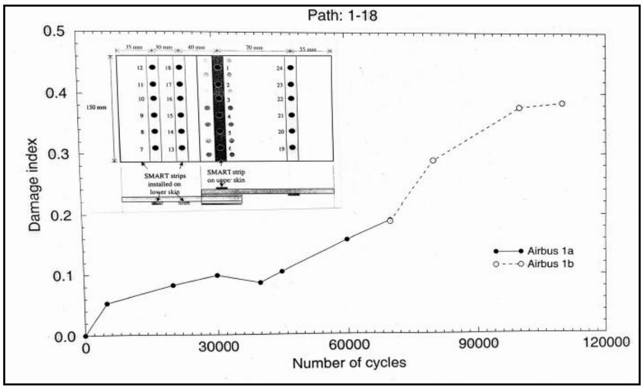

Figure 3: Crack detection results for the smaller fuselage aluminium lap joint panel shown in Figure 2a.

All Lamb wave responses were gathered using the single excitation approach described in Section 2. The phase of the responses was analysed to obtain damage index that could potentially indicate crack length. Two examples of crack detection are presented in Figure 3 and 4. The results for the smaller panel, for one actuator-sensor pair are given in Figure 3. These results show that the analysed damage index increases monotonically with the number of fatigue cycles, giving the opportunity for successful crack detection and monitoring. Since the results summarise two different (Test 1 and Test 2) experimental sessions on the same sample, the most interesting observation is that the last value of damage index in Test 1 matches the first value of damage index in Test 2. The good news is that this nearly perfect match has been obtained for different operational and environmental conditions; Test 1 and Test 2 were performed nearly one year apart in different laboratories. The results for the larger panel are presented in Figure 3b for various actuator-sensor wave propagation paths. The best monotonically increasing damage index characteristics can be obtained for these paths that are close to growing fatigue cracks. These results match quite well findings from eddy current NDT tests undertaken by professional technicians. More results that involved the same data and different data processing used can be found in [14-15,19].

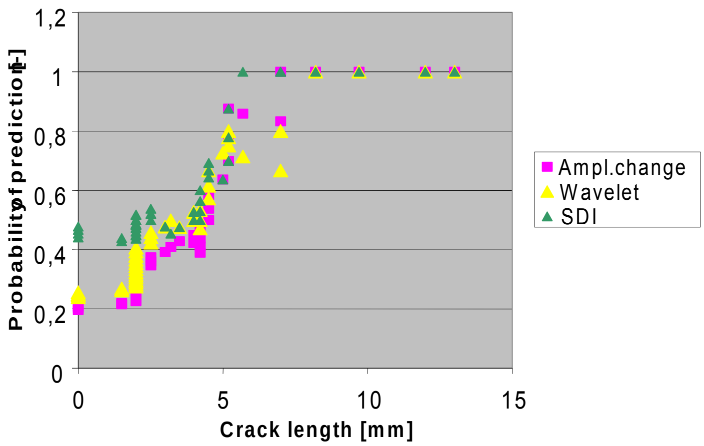

Figure 4: Crack detection results for the larger fuselage aluminium lap joint panel shown in Figure 2b.

3.2 Multi-riveted aluminium lap joint panel

The second case study demonstrates fatigue crack detection results in a 750 × 300 multi-riveted aluminium lap joint panel. The thickness of the panels varied from 2.0 to 5.6 mm. The panel was fatigue-tested to initiate a crack around the central rivet and grow cracks between rivets. *SMART Layer*^{TM} transducer strips were used for crack detection and monitoring. Figure 5 presents the tested panel, showing the lay-up of transducers. The panel was fatigued for 137 500 cycles. Lamb wave responses were gathered using the single excitation approach and processed to obtain damage indices based on the phase analysis. One example of results for a selected actuator-sensor path is presented in Figure 6. The damage index characteristics increases nearly monotonically with fatigue cycles.

Although damage indices - based on the phase analysis - give some indication about crack initiation and growth, the estimation of crack length is a challenge [24]. Figure 7 compares the crack propagation curve and the damage index characteristics for the crack initiated around the central rivet. The former is above the latter. Both characteristics – when plotted in a semi-logarithmic scale – are nearly monotonically linear and parallel. The crack growth rate can be estimated as an example from the most elementary form of the Paris-Erdogan equation given as

$$\frac{da}{dN} = C\,(\Delta K)^m \tag{1}$$

where a is the crack length, N is the number of fatigue cycles, ΔK is the range of the stress intensity and C and m are material constants that depend on stress ratio and environmental conditions. Figure 7 indicates that when material constants are known the estimation of crack length is possible from the damage index used.

Figure 5: Multi-riveted aluminium lap joint panel.

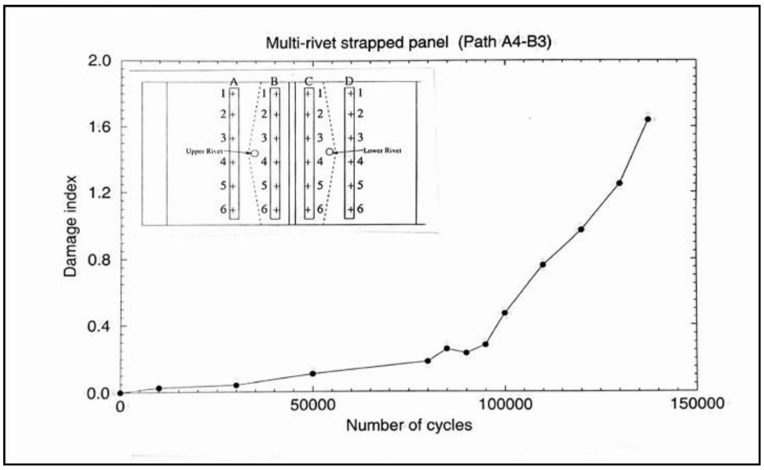

Figure 6: Crack detection results for the multi-riveted aluminium lap joint panel shown in Figure 5.

More results that involved the same data and different signal processing used can be found in [17,20,23].

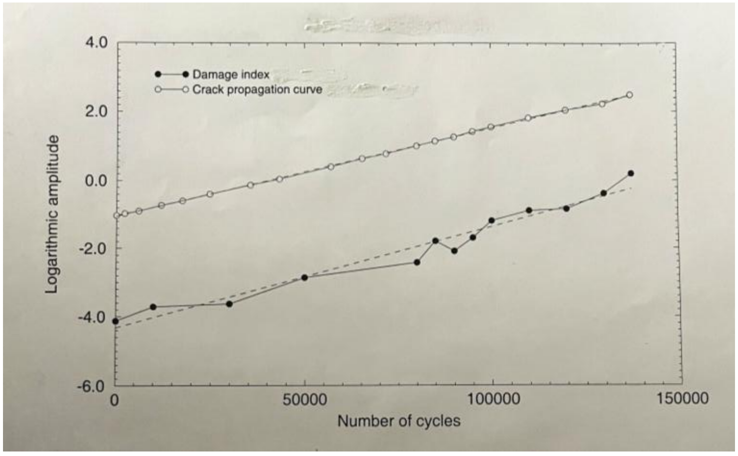

Figure 7: Damage index and crack propagation curve for the multi-riveted aluminium lap joint panel shown in Figure 5. Both characteristics are plotted in a semi-logarithmic scale.

3.3 Wing box reinforcement steel strap

The third case study investigated relates to crack detection in a reinforcement steel strap form a military jet wing box. The structural element investigated is shown in Figure 8. Seven single *SMART Layer*^{TM} transducers have been surface-bonded in the critical area for crack monitoring.

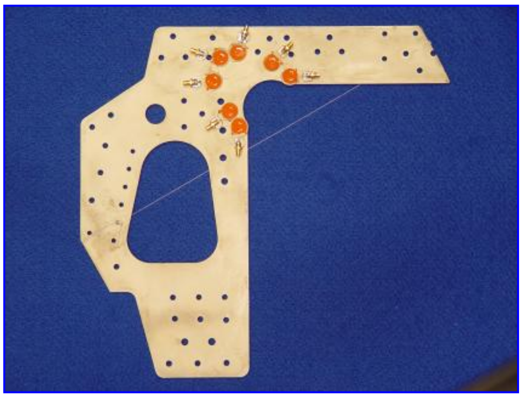

Figure 8: Wing box reinforcement steel strap.

The specimen has been fatigued up to 546 000 cycles to initiate and grow a crack. The VAU approach based on two excitations – described in Section 2 – has been used for crack detection. The phase of Lamb wave responses has been used to obtain the damage index. Figure 8 gives the damage index characteristic for various fatigue cycles. The 95% statistical confidence level has been established using mean and standard deviation values of the analysed damage index. This level is indicated as a solid red vertical line in Figure 9b. The results show that once the crack is initiated, an 0.5 mm crack can be reliably detected and monitored throughout the fatigue experiment. More details about this case study presented can be found in [22].

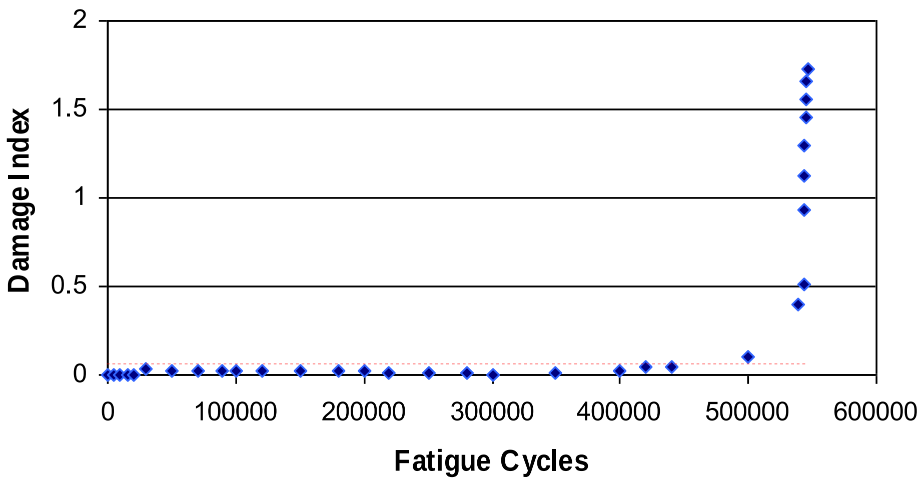

Figure 9: Crack detection results in a wing box reinforcement steel strap shown in Figure 8.

4 DISCUSSION AND CONCLUSIONS

The structural health monitoring case studies re-visited and briefly presented in this paper not only demonstrate some successful crack detection results but also lead to interesting observations. Some of these observations have been previously reported in the references given in the previous sections. The most important findings can be summarised as follows:

- More than one hundred *SMART Layer*^{TM} transducers have been used in all these experimental tests performed in different academic/industrial laboratories under various operational/environmental condition for the eight-year period. Interestingly, only one sensor failed, and this failure was not important for the crack detection success. Therefore, the performance of these transducers has been quite remarkable.
- The VAU method used for crack detection is relatively simple and easy for on-line continuous monitoring. In contrast to many previous applications, relatively low-voltage (maximum ±20 V) excitation was required to obtain good quality, high signal-to-noise-ratio responses.
- Since the diffuse Lamb wave field was used, physical understanding of Lamb wave propagation was not needed. It appears that modelling - required to obtain wave dispersion characteristics – is less important than originally thought.
- Relatively simple data processing was needed to obtain damage indices that increase monotonically with crack lengths. The research work undertaken shows that phase analysis of responses outperforms signal processing methods based on amplitude. The results also indicate that damage indices used do not depend on operational/environmental conditions.
- Interestingly, phase-based damage indices show some correlation with fatigue and fracture analysis and could be used potentially for crack length estimation.
- Bearing in mind, that reliable detection of tolerable cracks – or damage in general - in real aircraft structures based on conventional NDT inspection starts from crack lengths of 5 mm and beyond, the Lamb wave-based crack approaches reported here do have a considerable potential to be used for an automated monitoring approach in the sense of SHM, specifically when considering hidden and difficult to access areas.

Although a lot of valuable knowledge has been generated and experience has been gathered with the use of Lamb wave-based approaches in monitoring the damage tolerant condition of aerostructures in the past, it has still not found a true breakthrough for aerostructures so far. One of the main reasons is the extreme optimization of aircraft maintenance processes combined with a sophisticated design with respect fatigue fracture avoidance and ability to inspect by conventional means, as described in more detail in [25]. However, such an optimized maintenance process can be easily disturbed the maintenance process once an irregularity may appear in an aircraft's life cycle. Such irregularities do appear once an aircraft is considered as aged (> 15 years old) or after a possible accidental damage, which every aircraft is most likely to be exposed to. It is with those cases where the

SHM solutions presented here can lead to an economic value. However, for this, different conditions do have to be met, which includes:

- Possible likely damage cases and hence cases for monitoring must be publicly made available by the aerostructures related OEMs as well as the maintainers, such that the scientific community can deal with those damage cases and scenarios in detail before those cases may become relevant for application in real life.
- Procedures need to be made available, that allow the economic benefit of the SHM measures to be determined, because only this will allow to identify, how much an SHM measure and hence a resulting SHM system may be allowed to cost.
- Appropriate numeric tools need to be made available, that allow damage scenarios as well as its inspection to be simulated, because only with these non-standard damage configurations those damage scenarios can be analyzed beforehand with respect to their damage tolerance potential in the first place and the realization of the resulting hardware systems in the second. This needs to be done before the application case appears, since such a case may require a quick decision and a solution to be taken off the shelf.
- The SHM method to be considered needs to be qualified and even certified. This is a costly and laborious process, which is only realized once the economic gains of the measures taken can be clearly visualized.
- A sufficient database needs to be made available, that allows the statistical evaluations required to be made, such that the detection of a tolerable damage by an SHM system can be guaranteed with a probability of failure being say less than 10^{-7}. This requires a sufficient amount of useful data to be generated, that is most likely not to be generated short term.

A lesson learned so far and quite encouraging but unfortunately somehow forgotten is, that the observations made and described here could be confirmed in case the demonstrators from the past would still be available. This could enhance a potential database to be established and required for the potential SHM systems solutions to be developed. Many research projects conducted in this area and results obtained including many demonstrators realized could be re-visited for the benefit of the aerospace community. This could enhance the collaborative academic/research and industrial effort to develop new crack detection systems suitable for the specific aerospace structures damage scenarios. A major focus could be on laboratory developments and industrial testing. The former should relate to damage characterization, probability of crack detection and statistical analysis. The latter should involve experimental validation in different operational/environmental conditions. These are still major gaps that need to be closed in case SHM could see its full potential applied with respect to aerostructures.

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