Passive impact localisation for the structural health monitoring of new airframe materials

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Abstract. This experimental work considers the use of permanently attached sensors for the detection and location of impacts to a carbon fibre reinforced plastic panel with stringers. Deterministic knowledge of the propagation of Lamb waves in the structure is not used. Instead a statistical measure of the signal is used to determine the arrival time of elastic waves propagating in the structure as a result of the impact. A comparison is made between a conventional method and the statistical method. The conventional method, which has been routinely used in industry for acoustic emission imaging, uses the timing of a peak in the recorded signal. The statistical method uses the Rayleigh maximum likelihood estimator. The statistical method is shown to provide both more precise and robust estimates of the elastic wave arrival time. An array of just four sensors is used to locate the impacts. The accuracy of the localisations is used to visualise the effectiveness of the two methods for the low sensor density used. Low sensor density is necessary for minimising system weight and cost. The equivalent net sensor density used in this experiment was five sensors per meter squared. Carbon fibre reinforced plastic is today used for both exterior surfaces and primary structure of airframes entering service. The industrial relevance of this work is to mitigate the diminishing role of visual inspection for evaluating the health of aerospace structures, where impact damage may not be visible.

1. Introduction

This paper presents an experimental study into the localisation of impacts on a composite panel using a small number of sensors. The industrial relevance of the technique is due to new materials being selected in airframe design. Historically airframe structures have largely comprised aluminium alloy components. The aerospace industry and operators have consequently been heavily reliant on visual inspection as a means of detecting, for example, fatigue cracking or impact damage because it can normally be seen in these materials. Much recent design effort at Airbus has been spent on increasing the percentage of carbon fibre reinforced plastic (CFRP) in both civil and military products. The new military airframe A400M, as an example, widely utilises CFRP material on exterior surfaces. CFRP material fails in a different way to aluminium alloy, particularly under impact. Impact damage to CFRP material cannot always be seen and because of this the effectiveness of visual inspection, as a means of non-destructive evaluation (NDE), is set to reduce in the future.

For the ageing fleets of metallic airframes currently in service, the visibility of impact damage is an important factor in its detection. This is due to the predictable way aerospace alloys yield and fail. Visual inspection forms part of routine maintenance of these aircraft and when...
significant damage is found it is typically entered into the airframe logbook and an in-depth evaluation would be commissioned. An in-depth evaluation of impact damage requires suitable NDT techniques to be used. Such inspections require skilled engineers and specialist equipment to be brought to the structure and typically incurs substantial cost to the operator.

One important risk in migration to advanced CFRP composite material is that impact damage may be missed due to its poor visibility and consequently grow through fatigue. Barden and Almond et al. [1] compared optical and thermal methods as candidate screening tools for rapid evaluation of large structural areas of CFRP composite material, detailing the risk of barely visible impact damage. An alternative method to mitigate such risk would be to automatically monitor and locate structural impacts by measurements made from permanently attached sensors. This technique would use measurement of structure-borne elastic waves. Impacts to solid structures can be located passively by measuring time-of-arrival of resultant propagating waves at remote sensor locations. The precision of the time-of-arrival measurements determining the accuracy of impact localisation.

Firstly this paper discusses a conventional approach to measuring time-of-arrival which has routinely been used for acoustic emission structural health monitoring (SHM). Acoustic emission is the passive measurement of ultrasonic frequencies arising from brittle fracture events measured from sensors placed away from the fracture site. Tobias presented a method to localise sources in two dimensions using time difference of arrival from three sensors [2]. Triangulation techniques often applied to acoustic emission data fundamentally rely on measuring time-of-arrival for the purpose of locating sources. This can be particularly complex in anisotropic media [3]. Two common methods for measuring time-of-arrival are borrowed from acoustic emission techniques and are discussed for their relevance to impact localisation. This paper highlights difficulties with the common methods and show them to be unfit for purpose, often due to erroneous or unreliable localisation. This paper proposes an alternative signal processing method for time-of-arrival measurement taken from a recent publication on active SHM [4]. The alternative is found to improve the precision and reliability of time-of-arrival measurements leading to a convincing improvement in the accuracy of impact localisation when compared to conventional methods applied to the same data. The discussion section includes practical aspects of implementation and an interpretation of the results.

2. Method, equipment and materials

2.1. Background to a conventional approach

An extensive literature on SHM has developed over the past 25 years. The sequence of detection, localisation and characterisation of damage were all achieved by acoustic emission in the experimental work of Scruby and Baldwin et al. (1985) [5]. This was before the principles of SHM were defined, however the same sequence is generally still in use today [6]. The passive technique of acoustic emission continues to receive attention from manufacturers in the aerospace sector [3][7] and the overarching principles of SHM have been elaborated in the review work of Worden and Farrar et al. [6]. The method in this paper considers the problem of source localisation in isolation from other problems of detection and identification, which are not covered. The method applied is for localising structural impacts, however, the method bares relevance to acoustic emission source localisation and takes standard practice from this discipline as a benchmark for the alternative proposed.

The passive method of acoustic emission monitoring is one SHM method that has successfully permitted the localisation of sources from remote measurements at ultrasonic frequency. The sources of interest in acoustic emission measurement are typically brittle fracture events in metallics and other materials resulting from loading. The modelling work of Wilcox and Lee et al. [8] showed that source location and threshold level were critical factors affecting the probability of detection at either any or all sensors in an array. Acoustic emission monitoring equipment
has been developed by a consortium that included Airbus. The equipment uses a network of charge-amplified piezoceramic sensors. This equipment has been made airworthy to technology readiness level six by an extensive programme of testing. The equipment was developed for over a decade by a consortium comprising Lloyds Register, Ultra-Electronics and Airbus[3][7][9]. One key capability offered by the equipment is to communicate information for locating ultrasonic sources using a minimal transmission of data. Algorithms developed made progress on source localisation in anisotropic material, accommodating the anisotropic wave-propagation resulting from carbon fibre layup. Numerical studies such as Torres-Arredondo et al.[10] provide insight into the complex behaviour of wave propagation in these materials and show several ways to visualise it. Once anisotropy has been characterised, either empirically or numerically, there are methods available to compute source location from arrival times affected by the anisotropy of propagation[3][11].

Localisation algorithms, such as Paget and Atherton et al.[3], use time-of-arrival data to triangulate sources, however, one set back has often been the method in which time-of-arrival has been measured. Historically time-of-arrival has been obtained by threshold-crossing times or peak arrival times. The measured signal is normally rectified by the acoustic emission hardware, as shown in Figure 1. The purpose of applying either of these standard techniques being to measure the relative time-of-arrivals between different sensors in the array. The two standard measurement methods can be carried out with simple cheap light-weight electronics, making them attractive methods for applications in aerospace. However, both of these techniques are fundamentally flawed and are flawed for different reasons.

An example of an impact signal is given in Figure 1. The preprocessing step of rectifying the pre-amplified signal is achieved using diodes. The timing of a 0.4 Volt threshold-crossing and the detection of an amplitude peak have been marked on the signal using coloured cross-hairs.

![Figure 1](image-url)

**Figure 1.** A threshold crossing time, or peak time, are routinely used for measuring the time-of-arrival of propagating elastic waves for industrial acoustic emission applications

### 2.2. Difficulties with the conventional approach

Threshold crossing is flawed because Lamb wave dispersion and divergence causes delays in the timing and, furthermore, the threshold level needs to be set relative to ambient background vibration levels, which may change according to environmental conditions of operation. In a study of acoustic emission measurements applied to landing gear structures, el-Bakry showed that a 6dB amplitude change could lead to 25µs difference in time-of-arrival measurement using the threshold crossing technique on 300kHz-band sensors applied to a 300M steel plate[7]. The peak-detection method was introduced to overcome some of the basic problems associated with
threshold-crossing. The peak-detection method requires an arbitrary time-out parameter to be set which defines when the peak-hold circuit is reset, at which point the timing of a peak can be transmitted and a new peak detected. Like threshold-crossing, the peak-detection method can be implemented using simple light weight analogue circuits. However, the peak-detection method is flawed for a different reason. The reason the peak-detection method is flawed is because the reverberant field from a source can lead to higher recorded amplitudes than the original direct path of elastic waves. This is illustrated by the example given in Figure 1 where the blue cross-hairs marking the peak occurs significantly late in the time history. This can arise from either multiple Lamb wave modes propagating at different velocities or the transient interference pattern of waves reflected from large coherent reflectors such as stringers or edges. The uncertainty around the timing of the peak has been found to be a particular problem when applying the peak-detection method to metallic panels which have relatively low levels of visco-elastic absorption compared to CFRP composite. Peak-detection is consequently the standard method used for the acoustic emission testing of CFRP structure and therefore taken as the benchmark for the study here into impact localisation.

2.3. The proposed RMLE method as an alternative

A new approach is taken in this experimental work for estimating the time-of-arrival of propagating elastic waves resulting from structural impact. This approach adopts a technique that has recently seen attention for active guided wave SHM and uses the Rayleigh maximum likelihood estimate (RMLE) of parts of the signal\[4\].

The useful property of the RMLE method in application to source localisation is that an apex obtained at the time-of-arrival of the elastic waves. The RMLE method differs from the threshold-crossing method because there is no need to set a threshold parameter relative to the ambient structural vibrations or fretting noises featuring in the measurement. The new method uses a statistical treatment of the sampled signal rather than any direct interpolation from the rectified signal itself. The RMLE method has been termed the arrival filter in Flynn and Todd et al. where a full derivation can be found\[4\].

The RMLE method uses a variable sample index, η, to divide the signal into two parts. The samples either side of the division point have different amplitude distributions. The maximum likelihood estimates for the two regions of the signal, Equations 1 and 2, are shown as a function of the division point η, and the full arrival filter output ω[η] can be computed using Equation 3.

\[
\sigma_1(\eta) = \sqrt{\frac{1}{2(\eta)} \sum_{n=1}^{\eta} \nu^2[n]} \tag{1}
\]

\[
\sigma_2(\eta) = \sqrt{\frac{1}{2(N-\eta)} \sum_{n=\eta+1}^{N} \nu^2[n]} \tag{2}
\]

\[
\omega[\eta] = -\eta \ln \sigma_1^2(\eta) - (N - \eta) \ln \sigma_2^2(\eta) + 2 \sum_{n=1}^{N} (\ln(\nu[n])) - N \tag{3}
\]

where N is the number of points in the series and ν is the scalar magnitude of the sampled time series, which for computational reasons cannot be exactly zero at any point due to the logarithm used for calculation. It can be seen that the arrival filter is non-linear and acausal, however, this is not strictly a problem as many SHM systems operate in post-processing rather than in real-time \[12\].
2.4. The experiment

An experiment was designed to compare the arrival filter (RMLE method) with the standard method of peak detection. A photograph of the specimen used for the experiment is given in Figure 2. The CFRP panel containing two stringers was impacted at a number of locations. The impacts were provided by dropping a 10mm diameter steel ball bearing down a 30mm diameter tube from a 200mm height. A diagram is shown in Figure 3. The spacing between impact locations was 100mm. The impacts were to the exterior surface of the lower wing cover specimen, to the reverse of the stringer-side shown in Figure 2. Ten impacts were carried out at each of the 42 locations. Knowledge of the true impact location was therefore correct to ±15mm of the target impact site.

![Figure 2. The specimen used for the experiment was a CFRP composite panel containing two stringers](image)

![Figure 3. The experiment used a ball-bearing drop to provide an impact source](image)

Four sensors were used for the localisation of impacts over a 7 × 6 grid as shown in Figure 4. The array transducers and pre-amplifiers were centred on 7kHz frequency, significantly lower than typical acoustic emission measurement frequencies. The area covered by the array was 0.6 × 0.6 metres. If these array elements were to tessellate over a larger structure in a regular square grid with the arrangement shown, this would correspond to a net sensor density of 5.5
sensors per metre squared. The time-of-arrivals were taken from all four channels during the experiment using both standard and new method.

Figure 4. A grid of 42 impact locations were used

A significant problem with passive methods is that the impact event-time is not known. Only the relative differences in arrival times can be deduced from synchronous recordings at sensor positions. This is not a problem encountered with active imaging, because the time of transmission will generally be known using this method. The important difference between active and passive array equipment affects the electronic architecture that can be used, ultimately affecting cabling weight. The data from an active array can be built up sequentially by transmitting and receiving on different pairs each time. Active SHM networks therefore use multiplexing to enable a limited number of transmit/receive channels to cover a large number of elements. The transmitted signal can be repeated as many times as necessary to reduce random noise affecting the measurement, allowing low power excitation to be used. Michaels and Lee et al.[13] cite signal averaging as a common method to improve signal to noise ratio on active networks. They note this unfortunately leads to prohibitively long acquisition times when multiplexing over arrays larger than 10 elements. The alternative to averaging presented in their work uses pulse compression from recorded responses to chirped excitations, consequently speeding up the acquisition process. Whereas the active SHM network is able to use multiplexed channels, the passive technique intrinsically needs synchronous multi-channel recording. This emphasises the need for low sensor density particularly on passive techniques to avoid prohibitively high cabling weights.

The triangulation algorithm used in this paper is designed for localising sources in plates where wave-fronts propagate elliptically as a result of anisotropy. This kind of anisotropy might be expected in CFRP plate comprising unidirectional fibres. The intersection of two ellipses can be solved analytically as the real roots of a quartic equation using knowledge of two different group velocities in orthogonal directions. A full derivation can be found in Paget and Atherton et al.[3]. For this experiment these were measured empirically as \( c_{0\text{gr}} = 1560 \text{ms}^{-1} \) and \( c_{90\text{gr}} = 1390 \text{ms}^{-1} \) respectively using threshold-crossing. \( c_{0\text{gr}} \) is the effective group velocity in the predominant fibre direction, which in this case was parallel to the stringers and \( c_{90\text{gr}} \) is the group velocity perpendicular to stringers. This algorithm differs from that given in Scholey and Wilcox et al.[11], where the full angular dependence of group velocity must be obtained to compute likely source location. Whereas the method in Paget and Atherton et al. requires arrays to be of three or four sensors specifically, the method of Scholey and Wilcox et al. can be applied to an arbitrary number of sensors.

The aim of this work is not to evaluate triangulation method, but to evaluate the performance and reliability of time-of-arrival estimates. The triangulation is however helpful in presenting the large amounts of data collected during the experiment and gives a practical example of achievable accuracy.
3. Results
An example of the time-of-arrival measurements achievable with the two methods is given in Figures 5 and 6. Figure 5 shows the rectified signal from three sensors with the timings of the peaks from three channels marked by vertical blue lines. Figure 6 shows the RMLE method applied to the same signals shown in Figure 5. The time-of-arrivals are taken from the maxima in the RMLE output. The times at which these occur are indicated here by vertical red lines. The values interpolated for the two methods are given in Table 1.

![Figure 5](image-url)  
**Figure 5.** Measured times-of-arrival using the peak-detection method

![Figure 6](image-url)  
**Figure 6.** Measured times-of-arrival using the Rayleigh maximum likelihood method

| Channel | Peak  | RMLE  | ΔT_{\text{peak}} | ΔT_{\text{RMLE}} |
|---------|-------|-------|------------------|------------------|
| 1       | 158.40| -3.20 | —                | —                |
| 2       | 195.20| 40.40 | 36.80            | 43.60            |
| 3       | 274.00| 149.20| 78.80            | 108.80           |

Table 1. Time-of-arrival estimates produced by the peak and RMLE methods from examples given in Figures 5 and 6. All times in μs.

It can be seen from Figures 5 and 6 that the RMLE method measures the arrivals at significantly earlier times than the peak-detection method. There is also a subtle difference
in the time difference of arrival, seen by the horizontal spacing between the lines. The timings output from the two methods are summarised in Table 1 for a single impact event. It can be seen from the RMLE arrival time shown on Channel 1 that oscilloscope trigger is pre-empted by -3.2 µs. This corresponds to the arrival time at first-hit sensor, which would ideally be time zero, and demonstrates the sensitivity of the technique to the “true” first arrival time.

The times-of-arrival given by the two methods (Figures 5 and 6) were used to localise the 10 impacts of each of the 42 impact locations. The spread of localisations from the two methods are given in Figure 7. Figure 7 shows there is a greater spread in the localisations produced by the time-of-arrivals obtained using the peak-detection method than the RMLE method. The poorest performing localisations obtained using the peak-detection show extremely large error, to the extent that it cannot obviously be seen which localisations relate to the which impact sites.

These localisation results for both methods have been superimposed onto the surface that was impacted (Figure 8) and the reverse side of the panel (Figure 9) using image registration. Figure 9 reveals the stringer locations relative to the impact localisations. The red circles in Figure 9 show there is a greater extent of error near the bottom and right hand sides than in other areas of the panel using the RMLE method. This could perhaps be related to the layout of sensors in relation to stringer positions, which can be seen more clearly in Figure 9.

The magnitude of the localisation errors are plotted in Figure 10 for each of the ten repetitions at all impact locations. This gives an idea of the spread of results when the impact is repeated using the two techniques. The green line at the bottom of Figure 10 indicates the ±15mm tolerance on true impact location as mentioned in Section 2.4. This arises from insufficient control of the actual impact site. Firstly the figure shows that the errors from the peak-detection method are far greater in magnitude than the RMLE method for almost all impact sites. The second thing to notice from Figure 10 is that the variance between impact localisation errors is also greater for the peak-detection method than the RMLE method at each impact site. This highlights one key issue of the peak-detection method being that of extremely high sensitivity towards precise impact location. The RMLE method, in contrast to peak-detection, shows a
more robust and stable localisation from 10 repetitions. The higher error and variance from the peak-detection results making the RMLE method more favourable.

4. Discussion

4.1. Practical aspects of implementation

The RMLE technique is sensitive to changes in the signal distribution over time, rather than the sampled signal itself. Unlike threshold-crossing it does not require a threshold to be set above noise floor. Unlike peak-detection it does not require a time-out to be set, after which higher peaks cannot change the time-of-arrival. By removing input parameters such as these,
there are fewer obstacles for the technology to be implemented in industry. It may also be that the RMLE method is more robust against benign structural vibrations than the conventional methods, however, this would require further study.

One challenge affecting the deployment of the RMLE technique is that it requires the whole time history to be post-processed digitally, rather than using the analogue circuits available from acoustic emission methods. The RMLE method also requires a pre-trigger of signal prior to impact. Combining this with the need to capture pre-trigger on multiple channels, this affects data gathering requirements and therefore cost and weight.

4.2. Interpretation of results
If impact localisation is required as part of SHM, the difficulties of the conventional methods need to be overcome. The difficulties with the conventional approach were outlined in Section 2.2. These arise because impacts generate a superposition of many propagating and dispersive Lamb wave modes, making time-of-arrival difficult to estimate. It has been shown that this leads to poor localisation accuracy when using peak-detection and that the RMLE method shows significant improvement. Figure 10 shows greater error and lower consistency using the peak-detection method. The size of the error for the peak-detection method being comparable to the size of the plate specimen on many localisations. For this reason the peak-detection results are omitted from Figure 11 and, by contrast, the RMLE method attributes source location to an accuracy within the 100mm grid spacing of the impact sites. A large standard deviation on impact localisations can be seen in some areas of Figure 11. This can be attributed to a tolerance on actual impact location as indicated by the green line in Figure 10 relative to the impact location grid (Figure 4). The control over the actual impact site was not fine enough to consistently hit either above the stringer-foot area or open plate between the ten impact repetitions. This is thought to explain the results on the centre right hand side of Figure 11. Of the ten impact trials at this location it can be expected that the panel was impacted above the stringer-foot only on some occasions, leading to variance in the result. This is unlike the lower left hand side where the error was equally large but variance small.

5. Conclusion
The RMLE technique can locate impact when it occurs by use of permanently attached equipment. The new technique has been shown to give more repeatable time-of-arrival measurement using ball-bearing impact than conventional methods historically implemented.
on acoustic emission testing. More precise time-of-arrival measurement led to more accurate localisation using a small number of sensors. Impacts may be detected by threshold crossing, however, neither threshold crossing nor peak-detection should be used for impact localisation in large complex CFRP structures.

The reliability of electronics and sensor network are central to the business case for SHM technology. It is an open question whether digital equipment for post-processing can be made as reliable as previously used analogue circuits for acoustic emission testing. Any high costs of maturing this technique should be considered carefully against the changing demands of inspection, in particular the diminishing role of visual inspection in the long term.

This paper used source localisation accuracy as a performance metric for the purpose of evaluating arrival time measurement. A quantitative study into the precision of arrival times would be useful progress to this work, however, care should be taken when choosing the “true” arrival time for benchmarking, because the correct value is not necessarily clear. One practical question of importance is how many samples of the signal are necessary to enable the RMLE technique to work.

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