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Procedia CIRP 22 (2014) 103 – 108

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3rd International Conference on Through-life Engineering Services

Development of generic methodology for designing a Structural Health Monitoring installation based on the Acoustic Emission technique

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Abstract

The Acoustic Emission (AE) technique can be used to perform damage detection and localisation for structural health monitoring purposes. Implementation in aircraft structures however poses a significant challenge as its performance in terms of damage detection and localisation is not well understood when used with complex structural geometries and variable operational service environments. This paper presents initial developments towards a generic methodology for optimal design of a structural health monitoring installation based on the acoustic emission technique. Performance verification of the AE monitoring process was classified into two stages. The first is a mainly empirical process for quantitatively characterising AE generation from damage using the Probability of Hit (POH) metric developed and presented in this study. The second is a combination of mathematical, numerical and empirical modeling to characterise AE propagation and detection which can also be used to determine optimal system configuration and sensor design. It was found that for Structural Health Monitoring (SHM) techniques to be part of wider structural integrity programmes, there is need for standards that recommend best practices as well as providing specification of acceptable levels of performance in terms of damage detection and location.

Peer-review under responsibility of the Programme Chair of the 3rd InternationalThrough-life Engineering Conference

Keywords: acoustic emission; structural health monitoring

1. Introduction

Structural Health Monitoring (SHM) techniques are capable of detecting and locating the presence of damage in structures by performing continuous or on-demand monitoring using permanently installed sensors as an alternative to scheduled manual inspection. This can enable condition-based maintenance where savings in the through-life costs and increased reliability of the structures can potentially be realised.

Nomenclature

AE	Acoustic Emission
HOLSIP	HOListic Structural Integrity Process
NDT	Non Destructive Testing
POD	Probability of Detection
SHM	Structural Health Monitoring
TDOA	Time Difference Of Arrival

SHM can be seen as a component of a larger framework for maintaining structural integrity based on continuous monitoring systems. One of such frameworks is the HOListic Structural Integrity Process (HOLSIP), physics based analysis and design approach to assess the reliability and structural integrity of aerospace structures as illustrated in Figure 1 [1]. This framework consists of two main features. First is the flight condition monitoring branch that utilises recorded flight parameters with machine learning algorithms to predict load spectra and consequent fatigue degradation of critical components. The second is the flight loads monitoring branch that uses direct measurements of loads and the presence of damage using SHM techniques. HOLSIP also includes the need to understand the effects of environmental conditions, initial and current structural conditions as well as material properties. All of these components can serve as input to a

Peer-review under responsibility of the Programme Chair of the 3rd InternationalThrough-life Engineering Conference
doi:10.1016/j.procir.2014.07.122

model, which can be used in obtaining remaining useful life estimations of a structural component.

The performance and reliability of SHM techniques in real applications with varying geometric complexity and environmental conditions is however currently not well understood. A systematic means for quantitative assessment of the techniques' performance and reliability as well as a method for adapting their configuration to achieve optimal operation will be essential in achieving potential benefits.

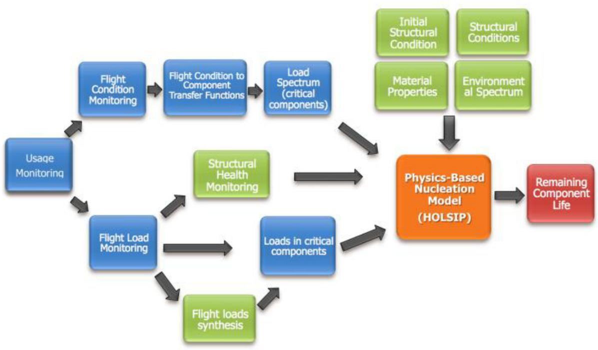

Figure 1: Usage monitoring flow chart for HOLSIP methodology [1]

The AE technique is an example of an SHM method. It performs damage detection by passively monitoring dynamic elastic waves generated from a damage site subjected to loads (e.g. growth of a fatigue crack in metal) using arrays of ultrasonic detectors. Measurement of the time difference of arrival of these signals detected at each sensor in the array can be used to deduce the location of damage via a triangulation process.

The performance of the AE technique in detecting and locating damage is however influenced by complex transfer functions between the source and processed signal [2]. These influences can be classified into four categories, namely: AE signal generation [2; 3], propagation [4], detection [5] as well as measurement and analysis of AE data [2], as illustrated in Figure 2.

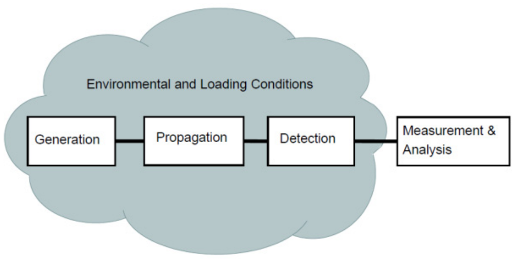

Figure 2: Sources of variability in the AE monitoring process

AE generation from fatigue cracks in metals can originate from different processes, such as fracture of inclusions, crack closure, plastic deformation or crack extension occurring during fatigue crack propagation [6]. Gagar [3] characterised the trend of AE generation from fatigue crack with cyclic stress and crack growth, as a function of loading conditions and sample geometry, and made correlations with these various sources. It was found that at a stress ratio (minimum stress/maximum stress) of 0.1 and stress range of 52 MPa the vast majority of AE signals generated were attributed to crack closure, which could also be used to develop empirical models for crack length estimation [3].

In thin plates AE signals are assumed to be Lamb waves which propagate as either extensional (anti-symmetric) or flexural (symmetric) wave modes. These signals exhibit dispersive behaviour where there is a characteristic relation between the frequency and propagating velocity of the wave modes [7]. This is also a function of the material properties (Young's modulus, density, Poisson's ratio) and thickness of the propagating medium [7]. Figure 3 illustrates the dispersion relation for the two fundamental wave modes of a 2 mm thick aluminium sheet. The wave velocity of an AE signal is used as an input in the localisation algorithms; however, inaccuracies in estimating the wave velocity will lead to increased localisation errors. Wave velocity calibration methods have been developed for improving the performance of this technique in anisotropic test samples, as well as those containing complex geometric features [4; 8].

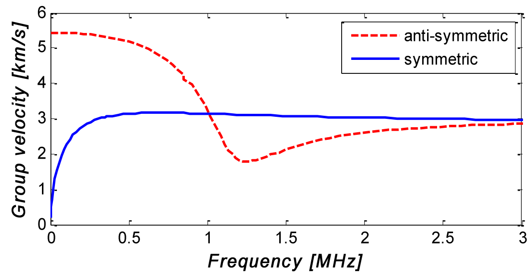

Figure 3: Dispersion relation of the extensional (anti-symmetric) and flexural (symmetric) wave modes in 2 mm aluminium material

Giurgiutiu [9] further explored the dispersion phenomenon and showed that the wavelengths of Lamb wave modes also vary with frequency. It was suggested that the maximum excitation and detection of a particular Lamb wave mode can be achieved when the length of the transducer equals half of its wavelength. This behaviour is generally referred to as Lamb wave tuning as a transducer can be designed to be sensitive to a particular wave mode and almost completely insensitive to another wave mode at the same frequency [10]. Figure 4 shows this effect for a 7 mm long piezoelectric transducer and 2 mm thick aluminium sheet, where the strain response of the transducer with respect to the wave modes can be seen for different values of frequency [11]. The integrity of sensor coupling with the structure can compromise AE detection [12].

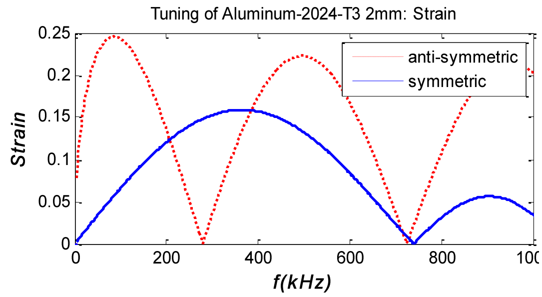

Figure 4: Lamb wave mode tuning effect for 7 mm long piezoelectric transducer and a 2 mm thick aluminium sheet [11]

The effect of temperature and loading on the dispersive behaviour of AE signals has been explored in references [13; 14]. It was found that for a temperature range of -40 ^{O}C to 70 ^{O}C and static load range from 0 MPa to 250 MPa the maximum variation in nominal wave velocity was 270 m/s. Assuming a nominal wave velocity of 5500 m/s this would result in a 4% error in time of flight measurement, for a fixed distance of propagation. This could be considered insignificant in AE SHM applications.

Measurements of Time Delay of Arrival (TDOA) used in localisation algorithms for damage detection are often performed using a fixed detection threshold used to determine the onset of the signal. This approach is however prone to errors due to varying levels of background noise relative to the amplitude of the signals.

This paper is focused on the development of a generic methodology for optimal AE system configuration to maximise the techniques performance and reliability in arbitrary installations.

2. Methodology Overview

The AE monitoring process begins with elastic waves dynamically generated from the damage site and ends with interpretation of the detected signal as illustrated in Figure 2. A logical approach for validation and verification of the techniques overall performance in arbitrary locations of an aircraft structure is therefore required to characterise variability in the end-to-end process in a stepwise manner. This would enable identification of significant sources of error and uncertainty in the AE techniques performance in terms of damage detection and localisation. There are currently no existing guidelines prescribing the level of sensitivity of damage detection or accuracy in damage location; however a benchmark for emulation is the 90% probability of detection (POD) with 95% confidence criterion for traditional Non-destructive Testing (NDT) techniques. The validation and verification process could also offer an opportunity for performance optimisation by adapting the AE systems configuration to minimise the effects of factors such as loading, component geometric and environmental conditions. This could be performed in the sequence of steps illustrated in Figure 5.

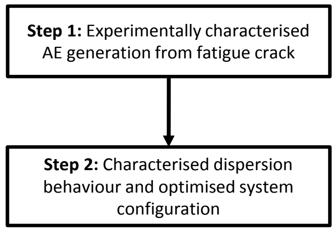

Figure 5: Sequence of steps for perform characterisation and optimisation

- **Step 1:** *Experimentally characterised AE generation from damage site*

Aircraft structures are manufactured with components of relatively complex geometry as compared with test samples used in laboratory studies. In addition, these same complex structures are subjected to dynamic loading and other operational, environmental parameters such as temperature variations. The intensity of AE generation from a damage site, fatigue crack for example, may be favourably or adversely affected under representative in-flight loading conditions, component geometry and material types. Such changes in AE generation therefore need to be determined. The viability of using the AE technique in any application can be established at this stage if a particular level of intensity is achievable with a predetermined level of reliability, to be specified by a regulatory body, at various crack lengths during crack growth. This could be done experimentally and the data obtained can in turn be used to derive empirical models which characterise AE generation during fatigue crack growth as a first step in allowing the scientific community to understand this phenomenon better. The final objective would lead to a physics based model on AE generation during fatigue crack growth in advancing the HOLSIP framework.

The POD curves used in characterising the performance of traditional NDT techniques are typically monotonic with POD approaching unity as the damage size (e.g. crack length) increases.

Gagar [3] however observed that even under nominally identical conditions there is significant variation in AE generation with crack growth, as well as at similar crack lengths across different samples. There are periods during crack growth when AE generation rates reduce significantly; implying that POD would not follow the monotonically increasing behaviour associated with conventional NDT methods.

The Probability of Hit (POH) metric, expressed in Equation 1, along with polynomial curve fitting is therefore proposed as a means to characterise variation in AE generation with crack growth. This is a point estimate probability of a certain number of AE signals being generated at a particular crack length across different samples. It is akin to the Hit/Miss model for generating POD curves used in the field of NDT, where binary indications of damage are derived based on predefined signal response levels [15]. In the case of the AE technique, there is a very weak correlation between signal response levels and the presence of damage; hence identification of damage is primarily based on AE hits i.e. number of AE signals detected. The POH metric also utilises binary criteria for damage detection, like in the derivation traditional POD curves for NDT techniques, however it is based on a variable threshold set to the minimum number of AE signals required for intelligible damage detection per increment in damage size.

$$POH_i = \frac{m\ h\ _i}{n}, \cap\ h > T \quad (1)$$

Where,
h – Number of AE signals generated
T – Threshold for
m – Number of successful detections
i – Crack length
n – Number of samples

- **Step 2:** *Characterise dispersion behaviour and optimal system configuration*

The dispersion behaviour of AE signals propagating in an aircraft structure will be affected by the complexity in geometry as well as the combination of different materials used in assembled components. Dispersion needs to be quantified for the structure being monitored so that the location of damage can be revealed using acoustic based sensors. The optimal locations and tuning of sensors can be assigned on this basis. Simple structures such as plates of constant thickness can be modelled analytically and readily validated by experiment. Ideally, these underlying principles should be extended to more complex structures using for example discretised, numerical simulations, i.e. finite element analysis which again must be validated using appropriate mechanical specimens.

In many circumstances it is the empirical formulations alone that are developed as engineering approaches since they have been found to be effective in many applications. A well-known example of this empirical formulation is the Paris Equation commonly used in fatigue crack growth in metallic materials. A fundamental physics based understanding of fatigue crack growth is still very empirically driven; hence there is a need for more research on the underlying physics to underpin the empirically observed behaviour.

Verification leading to a full validation of the solution can only be possible when a true understanding from physical principles to empirical solutions is achieved. Figure 6 illustrates the steps required, mapped on to the Technology Readiness Levels (TRL) scale [16]. This highlights the bi-directional research path needed to attain a validated understanding of the dispersion behaviour of AE signals in complex structures. This is because typically the industry and users of AE technology might approach the problem experimentally using empirical formulations obtained from tests conducted on demonstrators (TRL 3-6). On the other hand, the academic community would focus primarily on the fundamental development from a physics-based approach (TRL 1-3). The two approaches usually meet in the middle where readily accessible computational models are used by both communities (Industry and Academia).

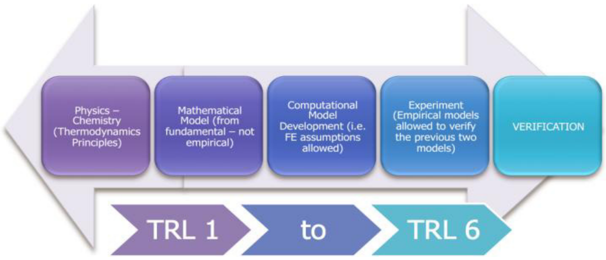

Figure 6: Performance verification process mapped to the TRL scale [1]

As previously mentioned, dispersion curves are often generated for simple plate-like structures by solving governing differential equations given particular boundary conditions using analytical and numerical methods; however this approach becomes intractable for more complicated geometries or for non-perfect samples [17; 18].

Dispersion curves can also be characterised numerically using finite element models [17; 18]. In comparison to analytical methods; this approach is more easily adaptable to complex geometries and also widely accessible via numerous commercial software packages, which eliminate the burden of creating custom-built software.

Currently, the experimental (empirical) approach however remains for the most accurate and a reliable way for characterising dispersion behaviour in realistic structures. This can be done by generating Lamb waves at particular frequencies and measuring the propagation time to a sensor at a fixed distance away from the wave actuation point. In addition, if setup correctly, it allows for understanding on the effects of complex geometrical features and boundary conditions. A combination of the experimental approach with the numerical methods can form the basis for obtaining verified information on the dispersion characteristics of AE signals propagating in an arbitrary structure.

Given the dispersion relation for a particular component, the sensors can be designed in such a way as to exploit this behaviour for a range of frequencies. For example, in the case of the tuning behaviour shown in Figure 4, favourable detection of the extensional (symmetric) over the flexural (anti-symmetric) wave mode can be achieved operating at a resonance frequency of around 300 kHz.

The introduction of geometric features will create a modified waveguide in the component which could consist of longer propagation paths, between the point of actuation and sensor location, as the waves circumnavigate these features. This effect between any given two locations can be approximated as a reduction in propagating wave velocity in determining the origin of these signals. For a fixed number of sensors installed at particular locations on a component, a ‘look-up’ table of their time of flight from any given point on the component to the various sensor locations [4; 8]. This is also referred to as ‘Delta T’ mapping and can be created by simulating AE sources at various points on the component and recording the respective propagation times. Although this is an effective means of obtaining the time of flight profile of AE signals in a component, the drawbacks are that it can be a tedious and time consuming exercise.

Application of FE modelling can also be extended to create an end-to-end model of the AE monitoring process, incorporating Lamb wave actuation, propagation and detection. This could also be used to determine the Delta T profile of AE signal propagation in the component. The benefits of this approach compared with experimental Delta T mapping are that the process can be automated and also could be more amenable to changes in sensor location as well as number of sensors. Furthermore, AE signals obtained experimentally from damage such as fatigue cracks can be introduced in the model at arbitrary locations. This would enable characterisation of performance of the AE technique in terms of detection sensitivity and location accuracy which can be optimised by modifying the number and location of sensors.

3. Discussion

One of the major obstacles impeding the implementation of the AE technique as a practical SHM solution is the lack of standards for recommending best practices as well as specifying acceptable levels of performance in terms of damage detection and location. In contrast to the field of NDT, there are prescribed standards which guide the use of inspection techniques during the phases of a components life cycle including production, maintenance and repair [19]. This can be expected to improve the safety, reliability, efficiency of procurement and use of the component [19]. Similar developments are required in the field of SHM although it should also be noted that it is a relatively newly emerging field compared to that of NDT. A pioneering step towards achieving this goal was taken with the first set of guidelines for implementation of SHM on fixed wing aircraft [20]. This provides guidance on structural maintenance practices using SHM methods, standardised SHM terminology as well as basic requirements to guide SHM technology development.

The two steps described in this paper are described from a top-level perspective and would require further consideration on the finer details of implementation. However, this gives a broad classification on how a standard set of practices can be achieved for installing an AE system in an arbitrary component to perform SHM. The POH metric proposed in Step 1 introduces alternative criteria for successful and unsuccessful detection of damage which are defined in terms of the number of AE signals detected. This can be used to set the minimum performance criteria for damage monitoring in a particular SHM application where AE is employed. At this point the viability of an AE SHM solution in a proposed application can be established.

Step 2 would enable optimal system configuration. A number of the processes described have been explored in various studies; however there are significantly fewer instances where the potential of applying an FE modeling of the end-to-end AE monitoring process is explored. This will be particularly useful for observing the Lamb wave propagation characteristics in complex structures as well as more flexible implementation of performance benchmarking algorithms. In the long term, such a methodology would be very complimentary to the wider HOLSIP framework which can potentially provide a more efficient approach for maintaining structural integrity of aircraft based on continuous monitoring systems which includes the AE technique.

4. Conclusions

- There is need for standards which recommend best practices as well as providing specification of acceptable levels of performance in terms of damage detection and location.
- The POH metric can be used to characterise the minimum performance criteria for damage monitoring in a particular SHM application where AE is employed.
- The generic tasks required for installation of an AE system in an arbitrary component can be classified into two stages.
- FE modeling of the AE monitoring process can bring significant benefits in performance benchmarking alongside experimental procedures.

Acknowledgements

This work is sponsored by BAE Systems.

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