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Integration of acoustic emission systems within Integri-Tech™ analysis system for structural health monitoring of pressurised engineering plant

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Abstract. The aim of this Acoustic Emission (AE) based Structural Health Monitoring project is to enable accurate location of AE sources in pressurised engineering plant and to use AE source location data to establish defect locations for use within Integri-Tech™; a finite element based analysis, monitoring and fitness for service assessment system. Integri-Tech™ is a windows based system which carries out combined analysis and assessment providing fatigue life and remnant life calculations and inspection priorities presenting the results in an accessible web portal format. The software uses finite element stress models created in the companion software Model Wizard. The AE monitoring system that has been developed can be used with an array of up to four AE broad band sensor channels with associated signal processing. Using a flexible approach in MATLAB, the authors have developed algorithms which were used for analysing the received AE signals to extract information about the nature and location of the source. The ability to carry out source location and possibly perform real time monitoring (detecting cracking as it occurs) is attractive feature of the AE system developed for this project. The time of arrival (TOA) data was used by Integri-Tech™ software to calculate source location using its own built-in algorithm, and this was verified independently using a MATLAB approach.

1. Introduction

Acoustic emission testing (AET) is a non-destructive technique that monitors defect creation and failure within a material through the detection and analysis of acoustic signals under load condition. AET is fundamentally different from other non- destructive testing methods because it passively detects energy that is released from a material, whereas other methods require an energy input for the defect to be detected (i.e., x-rays, ultrasound, thermal energy and microwaves). The technique is largely acceptable for the detection of possible AE events in pressure vessels, piping system and tanks. An important ability of this technique is to use the arrival times of the signals to estimate the AE source location. The arrival times from a single event at three or more sensors can be used to calculate the location of the source in the test object.

In this paper we cover the measurement aspects of our research work which include: monitoring of AE events in plate and pressure vessel samples, post-processing of AE raw data for calculating time of arrival at each single node in an array of transducers and source location on the object under test using a Trilateration algorithm implemented in MATLAB. The finite element stress models for the specimen geometries have been designed into Integri-Tech™ using its companion software Modal Wizard and the calculated arrival time value of the wave forms were used to estimate source locations on the designed models using the Integri-Tech™ built in source location algorithm.

2. Experimental Setup

Wide band sensors UT-1000 from Physical Acoustics (working frequency range from 100-1000 kHz) were used throughout this research work. Plate and pressure vessel specimen geometries were used which are representative of real structures encountered in pressurised engineering plant. The plate was manufactured from aluminium with dimensions of 2 mm thick, 550 mm long and 450 mm width. The vessel was manufactured from mild steel with dimensions of 5 mm thick, 1000 mm length and 675 mm circumference. For the plate structure, three transducers were coupled onto the plate surface in a triangular pattern, silicon grease was used as couplant to provide good acoustic coupling between the transducers and the surface of the geometry. For the vessel structure, four sensors were coupled on it. The transducers were arranged on the vessel surface in a fashion that they made four triangles for detecting possible AE events as shown in Figure 1. A four channel Tie-Pie pico-scope was used for AE waveform acquisition with the setting of 12-bit data resolution, 5000 data points and selected first transducer as trigger. Detected events were pre-amplified by four matched 40 dB preamplifiers. The acquired waveforms were stored on to the computer for further analysis.

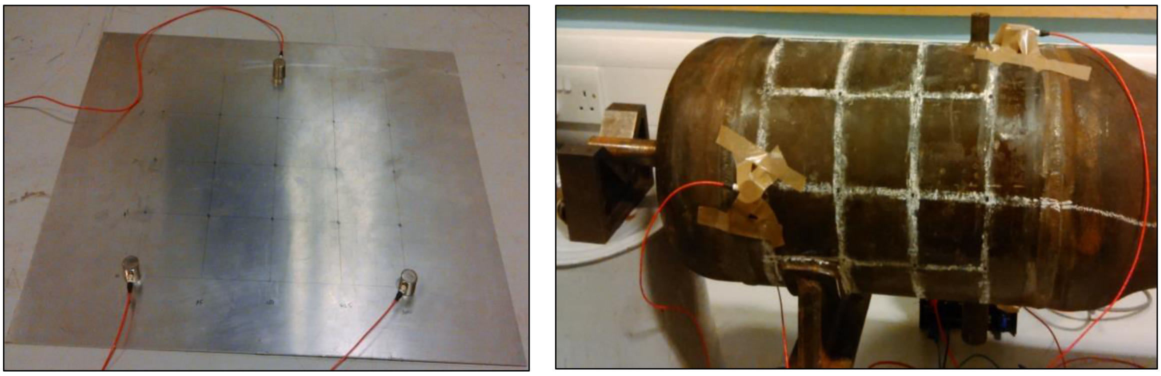

Figure 1. Experimental specimens for source location experiment

For the plate sample, an area of 300 mm by 300 mm was selected on the surface and a grid with size of (75x75) mm^2 was drawn (Figure 1). Out of 25 points on a grid, Hsu-Nielson (H-N) sources [1] were conducted at 22 points. AE signals were generated by breaking 0.7 mm pencil leads at selected locations on the plate. To standardise the tests, the pencil was held at the same angle to the surface using a bespoke of aluminium shoe and the same length of leads were broken for each test. A grid with a spacing of (75x75) mm^2 was drawn on the vessel surface to cover 675 mm circumference and 300 mm length (Figure 1). Out of 30 points on a grid, Hsu-Nielson (H-N) sources were excited at 23 points in the same manner as conducted for plate geometry. To verify the reproducibility of lead break tests for both geometries the tip of a pencil was broken 8 times on a randomly selected point on each sample.

3. On-Set Time Calculation for Source estimation

The ability to locate the source is one of the advantageous characteristic of the acoustic emission technique, but in complex material and structures it can be difficult to locate an AE event accurately. A significant volume of research has been carried out to improve the accuracy of AE source location. Recent advances in signal analysis using a statistical approach. The objective of this technique is to statistically differentiate the noise and meaningful data from the raw AE signal [2]. This approach called the *AIC* method [3-5] and can be applied to AE signals coming from a structural monitoring.

Zhang et al. [6] and Akaike [3] have shown that a time series can be divided into locally stationary segments, each modelled as an autoregressive (AR) process [3,4].

The approach described in this paper has focused on using an autoregressive process first proposed by Akaike [3] also known as Akaike information criterion (AIC). According to this approach, the AE signal can be divided into two intervals. Each segment is modelled as an autoregressive process and represents the part of the AE signal mostly dominated by the noise and the original signal, respectively. Then the two series are separated by the point at which the AIC is minimised and this point corresponds to the onset time of the signal of interest [7].

The minimum of the AIC function can be calculated using Equation1 for defining the arrival time of an AE, the function can be derived directly from the raw AE signal according to Yokota et al. [7] and Maeda [8] as:

$$AIC\,(t_w) = t_w \,.\, \log\,(\mathrm{var}\,(R_w\,(t_w\,,1))) + (T_w - t_w - 1)\,.\,\log\,(\mathrm{var}\,(R_w\,(1 + t_w\,,\, T_w\,))) \quad (1)$$

Where $\boldsymbol{R_w}$ is the selected window, $\boldsymbol{T_w}$ is the last sample of the selected window, $\boldsymbol{t_w}$ ranges through all samples of $\boldsymbol{R_w}$ and **var** is the variance function. $\boldsymbol{R_w\,(t_w\,,1)}$ expresses the variance that is measured from the beginning of the window until the current value $\boldsymbol{t_w}$, while $\boldsymbol{R_w\,(1 + t_w\,,\, T_w\,)}$ expresses the variance that is taken for all samples ranging from $\boldsymbol{1 + t_w}$ to $\boldsymbol{T_w}$.

For this research work the AIC algorithm was coded using MATLAB. Considering the nature of an artificial AE source, asymmetric group velocity values for plate and pipe (2400 m/s and 3100 m/s) respectively were extracted theoretically using dispersion curves and were used in the algorithm for arrival time estimation. The threshold defined for the AIC algorithm was 0.4 for the waveforms in the higher frequency range (40 kHz-250 kHz), and it could be increased up to 0.8 for lower frequency signals as the observed level of noise in these frequencies was considerably higher. The window around the prearranged on-set was selected to be from the starting point of the waveform until 100 sampling points after the prearranged onset point. However in the lower frequency range signals, this interval can be adjusted starting from the beginning of the waveform until 450-650 sampling points after the prearranged onset point. This ensured that the onset point would not be `buried' in the high levels of noise.

4. Source Estimation using Trilateration Algorithm

One-dimensional geometry problems are rare in AE source location. Although, a good understanding of the principles of source location in one-dimension provides a solid grounding for higher dimensional problems, two-dimensional problems are more prevalent in AE source location than those in one-dimensional geometries. An illustration of two dimensional source location geometry can be seen in Figure 2. Three sensors **S1**, **S2** and **S3** are placed on the surface of a structure at locations $\mathbf{(x_1, y_1)}$, $\mathbf{(x_2, y_2)}$ and $\mathbf{(x_3, y_3)}$. The location of the source, to be determined, is $\mathbf{(x_s, y_s)}$. The distance between the sensors are $\mathbf{D_1}$, $\mathbf{D_2}$ and $\mathbf{D_3}$ (which are known), and the distance between the source and the sensors are $\mathbf{d_1}$, $\mathbf{d_2}$ and $\mathbf{d_3}$ (to be solved). $\mathbf{t_1}$, $\mathbf{t_2}$ and $\mathbf{t_3}$ are the times the signal takes to reach the sensors **S1**, **S2** and **S3** respectively.

Using the derivations as made in [9], the distance $\mathbf{d_1}$ can be written to be:

$$d_1 = D_1^{\,2} - \Delta t_1^{\,2}\,.\,c^2\,[2(\Delta t_1\,.\,c + D_1 \cos\,(\theta - \theta_1))]^{-1} \quad (2)$$

$$d_1 = D_2^{\,2} - \Delta t_2^{\,2}\,.\,c^2\,[2(\Delta t_2\,.\,c + D_2 \cos\,(\theta_3 - \theta))]^{-1} \quad (3)$$

Where angles $\boldsymbol{\theta}$, $\boldsymbol{\theta_1}$ and $\boldsymbol{\theta_3}$ are marked in Figure 4 and

$$d_2 - d_1 = c\,(t_2 - t_1) = \Delta t_1.c \quad (4)$$

$$d_3 - d_1 = c\,(t_3 - t_1) = \Delta t_2.c \quad (5)$$

$\mathbf{\Delta t_1}$ and $\mathbf{\Delta t_2}$ are time differences $\mathbf{(t_2 - t_1)}$ and $\mathbf{(t_3 - t_1)}$ and **c** is the wave speed.

The location of the source is given by

$$x_s = x_1 + d_1 \cos\theta \quad (6)$$

$$y_s = y_1 + d_1 \sin\theta \quad (7)$$

For this research work MATLAB codes were used for writing the trilateration algorithm. For the calculated arrival times of the signals the time differences were calculated in the trilateration algorithm. Using a suitable iteration scheme, the values of **θ** are varied and those that minimise the error between two calculated source locations were used to identify the AE source location.

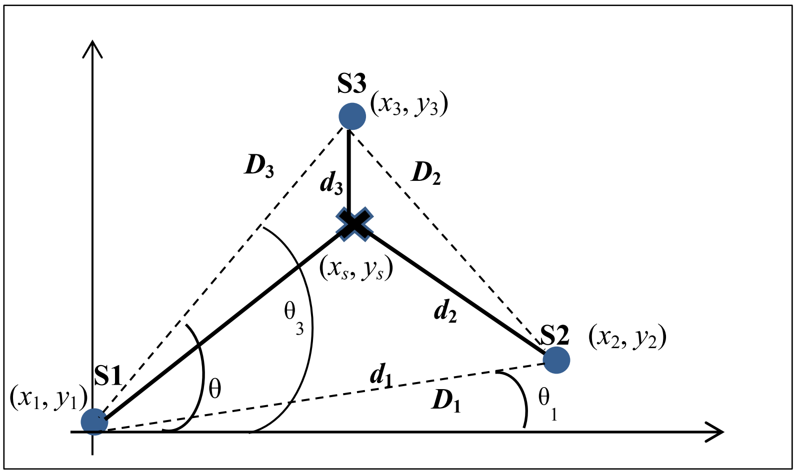

Figure 2. Two Dimensional source location [9]

For the plate sample, because of the 2-D nature, this algorithm was applied directly and calculations were done for all emission sources. For the pipe, the region of interest was divided into four non-equilateral triangles in such a way that all of four triangles cover the complete region. Four sensors were placed on a pipe to cover all possible AE events within the area of interest. Division of the pipe surface in four triangles made easy implementation of the trilateration algorithm. The pipe sample was unfolded and 2-D coordinates were used in calculations for source estimations. For both geometries the results are presented graphically in Figure 3. In this figure the actual source locations were indicated by circle (black in colour) and the estimated source locations were indicated using cross (blue in colour), the lines joining the calculated source locations with their respective actual locations.

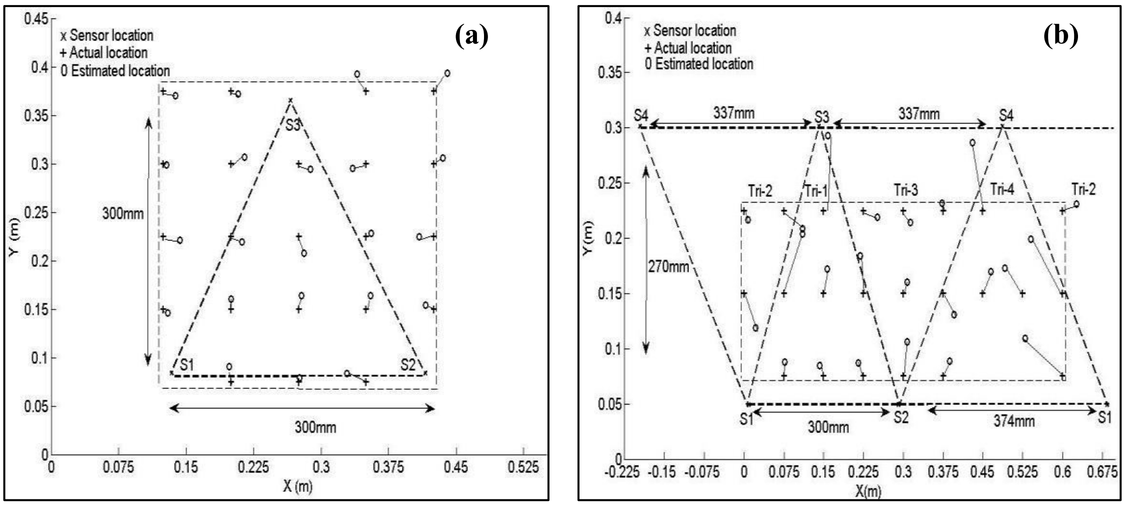

Figure 3. Trilateration Source locations for plate and unwrapped vessel in 2D plane

5. Source Estimation using Integri-Tech™ Software

Integri-Tech™ is a Windows application which carries out a combined finite element analysis and fatigue life calculation, presenting the results in an easy to understand web portal format. The software uses finite element models created in the companion software Modal Wizard. For this research work this software was used for the first time to estimate AE events location on the specimen under test. The software utilises its own built-in proprietary algorithm for source location. Initially the specimens were modelled using Modal Wizard as per experimental geometries measurements. The sensors were placed in the same fashion on the models and at same locations as in experiments. Figure 4 shows both plate and vessel models designed in Modal Wizard with AE sensors placed on them. The on-set time values for each of four sensors in response to the AE events were calculated using AIC algorithm and given as input AE primary parameter to Integri-Tech™ for estimating source location. Depending on the given arrival time of wave forms on each node, the estimated source locations were calculated by Integri-Tech™. Figure 5 presents 3D geometry models with estimated source locations calculated by Integri-Tech™ source location algorithm and its 2D graphical presentation.

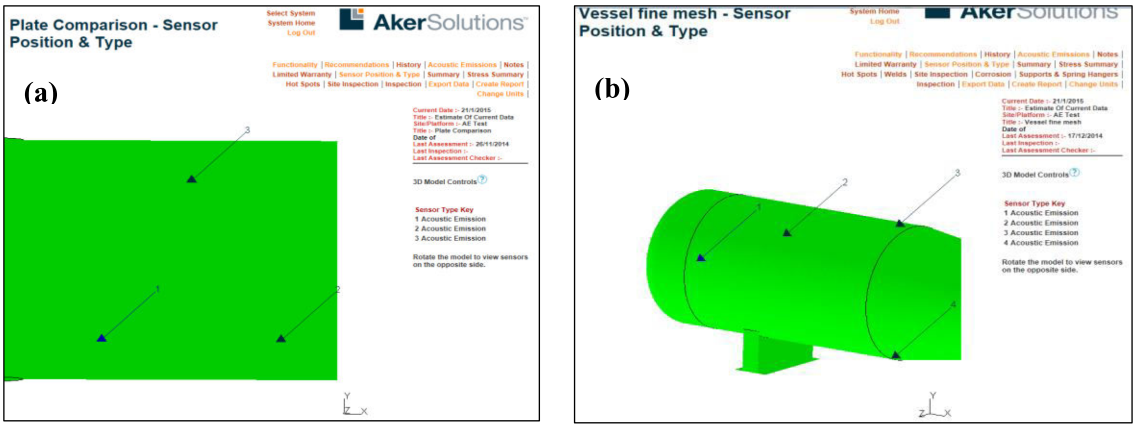

Figure 4. Integri-Tech™ 3D model for each specimen with sensors positions

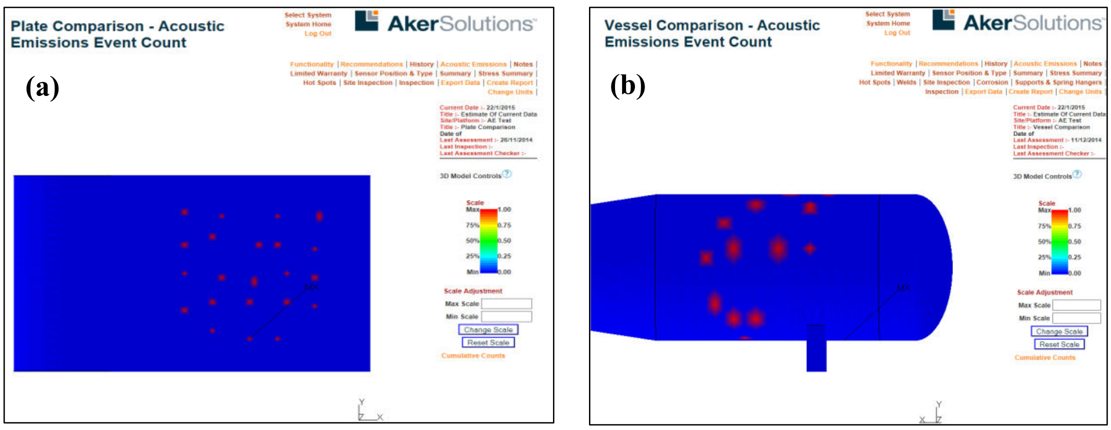

Figure 5. Estimated source locations on 3D model of each geometry using Integri-Tech™

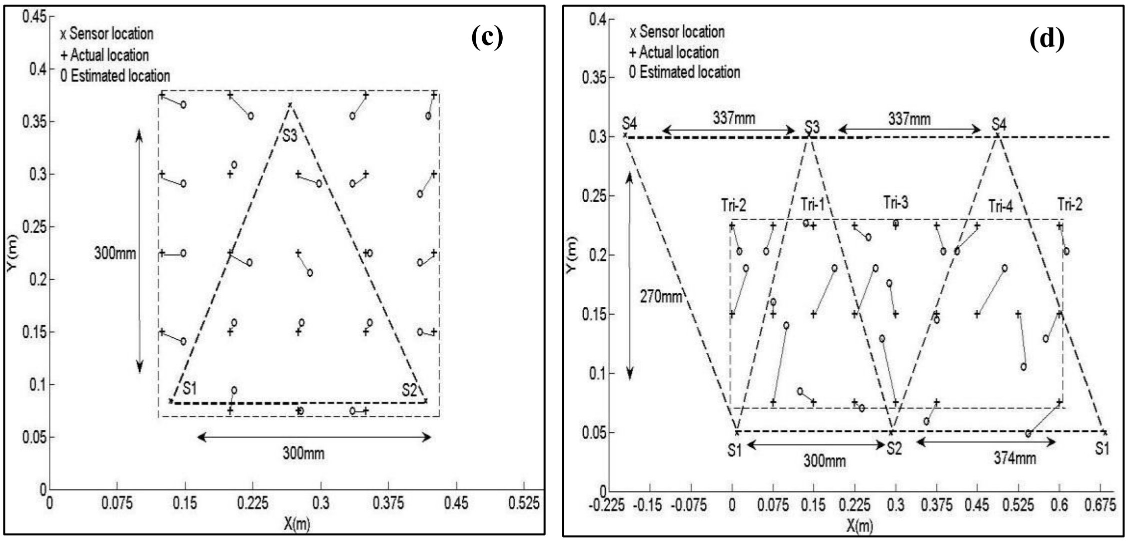

Figure 5. Integri-Tech^{TM} Source locations for plate and unwrapped vessel in 2D plane

6. Results and Discussion

Figure 6 shows the plate and vessel samples in a 2D plane, the graphical presentation compares calculated source positions with actual source locations. The figure indicates estimated source locations calculated using two algorithms: (i) Trilateration MATLAB & (ii) Integri-Tech^{TM} multilateration in comparison to actual source locations. Figure 6(a) shows 22 AE events on a selected grid area of a plate which represent 66 AE signals. The location analysis was done using Trilateration technique in MATLAB, a mean of distance error for all 22 AE locations was found to be 14mm (RMSE). Using the Integri-Tech^{TM} source location algorithm for plate, a mean of the distance error for all 22 AE locations was found to be 18mm (RMSE). For the vessel, the geometry was unfolded and divided into four triangles to perform trilateration technique in MATLAB and cover whole area of interest as shown in Figure 5(d) total 23 AE events were made on a selected grid area of vessel which represent 92 AE signals. The graphical presentation in Figure 6(b) indicated four sensors positions with actual source locations and estimated source locations calculated using both source location algorithms. From trilateration technique, a mean distance error for all 23AE locations was found to be 34mm (RMSE) on the other hand with Integri-Tech^{TM} multilateration technique the mean distance error for all 23 AE locations was found to be 38mm (RMSE).

The errors between the calculated and real source locations may be due to variability of the artificial AE sources, error in the measurement of actual source locations on a specimen, sound attenuation, and uncertainty of the wave propagation path. Additionally, the Integri-Tech^{TM} introduced another source of error which is called mesh error. Since the model is built from a finite element mesh with a mesh size of (55 x 55) mm^2, the discretization error associated with the mesh density provides a limit to the source location accuracy as the AE event can only be located at a mesh node. The Integri-Tech^{TM} reports the *Mesh Error* for each AE event. This is the difference between the measured time of arrivals, and the expected times of arrival for an event at the reported location calculated from the model geometry and the input velocity. Events are assigned to the node with the lowest error. Improved accuracy can be obtained by using a finer mesh, at the cost of increasing analysis times.

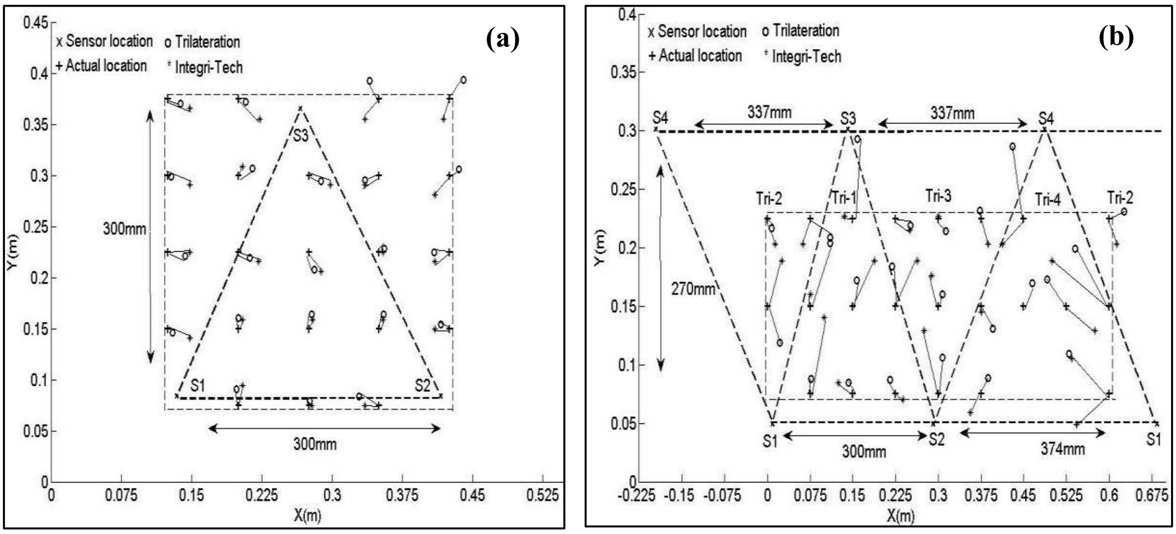

Figure 6. 2D Plate and Vessel models with estimated source locations using both algorithms

For both geometries, a final comparison table with selected AE events was then produced (Table 1 - 4). It is concluded that the Integri-Tech^{TM} has good capability for locating AE events. AE source location can be estimated more accurately using the Integri-Tech^{TM} by making reasonable changes in mesh setting.

Table 1. Comparison of source estimation using both algorithms for Vessel

Actual source location		Trilateration (MATLAB)		Integri-Tech^{TM}	
x(mm) ±10mm	y(mm) ±10mm	x(mm)	y(mm)	x(mm)	y(mm)
0	150	22	119	25	189
300	150	308	160	288	176
375	150	396	131	375	145

Table 2. Location error as a percentage of the distance from the source for Vessel

Actual source location		Trilateration (MATLAB)	Integri-Tech^{TM}
x(mm) ±10mm	y(mm) ±10mm	% of Error	% of Error
0	150	14	17
300	150	7	16
375	150	15	3

Table 3. Comparison of source estimation using both algorithms for plate

Actual source location		Trilateration (MATLAB)		Integri-Tech^{TM}	
x(mm) ±7mm	y(mm) ±7mm	x(mm)	y(mm)	x(mm)	y(mm)
0	150	18	146	23	150
150	150	156	133	163	131
225	150	231	154	229	150

Table 4. Location error as a percentage of the distance from the source for plate

Actual source location		Trilateration (MATLAB)	Integri-Tech^{TM}
x(mm) ±7mm	y(mm) ±7mm	% of Error	% of Error
0	150	8	10
150	150	9	12
225	150	3	2

7. Conclusion
Originally the Integri-Tech^{TM} software was designed for remote integrity and fitness for service monitoring (vibration, strain and process), remaining life and inspection priorities. This work has demonstrated that the software can also be used to make reliable estimates of acoustic emission source location. This paper has presented the results of experiments aimed to verify source locations calculated by Integri-Tech^{TM} multilateration with a standard trilateration technique coded in MATLAB based on Akaike information criterion (AIC) for on-set time calculation. Two different geometries were selected for this research work to locate AE events. A plate specimen was used in experiments with an array of three transducers to detect possible AE events. Similarly a vessel specimen was used with an array of four transducers to detect possible AE events. Recorded waveforms from H-N sources at each known location were processed in MATLAB using the AIC algorithm to find on-set time on each node. For the current work all tests were carried out in a lab environment, however for future use of AE system a high level of noise would be encountered in the resulting signals due to the environmental condition of pressurised engineering plant. For the plate sample RMS errors of 14mm were obtained in MATLAB vs 18mm in the Integri-Tech^{TM}. For the vessel sample RMS errors of 34mm were obtained in MATLAB vs 38mm in the Integri-Tech^{TM}. This close level of agreement provides confidence in the basic AE source location capabilities of the Integri-Tech^{TM} software; however future work is essential to focus on testing the robustness of the technique for accurate operation in noisy environments.

8. Acknowledgements
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9. References
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