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The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the Commandant or of the U.S. Coast Guard.

In-service Acoustic Emission (AE) Monitoring is capable of global surveillance of major structural detail regions for early detection of active cracks and damage evolution. The AE source severity is a measure of defect severity and the associated risk to the structure, thus reducing the current uncertainty in structural evaluation based on conventional inspection and modelling methods. When combined with Strain Monitoring and the latest developments in Fracture Mechanics Analysis it is a powerful tool for fatigue crack detection and through life damage assessment with the potential for improving platform availability. This paper outlines the underlying physics of stable fatigue crack growth in metals and the acoustic emission produced by the associated micro-fracture events. Examples are given of in-service global AE surveillance of ship hull structural details. New analytical software for modelling fatigue crack growth and the associated acoustic emission, incorporating the latest developments in our understanding of the mechanics of fracture on an atomic scale, is described. The AE sensing frequency band used to detect fatigue damage in marine steel structures is usually between 50 and 300 kHz, depending on the background noise. The maximum acceptable defect size defines the required AE ‘detectability’. The detectability depends on the magnitude and rate of the crack growth steps and this decides the sensor spacing and duration of monitoring for reliable detection, location and evaluation purposes. Important additional information for fatigue damage assessment and crack life prediction is the nominal cyclic strain at key locations in the subject structural details of interest. This crack life prediction, together with the AE, gives a structural fatigue response profile experienced by the ship. Knowledge of the operational and environmental profiles associated with the measured AE will provide a basis for structure lifecycle management. Provisional results are given for potential fatigue sensitive structural detail on the “USCGC BERTHOLF” as part of the USCG VALID Project. A similar larger scale application on a UK naval ship is outlined.

INTRODUCTION

This paper describes the application of in-service acoustic emission (AE) and strain monitoring for locating stable propagating fatigue cracks in ship hull structures. It describes a new fracture mechanics approach to fatigue damage assessment and crack life prediction as the basis for the interpretation of results. Provisional results are given for potential fatigue sensitive structural details on the “USCGC BERTHOLF”, as part of the USCG VALID Project. A larger scale application on a UK naval ship is outlined. Unless otherwise stated, reference to acoustic emission monitoring in the paper implies in-service continuous monitoring for detection and location of fatigue cracks.

The acoustic emission effect in metals

Portevin and Le Chatelier (1923) were among the first to report noise (petit bruit sec) accompanying stress jumps in metal (aluminium) during plastic deformation. The weak ‘crackling’ and ‘ticking’ sounds coincided with the appearance of striations, Luder lines, on the surface of the samples. We refer to this noise as acoustic emission (AE) and the plastic deformation as Portevin Le Chatelier yielding, see examples Figures 1a and 1b (Fleischmann, 1985). The noise is wide-band, extending from audio to high ultrasonic and even GHz frequency (heat) associated with the breaking of atomic bonds (Fitzgerald, 1966).

If the applied load is reduced to zero at any point during the deformation and increased to the previous high level, AE activity will recommence only when the previous high stress is exceeded, the work hardened material behaving perfectly elastically up to this point with the same modulus as the undeformed material. The effect was first reported by Kaiser (1950) in his PhD Thesis and is referred to as the Kaiser effect. At the point of fracture instability the material is critically work hardened and behaves in a brittle elastic manner, hence the applicability of Linear Elastic Fracture Mechanics (LEFM) for crack growth prediction. The fall-off in AE activity as the deformation proceeds, Figure 1a, is a consequence of the transition from discrete to continuous deformation at a limiting value of stress determined by the mechanical properties of the material. This was eloquently explained by Edwin Fitzgerald (1966) in his book “Particle waves and deformation in crystalline solids”. Combining the wave mechanics approach with classical fracture mechanics provides a quantitative basis for interpretation of AE results.
By the late 1960s interest in AE as a non-destructive test (NDT) method was growing fast (Dunegan, 1968; Pollock, 1968). The 1970s saw the appearance of commercially available multi-channel acoustic emission source location systems, their development being driven by industry’s appetite for improved non-destructive testing tools. The American and European Working Groups on Acoustic Emission were formed at this time, which continue to this day, and in January 1982 the first edition of the Journal of Acoustic Emission was published by the Acoustic Emission Group of the University of California, editor Kenji Ono (1982). A key European milestone was the adoption in 1991 of acoustic emission testing (AT) as an NDT method under Working Group 7 within the Commission for European Nons Technical Committee 138 (CEN, 2005) – Non-destructive testing.

The nature and power spectrum of acoustic emission depends strongly on the magnitude and duration of the physical events occurring in the material (Rogers, 2001) namely:

i) ‘Continuous noise’ form many uncorrelated low energy dislocation events (atomic imperfections)

ii) ‘Burst type noise’ due to the coordinated motion of many dislocation events (a dislocation avalanche)

iii) Relatively high energy bursts from micro-fracture events associated with stable crack growth e.g. fatigue and stress corrosion cracking.

The acoustic emissions of interest to the structural engineer are the stress waves produced by micro-fracture events accompanying stable crack growth in metallic structures and pressure equipment, the subject of this paper.

Stable fatigue crack growth in metals is a ‘step’ process (Rogers, 2001; Davidson, 1992) where each step is preceded by a relatively long period of plastic slip and the creation of Luder lines (fatigue striations) on slip planes, see Figures 2a and 2b (Suresh, 1998). It is this process of steady embrittlement of the crystal grains of metal at the crack tip which eventually leads to local fracture instability i.e. a crack step which is typically of the crystal grain-size dimension.

The cumulative strain energy necessary to achieve local fracture instability over a small distance ahead of the crack tip (the threshold plastic zone size) is considerably greater than that required to produce fracture once the material is critically embrittled. Table 1 gives the relative energy of plastic deformation events and micro-fracture events together with their corresponding characteristic frequencies. The individual plastic deformation events are considerably less energetic than microfracture events, even when the deformation involves slip over many planes of atoms and the creation of equi-spaced lines of interstitial atoms (Luder lines). Micro-fracture events by comparison generate large amplitude stress waves (bursts) with a ‘characteristic’ high frequency given by the fracture velocity divided by twice the crack growth step, typically (250 m/s)/(2x50 microns) = 2.5 MHz in embrittled grains of medium strength steel. The wavelength of the resulting compression sound wave is around 2 mm i.e. much greater than the crystal grain size and is therefore little affected by grain size during propagation. The resulting acoustic emission can be detected at distances up to 4m under typical marine platform operational conditions. A feature of fatigue crack growth AE which aids detection in high background noise is the associated fretting between the ‘clean’ un-oxidised fracture faces following a crack growth step. This results in ‘ring on’ noise from the crack front on successive loading cycles, which eventually dies out if there is no further crack growth (Rogers, 2001).
There are two ways of applying the AE technique for crack detection and location:
(a) During a ‘controlled’ overload test, e.g. a proof test, and
(b) For continuous in-service monitoring

**Acoustic Emission Testing (AT) of pressure equipment and structures during monotonic loading**

This is a controlled overload test to between 1.1 and 1.5 times the safe working pressure, depending on the application, similar to the manufacturer’s proof test. It relies on any cracks present propagating a small amount in a stable manner during the test. The aim is to locate structurally significant defects e.g. fatigue and stress corrosion cracks. Fatigue cracks are usually more difficult to detect during an overload test. The crack depth must be sufficient for the stress intensity to exceed the ultimate strength of the material a short distance ahead of the crack tip to achieve local fracture instability. At this point the material will have become sufficiently embrittled (work hardened) to trigger a stable crack jump. Further growth is arrested by crack tip blunting, effectively signalling the end of the test. The crack tip will require ‘re-sharpening’ by the original crack growth mechanism for the embrittlement and crack growth process to continue. The number of burst signals expected from stable growth of a fatigue crack during an overload test will in general be small, and may not be discernable above innocuous background noise sources. In the case of stress corrosion cracking however, it is likely that many metal grains will already be sufficiently work hardened to fracture and generate detectable AE during the overload test.

AE signals from the plastic deformation process, preceding a micro-fracture event are, in general, of insufficient energy to be of value for crack detection and location purposes when using a practical sensor spacing of typically 3 to 4m. Determination of the maximum allowed sensor spacing for ‘planar location’ of AE sources is considered later in the paper (CEN, 2005).
In-service acoustic emission monitoring

The alternative to AT during an overload test is to continuously monitor the structure. This is considered the best option as it detects stable crack growth under actual operational loading and environmental conditions. The equipment requirement however is more demanding but can be justified in terms of improved detectability and damage diagnosis. This paper focuses on in-service continuous AE monitoring for the detection and location of stable propagating fatigue cracks (Rogers, 2001). By continuously monitoring a vessel or structure for a period of time, usually several months, depending on the maximum acceptable defect size, enhanced assurance of structural integrity can be obtained. The period of monitoring must be predetermined as adequate for a measurable amount of crack growth to occur from any structurally significant defects (cracks) present, referred to as the minimum detectable crack growth rate. This must encompass at minimum one crack growth step over the crack front but at least three steps are recommended.

The most commonly encountered structural degradation mechanisms are fatigue and stress corrosion cracking, both of which are strong sources of acoustic emission. They involve steady embrittlement of the crystalline grains of metal at the crack tip to the point of local fracture instability resulting in a crack growth step. The cycle then repeats at increasing rate with increasing crack depth.

The stepped nature of the fatigue crack growth process has been modelled by a combined fracture mechanics and particle wave mechanics approach (Rogers, 2013). This new approach provides a quantitative model for specifying the required sensor sensitivity and band width for detection of stable crack growth in different metals. By relating the measured acoustic emission to the loading (strain energy driving the crack) and the associated stress concentration due to component geometry, it is possible to predict the crack growth corresponding to the observed AE activity and to estimate the defect size and crack life, (Rogers, 2013).

FATIGUE DESIGN ASSESSMENT OF SHIP HULL STRUCTURES - APPLICATION OF ACOUSTIC EMISSION MONITORING

As part of the classification process that a ship in service continues to meet the maintenance requirements of class, the Condition Assessment Programme (CAP) produced by the classification authority specifies that hull inspection surveys, guided by a Fatigue Design Assessment (FDA) of the hull structural detail, shall be performed at periodic intervals. The FDA is primarily an assessment of design, not current condition, and makes no provision for possible anomalies in structural connections and material quality and their consequential effects on fatigue life. It considers each structural connection, its location and the ship’s trading/operating pattern to identify where fatigue problems are likely to occur so that the through life periodic inspections can be focussed on the stress ‘hot spots’.

Inspection usually comprises an initial visual survey to detect cracks revealed by e.g. cracked paintwork, via associated paint discolouration due to corrosion. This may occur when the crack faces part sufficiently, as with deep cracks close to ligament failure. Closer examination of the structurally significant welds may be performed using an appropriate non-destructive testing (NDT) method e.g. dye penetrant, magnetic particle, eddy current or alternating current field method, to reveal smaller surface breaking cracks. Ultrasonic testing or the ac potential drop method may then be used to size a crack once located. The work is operator intensive, invasive, requires extensive logistical support, is time consuming and consequently expensive. In addition there remains the uncertainty associated with crack detection and sizing. Also, it provides only a snap shot in time of the existence of possible anomalies and no information on their structural significance. Damage diagnosis and the evaluation of its effect on the structure are separate functions.

The aim of Acoustic Emission and Strain Monitoring is to determine the state of critical structural details of the ship’s hull on the basis of the AE signal characteristics, measured over a period of time representative of the full range of dynamic loading of the hull. This is usually, at minimum, a complete 6 to 8 months deployment in e.g. the North or South Atlantic.

Acoustic emission monitoring is the only inspection method capable of passive global surveillance of major structural areas for crack detection. The method locates ‘acoustic hot spots’ associated with growing cracks and measures their severity with respect to service operating (loading) conditions. The source severity is a measure of defect severity and the risk to the structure, thus reducing the current uncertainty in structural evaluation based on conventional inspection methods.

Features of AE monitoring which differentiate it from more familiar NDT methods of crack detection are:

(i) An array of passive AE sensors is attached to the structure so as to provide 100% volumetric surveillance of the subject structural detail

(ii) Continuous monitoring is necessary for a period of time sufficient to achieve a specified minimum amount of crack growth for detection purposes. This depends on the crack growth rate, hence crack depth, and the maximum acceptable defect size from a structural design and fracture mechanics assessment.

(iii) It is also necessary to continuously monitor a parameter related to the environmental loading, e.g. strain at one or more suitable locations.
Fig. 3a) Fatigue crack development in a tubular brace/chord weld line from crack initiation to failure, measured by the MPI and ACPD methods and b) corresponding normalised crack depth and crack area as a function of loading cycles to failure.

(iv) AE from crack growth steps is detected and correlated with the environmental stressing for source severity grading purposes.

(v) A crack life and damage assessment analysis is performed to evaluate source significance and the associated risk to the structure.

FATIGUE ENDURANCE OF SHIP HULL STRUCTURES

Fatigue damage assessment in marine structures requires detection of cracks which range in size from around 10% through wall thickness in critical welds to a meter or so in length at less sensitive locations depending on material toughness. Figure 3a shows the progress of a fatigue crack in a tubular steel node joint as used in Offshore Production Platforms (Rogers, 1987). The Magnetic Particle Inspection (MPI) method was used to locate the crack and measure its surface length. The Alternating Current Potential Drop (ACPD) method was used to determine the crack depth. In the latter case, a low voltage high frequency current is passed between electrodes attached to each side of the crack, on a line perpendicular to the crack. A voltage probe, comprising two sharply pointed titanium electrodes, with spacing ‘b’ typically 10mm, is used to measure the potential difference across the crack $V_1$ and just to the side $V_2$. Since the electrical resistance relates to the ‘skin depth’, the voltage is proportional to the current path length, and the crack depth ‘ℓ’ is given by:

$$2(ℓ + b)/b = V_1/V_2$$

Platform node joints, as with ship hull structures, are damage tolerant and can support a large fatigue crack without seriously affecting the load bearing capacity of the associated structural element (Stacey-Sharp and Nichols, 1996). In this example, the 360 deg. brace weld (wall thickness 32mm) has been developed into a straight line and the crack surface length and crack depth shown at constant intervals of stressing cycles from initiation through to failure of the joint. When the crack depth reached approximately 50% through wall thickness, its critical value corresponding to the fracture toughness and strength of the material, the crack growth moved principally to the sides. At this point the joint was just 45% into its life, defined as the loss of structural stability and imminent failure. The crack depth in this case is not solely the residual strength determining factor. Figure 3b shows the same crack data where the crack depth has been normalised with respect to wall thickness and the crack area normalised with respect to the crack area at failure. Note that the crack area when the depth was 50% through thickness was just 5% of the critical crack area at failure. From this point, crack growth through the thickness slowed considerably as the load was shed to the sides driving the growth in these directions. In this example, it appears the rate of increase in crack area is a better indicator of the residual strength of the joint, provided the material remains on the upper shelf of the ductile-brittle transition curve (Stacey et al, 1996).

DETECTION OF ACOUSTIC EMISSION ASSOCIATED WITH STABLE FATIGUE CRACK EVOLUTION.

Initial considerations

Acoustic emissions are broad band wave packets of sound energy radiating from discrete physical events associated with crack evolution in metals. However, the corresponding AE signal from a resonant AE sensor is a very convoluted function of the original wave shape, due to the transfer function of the sensor and the sound propagation medium. This is illustrated in Figure 4, which shows the true out of plane displacement of a simulated stress-wave using a Hsu-Nielsen source (0.5mm or 0.3mm diameter pencil lead break,
lead hardness grade H2) on a test plate, measured using a Laser interferometer, and the corresponding signal form a resonant AE sensor. It is very important, therefore to distinguish carefully between the waveform of the stress-waves in the material and the burst signal waveforms generated by the sensor. These often bare little relationship to each other, apart form the proportionality of their peak to peak amplitudes close to the source event (within a few plate thicknesses).

The different types of stress wave from a micro-fracture event are illustrated schematically in Figure 5. Two compression wave lobes and four shear wave lobes are produced, each wave type travelling at a different velocity with different wave propagation and attenuation characteristics

Mode conversion at the surface generates surface waves which propagate with their own characteristic velocity and attenuation. A single event therefore produces a complex series of waves which change in character as the sound propagates through the structure. In addition to the complexity of the wave train from a single AE event, the high frequency end of the power spectrum will be attenuated most, leading eventually to just plate waves surviving in the far field, i.e. at distances greater than typically 20 to 40 plate thicknesses from source.

Hence in order to maximise the range of detection of AE it is usual to choose a sensor which is resonant around the primary plate wave (lamb wave) modes for the test plate. The sensing frequency used will also depend on the maximum acceptable defect size and the background noise level.

The first step therefore with an in-service acoustic emission monitoring application is to investigate the background noise and sound propagation in the structure to determine the optimum sensing frequency and sensor placement consistent with the required ‘detectability’ of AE, in accordance with EN14584 (CEN, 2005). All aspects of the scope of work are considered at this stage.

**Choice of sensing frequency**

The sensors are usually of the resonant type with a response near the centre of an octave frequency band within the range 50 kHz to 2 MHz depending on the application. The choice of sensing frequency depends primarily on the following:

(i) The magnitude of the micro-fracture events and the fracture velocity.
(ii) The structure geometry, plate thickness, surface coating and surrounding fluid medium.
(iii) The character of the background noise.
(iv) The attenuation characteristics of the sound propagation medium, with particular attention to welds and geometry.

The efficient utilisation of sensors has important logistical and commercial implications when global surveillance of major structural elements is required.

**Stress-wave attenuation (losses), detectability ‘κ’ and maximum allowed sensor spacing.**

The detectability ‘κ’ is a measure of the sensitivity of the monitoring equipment to micro-fracture events of a specified magnitude relative to the standard 0.5mm Hsu-Nielsen source. The sensor placement shall be consistent with the required
detectability for the test. The detectability corresponds to the difference between the signal amplitude of the smallest AE event that requires detection and the signal amplitude from the standard Hsu-Nielsen source at the same position. The value of ‘κ’, together with the background noise level and the sound attenuation curve(s) for the structure, decide the maximum sensor spacing that can be used for the test. This shall be consistent with the requirement for detection by a minimum of three suitably positioned sensors for AE cluster location purposes.

The methodology for determining the maximum allowed sensor spacing ‘\( r_{\text{max}} \)’ for a specified detectability ‘κ’ is shown in Figure 6. It is given by the intersection of the attenuation curve for the Hsu-Nielsen source with an evaluation threshold ‘\( A_e \)’, set ‘κ’ dB above the detection threshold ‘\( A_d \)’. The detection threshold is set ‘X’ dB (typically 6dB) above the peak background noise Average-Signal-Level (ASL).

The recommended minimum value of ‘κ’ for in-service detection of stable fatigue crack growth or stress corrosion cracking is 18dB. However, good practice is always to strive for as large a value of ‘κ’ as possible.

**LOCATION AND GRADING OF AE SOURCES**

In-service AE monitoring of offshore production platforms is well established (Rogers, 2001) and has provided a comprehensive field test and laboratory test data base on fatigue crack growth AE in structural steel joints e.g. Figures 3 and 7. The following methodology for resolving AE sources in high background noise and grading the sources in relation to fatigue damage is based on this experience, which relates directly to ship hull structures.

![Diagram](image1)

**Fig. 6.** Determination of the maximum allowed sensor spacing ‘\( r_{\text{max}} \)’ from the attenuation curve, for a particular detectability ‘κ’, in accordance with EN14586.

![Diagram](image2)

**Fig. 7.** Amplitude distribution of AE burst signals for a fatigue crack in a tubular welded joint of BS4360 grade 50C steel at different stages of crack growth (values of alternating stress intensity factor ΔK).

![Diagram](image3)

**Fig. 8.** Methodology for grading sources of AE from fatigue crack growth in ship structural steel welds according to signal amplitude, measured in sensing frequency band 100–200 kHz.
Database
Before considering an in-service AE monitoring application it is necessary to investigate the character of the acoustic emission that can be expected from stable fatigue crack growth in the subject material, emulating as near as possible the in-service environmental and loading conditions. The data contribute to the material data base. The sensing frequency band should be the same as that intended for use in service. Figure 7 gives laboratory fatigue test results for a tubular welded joint of BS4360 grade 50C steel at different stages of crack growth, measured using 150 kHz resonant sensors (Rogers, 2001). Note the general increase in signal amplitudes with increasing stress intensity factor (crack depth). This is the basis of the AE source severity signal amplitude grading criteria.

Amplitude grading of AE sources in relation to through thickness crack depth using the sound attenuation curve
The sound attenuation curve for the subject structural detail is determined using the Hsu-Nielsen source, see curve defining the boundary between bands 'c' and 'd' in Figure 8. The curve in this case corresponds to the most severe (worst case) sound attenuation in a steel shell structure (25mm wall) with one face in contact with sea water and the other face, the sensing side, in contact with air. The remaining curves correspond to detectability values of 15dB and 30dB relative to the Hsu-Nielsen source. Different curves will apply for different materials, component geometries and sensing frequency bands. These curves define four bands of signal amplitude a, b, c and d, corresponding to different stages in the fatigue crack growth process, from initiation to rapid growth close to failure, see related bands in Figure 7. The amplitude grading criteria are as follows:

a) Band ‘a’ relates to ‘insignificant’ sources
b) Band ‘b’ relates to the signal amplitudes expected from micro-fracture events occurring at the crack tip during the early stages of fatigue crack growth.
c) Band ‘c’ relates to crack growth increments involving the fracture of several crystal grains simultaneously over a significant width element on the crack front, expected when the crack is around 20 to 30% of the critical depth.
d) Band ‘d’ relates to ‘major’ events which increase in number as the crack approaches the critical depth, corresponding to ligament failure (yielding), and dominate the emission when the crack breaks through wall thickness in major structural steel welded joints.

In the above case the maximum range of detection of events with amplitude 15dB less than the Hsu-Nielsen source using the detection threshold 33dB$\text{ae}$ is 4.0m, i.e. the boundary between ‘b’ and ‘c’, corresponds to detectability $\kappa = 15$dB. In the same way, the boundary between bands ‘a’ and ‘b’ corresponds to $\kappa = 30$dB. The maximum sensor spacing for $\kappa = 18$dB, i.e. a signal amplitude 18dB below the Hsu-Nielsen source, is 3.3m.

Source location in Delta-T space and grading according to signal amplitude
The primary method of filtering used to extract ‘true’ AE source data from background noise is based on the ‘sharpness’ of the ‘location clusters’ in delta-T space. A delta T is the difference in the arrival time of a stress wave at any two sensors. Delta Ts are measured by the AE source location equipment relative to the first hit sensor of an array, e.g. see column 4, Table 2. The word ‘hit’ relates to the detection of one AE burst by a sensor channel. Assuming a constant velocity of sound, each delta T corresponds to a delta X and vice versa. Due to uncertainty associated with wave type and hence wave velocity, it is usual practice to identify AE clusters, working directly with the measured delta Ts; of which there are (n – 1) in number, where ‘n’ is the number of sensor channels which detects a stress wave (no. of hits). The raw data are ‘clustered’ with respect to (i) the order in which the sensors are hit and (ii) the corresponding delta-Ts within typically 4μs steps, and the results tabulated in order of significance. Table 2 shows the top 10 clusters for major events with sensor hit order 10:9:12:11, detected in a brace/column node joint of an Offshore Platform during a storm, based on four hits and three delta Ts to ±4μs. Notice the similarity in the delta T sets for each cluster.

A [2D] delta T space location map is then produced, where the ‘X’ and ‘Y’ axes correspond respectively to the delta T's derived from selected pairs of sensors.

Table 2. Top 10 clustered data records with respect to 4 Hits and 3 Delta Ts to ±4μs for major events during storms 1 and 2.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Burst count</th>
<th>Sensor hit order</th>
<th>Delta T (μs)</th>
<th>Burst Amplitude (dB$\text{ae}$)</th>
<th>Average Signal Level (dB$\text{ae}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>169</td>
<td>10:9:12:11</td>
<td>532:673:776</td>
<td>78.8:54.1:42.2:51.3</td>
<td>34.1:35.5:34.4:32.9</td>
</tr>
<tr>
<td>2</td>
<td>112</td>
<td>10:9:12:11</td>
<td>534:680:774</td>
<td>79.2:54.5:42.0:51.7</td>
<td>34.0:35.7:34.5:32.8</td>
</tr>
<tr>
<td>3</td>
<td>83</td>
<td>10:9:12:11</td>
<td>532:673:743</td>
<td>81.2:56.2:43.3:53.2</td>
<td>33.8:35.5:33.9:32.8</td>
</tr>
<tr>
<td>4</td>
<td>27</td>
<td>10:9:12:11</td>
<td>532:667:722</td>
<td>81.7:56.8:50.5:54.5</td>
<td>33.0:34.5:33.1:31.5</td>
</tr>
<tr>
<td>5</td>
<td>27</td>
<td>10:9:12:11</td>
<td>530:677:723</td>
<td>81.0:56.8:50.3:54.0</td>
<td>33.5:33.7:33.4:32.3</td>
</tr>
<tr>
<td>6</td>
<td>22</td>
<td>10:9:12:11</td>
<td>539:673:774</td>
<td>80.0:55.1:42.5:52.6</td>
<td>34.6:36.3:35.0:34.3</td>
</tr>
<tr>
<td>7</td>
<td>21</td>
<td>10:9:12:11</td>
<td>532:672:724</td>
<td>81.5:56.9:50.4:55.0</td>
<td>33.5:34.9:33.5:33.0</td>
</tr>
<tr>
<td>8</td>
<td>18</td>
<td>10:9:12:11</td>
<td>527:673:777</td>
<td>80.2:54.9:42.9:52.8</td>
<td>34.3:37.2:35.0:33.1</td>
</tr>
<tr>
<td>9</td>
<td>16</td>
<td>10:9:12:11</td>
<td>530:664:740</td>
<td>81.9:56.6:49.9:54.2</td>
<td>33.8:34.8:33.7:33.0</td>
</tr>
<tr>
<td>10</td>
<td>12</td>
<td>10:9:12:11</td>
<td>508:669:725</td>
<td>82.1:57.6:51.0:55.3</td>
<td>34.3:36.8:35.1:32.8</td>
</tr>
</tbody>
</table>
This is best illustrated by considering a square array of sensors, with origin at the centre of the square. Using the delta Ts derived from diagonally opposite pairs of sensors, the delta T space representation of the ‘real’ space is also a square with origin at its centre, but rotated 45 degrees to the side. Figure 9 shows results for all data with the hit order 10:9:12:11. In this case the ‘X’ axis corresponds to (time to sensor 11) minus (time to sensor 9) and the ‘Y’ axis (time to sensor 10) minus (time to sensor 9), taking account of the sign of the result.
Once the clusters have been identified, various methods are used to locate their source in 'real' space, e.g. Tobias algorithm (Tobias, 1976), Apollonius Construction and Weld Mapping in delta T space (Rogers, 2001). The more sensor hits in the clustered data records (Table 2) the more reliable the source location.

The next step is to plot the AE cluster signal amplitudes as a function of distance from source, see Figure 10. This shows if the signal amplitudes and source location are consistent with the sound attenuation curve(s) for the structure. Importantly, the AE source can now be graded according to the appropriate amplitude grading criteria for the test. In this example, the signal amplitudes fell predominantly within band ‘c’ but also extended marginally into band ‘d’. This suggested, by reference to the laboratory test data base, Figure 7, that the crack depth was around 30% of the nominal critical crack depth corresponding to the fracture toughness and ultimate strength of the material, which was subsequently confirmed by UT inspection of the suspect area.

**Cumulative AE activity – related to crack area - and correlation with load/stress parameters.**

The relationship between the loading and the cumulative AE activity, Figure 11, is an important indicator of potential damage. The Figure shows the cumulative burst count for the same fatigue crack data as in Figure 9 together with the nominal axial cyclic strain in the brace. Both the ‘sharpness’ of the primary location clusters (the twin peaks in Figure 9) and the correlation of the AE activity with stress are strong indicators of a propagating fatigue crack.

**CHARACTERISTICS OF CRACK GROWTH - ‘TRUE’ AE SOURCES**

**Spectrum**

The characteristic features of ‘true’ AE sources associated with stable crack extension result from the nature of the source mechanism, which has certain unique features compared with the background noise normally encountered in practice. The most important of these is the broad band character of the stress-wave packet which resembles a sharp single cycle pulse close to source, Figure 4. The shape of the pulse and hence its bandwidth is defined by the magnitude of the crack growth step $\Delta L_c$ (Rogers, 2001), given by

$$\Delta L_c = d_i (\Gamma E_i / \sigma_{ui})^2$$  \hspace{1cm} (1)

and the velocity of fracture is given by:

$$v_f = \sqrt{\sigma_{ui} / \rho}$$  \hspace{1cm} (2)

where $d_i$ and $E_i$ are the inter-atomic distance and elastic modulus in the direction of slip, $\Gamma$ is a constant close to unity depending on the crystal lattice structure, $\sigma_{ui}$ is the true ultimate strength of the crystal grains, $\rho$ is the mass density of the metal ($= m_1 / d_i^2$ for a simple cubic lattice) and $m$ is the atomic mass. These parameters define the characteristic frequency of the stress-wave given by:

$$v_f = 1/2 \pi$$  \hspace{1cm} (3)

where $\tau = \Delta L_c / v_f$. The magnitude of the event $M_{AE}$ is defined as the logarithm of the fracture area relative to the reference value $1\mu m^2$ e.g. a fracture event of area $10^4\mu m^2$ corresponds to $M_{AE} = 4$. This is analogous to the Richter Scale where the reference value approximates to a $1m^2$ fracture event in concrete (Rogers, 2005) and Magnitude 4 corresponds to a $10^4$ $m^2$ fracture.

Substituting suitable values for the material properties of structural steel into equations 1 to 3 gives a characteristic frequency around 2 MHz for the compression stress-waves associated with a crack growth step, close to the source. The associated short duration (wide band) pulses of sound, Figure 4, are an important feature of micro-fracture events accompanying stable crack growth in metals.

**Burst rate**

Another important characteristic of the acoustic emission from stable crack extension is that microfracture events tend to occur in rapid succession over short periods during the process of crack extension. In the case of fatigue, this process is accompanied by crack face friction events resulting from ‘sticking and breaking’ of points of contact on the newly created unoxidised fracture faces at the crack tip. The occurrence of short duration wave packets in quick succession from a localised point on the component (the crack) is a useful feature for crack detection in high background noise originating from machinery, mechanical impacts and hydrodynamic sources.

**Stress-wave attenuation**

As the sound propagates through the material it experiences high attenuation (energy loss) as a result of geometric spreading of the wave front (from what is essentially a point source) and ‘losses’ due to interaction with the propagation medium and surroundings. The high frequency end of the power spectrum is affected most. This high attenuation however can be useful as an aid to source location verification.

**Optimum sensing frequency band for crack detection and location**

By the time the sound has propagated typically 20 x plate thickness, plate waves (Lamb waves) begin to dominate the wave spectrum. Plate thickness is therefore a further important factor in determining the optimum sensing frequency for crack detection when using as large a sensor spacing as possible. Background noise within the same frequency band as AE, originating from outside the perimeter of the sensor array, will
be attenuated similar to acoustic emission and therefore the final choice of sensing frequency is a compromise between maximising the signal amplitude and minimising the effect of background noise.

Location cluster
The shape and distribution of ‘location clusters’ of AE events in delta T space, using an appropriate mesh size (typically 4μs), provide a powerful way of resolving ‘true’ sources of acoustic emission in high background noise. Figures 12 shows raw AE data from a fluid transmission line analysed using (a) course and (b) fine mesh ‘delta T matrix’ filters. The fine mesh filter clearly resolves crack growth related AE from the background noise which in this case originated from fluid particles impacting with the inside surface of the flow line.

AE activity
AE activity from a source meeting the above criteria for a propagating fatigue crack is a measure of the crack growth rate per cycle Δℓ/Δn given by the Paris law:

\[ \frac{\Delta \ell}{\Delta n} = C \Delta K^s \text{ m/cycle} \]  

(5)

where C and s are constants which take the values 6.9x10^{-12} and 3 respectively for a ferrite-pearlite steel (Rogers, 2001) and ΔK is the alternating stress intensity factor, given by

\[ \Delta K = \gamma \Delta \sigma_n \sqrt{\pi \ell} \] \( \text{MNm}^{3/2} \)  

(6)

where γ is a factor depending on the crack shape relative to the component geometry. Initially γ is close to unity but increases rapidly as the crack depth approaches the critical value at ligament failure. The crack growth rate therefore depend strongly on crack depth \( \ell \) and the nominal stress range \( \Delta \sigma_n \), e.g. see experimental data for fatigue crack growth in full scale tubular welded node joints, Figure 13a. The different straight lines in the Figure define upper bounds to the crack growth rate in air (full circles) and sea water (open circles) and correspond to the standard Paris Law relationship for this steel and weld class.

The rate of crack growth steps increases by 3 to 4 orders of magnitude as the crack grows from its threshold value for valid fracture mechanics (around 0.25mm) to the critical depth at ligament failure (depending on the fracture toughness of the metal), see Figure 13b. This is reflected in the AE activity, e.g. see Figure 7.

AE activity approaching ligament failure
When a fatigue crack approaches the critical crack depth, acoustic emission activity is usually very intense even at low amplitude cyclic stress, considerably enhancing the detectability. This condition usually equates to the first visible indication of cracking, on which crack detection during routine surveillance of ship hull structures is often based. The latter is justified on the basis of the high damage tolerance of the welds and implies that the maximum acceptable defect size is the critical crack depth corresponding to ligament failure (local plastic collapse). Detection of such cracks by acoustic emission monitoring is relatively straight forward, requiring a lower detectability than would normally be used and allowing the use of a larger transducer spacing at corresponding reduced equipment cost.

Fig. 12. Delta-T space representations of the same data using (a) course and (b) fine mesh filters, showing how crack growth AE is resolved from (in this case) fluid noise, using a fine mesh filter.
Modified Paris Law to account for incremental crack growth

Fig. 13a. Measured fatigue crack growth rates for full scale tubular steel node joints in air and sea water (Sharp-Stacey and King, 1995).

CHARACTERISTICS OF INTERFERENCE NOISE - ‘FALSE’ AE SOURCES
The most frequently encountered false alarms in acoustic emission monitoring result from sources which exhibit one or more of the characteristics of growing cracks. These include:

a) Welds of poor quality with innocuous non metallic inclusions which can fracture/disbond under cyclic stress without developing a crack.

b) Localised fretting/abrasion/friction at contact points with other metal components within the sensor array perimeter.

c) Friction between two components as a result of relative movement due to vibration or differential thermal expansion e.g. at pipe support saddles.

d) Repetitive impacts of loose parts or from particles/liquid droplets impacting at the same point/area on a structure.

e) Occasional use of mechanical tools or localised abrasion of the metal surface during maintenance work; however this is not usually undertaken when the structure or vessel is in operational service and the loading most severe e.g. storm conditions at sea.

f) Disbonding and fracture of brittle coatings and corrosion.

g) Opening/closing of door latches associated with watertight bulkhead

h) High pressure leaks and certain low pressure leaks.

Background noise sources can usually be identified and rejected on the basis of their location cluster characteristics in delta T space, as described above. Such filtering to a degree is usually incorporated into the data acquisition system. If the AE source is outside the perimeter of the sensor array, the noise may be rejected directly by allocating a ‘guard’ sensor to the source and invalidating the sound on the basis of sensor hit order. By the careful placement of sensors on the component, guard sensors may still be used for the detection and location of ‘true’ sources of acoustic emission, provided they always appear further down the hit order in the burst record descriptor. However, if the background noise is continuous as monitored by the average signal level, see final column of figures in the cluster data listing Table 2, and exceeds the detection threshold, then leading edge burst (LEB) detection and timing is no longer possible. If the peak AE signal still exceeds the background noise then peak detection and timing will still be possible. This feature is usually incorporated as back-up in the event of fluctuating extreme background noise. Using appropriate monitoring equipment and test procedure, background noise is generally not problematic, as illustrated by the ASL values in Table 2. These data were obtained on a column brace node joint in the wave splash zone during storm force 10 conditions in the Northern North Sea. Real time cluster and filter algorithms have become a standard feature of multi-channel AE data acquisition systems for fatigue crack detection in varying background noise conditions (Rogers, 2001).
APPLICATION ON “USCGC BERTHOLF”

Background
As part of the USCG Ship Fatigue Validation Project “VALID”, the gas turbine intake structural segment of “USCGC BERTHOLF”, located midships between the 01 and 02 levels, was selected for acoustic emission and strain monitoring. The subject segment, Figure 14, extended from Frames 44 to 46. Regions of this segment had been identified by the Coast Guard as potentially fatigue sensitive. The objective of the AE monitoring was to provide global surveillance of the subject segment to detect evidence of fatigue damage. The AE sensors were located at the corners of the three bulkheads making up the segment. In addition, strain transducers LC1 to LC6, were positioned at the 02 Level symmetrically about the major axis of the hull to measure axial strains, Figure 15.

Fig. 14.a) Isometric of the gas-turbine intakes showing AE sensor positions 1 to 16 and b) view from inside the Starboard segment looking Aft (strain gauges LC4 and LC3 on the underside of the 02 level are visible to the left and right in the centre of the picture).

Fig. 15a) Detail at 02 Level showing positions and orientation of strain gauges LC 1 to LC6 and b) strain gauge LC 5 and AE sensor S5 viewed from inside the gas turbine intake, Port.
**Preliminary Results**
Monitoring was continuous from 16 January to 17 August 2009. It included the VALID test programme of ship manoeuvres in the North Pacific Ocean.

**AE measurement**
Three sources of acoustic emission were detected, identified by the sensor hit orders 1:2:4:3, 3:4:2:1 and 10:11:9:2. The burst emission rate and signal amplitudes were consistent with possible micro-cracking associated with incipient fatigue, but being a new Cutter, the results could also be explained by the natural stress relieving (shake-down) of innocuous weld defects. The AE sources did not warrant investigation by NDT at the time. Source 10:11:9:2 located close to strain gauge LC4, which was approximately 300mm directly FWD of a Kawasaki fatigue damage sensor (Nihei-Muragishi-Kobayashi-Ohgaki and Umida, 2010) on the same surface at the 02 level, Figure 14b. The latter was directly below a Marin strain gauge F36S13 located on the outside surface at the 02 Level.

**Strain measurement**
Assuming a linear relationship between the measured nominal dynamic strain and the wave height, the measured cyclic strains at the 02 level for gauges LC5 and LC6, positioned close to predicted stress hot spots, were consistent with the peak principal stresses calculated by the US Coast Guard at these locations (as part of the original Structural Design Assessment).

**Fracture mechanics analysis**
Linear-Elastic-Fracture-Mechanics (LEFM) crack growth predictions (Rogers, 2013) for the period July 2009 to December 2012 were made using monthly stress amplitude/cycles histogram data (1 MPa bins) for the Marin strain gauges F47S1, F47S2 and F36S13. They were compared with the corresponding fatigue damage predictions using appropriate design S-N curve. Standard LEFM default parameters for BERTHOLF hull steel, together with the appropriate stress concentration factor $K_t$ and plate thickness parameter 'T', see Table 3, were used in the crack life predictions.

Table 3 LEFM default parameters used for the growth prediction using Marin gauge F47S1 data (Rogers, 2013).
The crack growth associated with each strain gauge, calculated to nine decimal places after each month, is given in Figure 16. This is an ‘effective’ crack growth, proportional to the plastic deformation damage. The ‘true’ crack growth corresponds to crack growth step occurring at the point of local fracture instability, defined by the threshold alternating stress intensity factor. The modified Paris Law, Figure 13b, is therefore required to reflect more closely the true crack growth and progressive damage process in the LEFM analysis.

Table 4 gives the predicted crack life assuming the “available” stress history data from 2009_08 to 2012_12 represents one block of loading cycles and this is repeated through to ligament failure. It should be noted that ‘Damage’ from the fracture mechanics stand point is defined by the ratio (crack depth $l$)/(critical crack depth $l_c$) such that $l/l_c = 1$ at ligament failure. This is different from the damage parameter determined using standard design S-N curves and the Miner’s Rule, which is a linear function of blocks of repeat stressing cycles to failure. However the LEFM analysis, using the standard default parameters, predicts the same fatigue life as the corresponding design S-N curve, as illustrated in Figure 16. It should be noted that a crack depth of 1mm in this example corresponds to an S-N Miner’s summation damage of 0.75 i.e. close to the value 0.8 used in the FDA for defining fatigue life.

The LEFM analysis of the data, using an initial crack depth of 2.64E-04 m, predicted that around 5% of the fatigue life of the subject structural detail at gauge positions LC5 and LC6 was used up between August 2009 and July 2011. This equated to crack growth of 0.025 mm from an initial depth of 0.264 mm, which is less than one crack growth step. If the initial crack depth was 1.36 mm (representative of the minimum detectable defect size using industrial NDT practice) then around 14% of the fatigue life would have been used up, corresponding to crack growth of 0.30mm or 8 crack growth steps. Such growth should readily be detected by AE monitoring.

Due to BERTHOLF’s anticipated docking for a significant period of time following the Valid sea trials, it was decided to
suspend the AE monitoring until the Platform had experienced cyclic stressing more representative of the full range of design loading conditions. The above fatigue analysis, depending on initial defect size, suggests that BERTHOLF may now have experience sufficient cyclic stressing to justify recommissioning of the AE monitoring of the subject structural segment, which is being considered.

APPLICATION ON A UK NAVAL PLATFORM
This application is part of an on-going programme of work with the aim of:

(i) Proving AE crack detection technology for verifying ship hull integrity on different types of platform under different operational conditions.

(ii) Defining the capabilities of the latest commercially available technology in support of through life inspection.

Background
The chosen segment of hull was aft of the last water tight bulkhead, immediately above the propellers and rudders. This was chosen due to the existence of a prior crack in a door frame within the segment, that was previously repaired, which appeared soon after the Platform entered service. It was also a general region identified for periodic inspection in the “Survey and Repair Guide” for the Platform. The monitoring covered the period April 2012 to May 2013 during deployments to the South and North Atlantic. It provided the opportunity to evaluate both ‘global’ and ‘local’ surveillance using two independent arrays of AE sensors, see Figure 18, namely

(i) A global array comprising 16 sensors (array 1) with sensor spacing 3 to 4 metre, which provided coverage of the complete structural segment, and

(ii) A local array of 4 sensors positioned at the corners of the subject door frame (array 2), to provide high sensitivity coverage of the doorframe and the immediate vicinity.

Four strain extensometers were used to monitor axial stress at accessible positions (i) close to the subject crack (gauges S1 and S2) and (ii) in a central vertical girder and a longitudinal girder (gauges S3 and S4), shown in Figure 18. In addition to providing supporting information for the interpretation of the AE results, the strain sensors provided an operational stress range response profile of the platform at this location for fatigue endurance assessment.

AE results.
At the time of the AE monitoring, no evidence of reoccurring crack growth was detected in the subject doorframe, but one AE source, indicative of an incipient fatigue crack or other weld anomaly was detected. The sensor hit order was 1:4:2:3 on array 2 and 16:15:17 on array 1. It can be seen in the delta T space representation for array 2, Figure 19, as a ‘sharp’ cluster near the perimeter of the doorframe between sensors 1 and 4.
Figure 18. (a) Isometric of subject structural segment showing AE and strain transducer positions and (b) the door frame with the subject crack.

Figure 19 gives different delta T space representations of the same data for the door frame. The delta Ts for the X and Y axes were derived from the arrival times of the sound at diagonally opposite sensors of the array namely: (time to sensor 4) – (time to sensor 2) for the X axis and (time to sensor 3) – (time to sensor 1) for the Y axis, taking account of the sign. In this way the origin in delta T space coincides with the centre of the array. The tendency for background noise (and AE sources) originating from outside the perimeter of the array to gather at the perimeter is a feature of delta T measurements and helps define the shape of the door frame in delta T space.

Fig. 19. DeltaT space location plots for the subject door frame (dashed outline) indicating a potential incipient fatigue crack, see ‘sharp’ peak corresponding to the hit order 1: 4: 2: 3. The pixel colours represent different ranges of AE burst count.
The sound attenuation curve for source 1:4:2:3 was inconsistent with the source being at the location indicated in delta T space for array 2 and therefore fell into this category of possibly originating outside the array. Closer examination of the data suggested it originated some distance away in the direction of sensor 16. The same source was detected by array 1 with the hit order 16:15:17 which appeared at the top of the clustered data records for sensors 15, 16, 17 and 18. Understandably, the burst count was reduced compared with that on array 2, due to the wider sensor spacing and the requirement for a minimum of three sensor hits for detection and location purposes. The source located close to sensor 16, at the corner of the associated bulkhead, and the signal amplitudes at the sensors of both arrays were consistent with this location, see Figure 20.

The AE activity from this source correlated well with the cyclic strain and met the amplitude criterion for a ‘Grade B’ AE source. However, the cumulative activity level (burst count) was low by fatigue crack growth standards and did not warrant investigation by other NDT method(s) at the time.

Both AE sources served to demonstrate the sensitivity achieved by remote monitoring during a typical deployment of the Platform and in a part of the ship subjected to high hydrodynamic noise and associated structural vibration.

Strain results
The cyclic strains originated primarily from wave motion and hydrodynamic propeller induced structural vibration (around 15 Hz). The calculated fatigue endurance of representative weld class detail within the subject segment of hull was consistent with the Fatigue Design Assessment. Hydrodynamic propeller induced vibration for a projected operating profile of high speed manoeuvres was estimated to contribute approximately 10% to the fatigue endurance.

CONCLUSIONS
1. Current practice for assessing hull structural integrity involves periodic inspection during planned shutdowns/turnarounds. In service AE monitoring can provide global surveillance of collections of details in structural regions for early detection of active cracks and damage evolution. It allows through life damage assessment guiding subsequent NDT for damage verification and crack sizing purposes.
2. AE monitoring therefore sheds new light on the ‘global’ fatigue aging of potentially fatigue sensitive regions by signalling active cracks and other damage. Sources of AE activity are located and graded in terms of related crack growth rate and hence crack size by reference to an experimental fatigue test data base for the steel.
3. When combined with strain monitoring at suitable locations in the same structural area, the estimated crack growth from the AE measurements can be modelled as a function of the strain energy input to the platform (cumulative cyclic loading) to predict the crack propagation life.
4. The fatigue life prediction is updated through life from the ship operating response profile obtained form strain data.
5. The inspection and maintenance strategy for the ship can be optimised by:
   a. Focusing NDT resources on the areas of most significant AE activity (acoustic hot spots).
   b. Improving platform availability by avoiding unexpected local structural failures and unnecessary long periods out of service.
   c. Scheduling maintenance according to the AE activity and operational stressing of the ship to minimise through life maintenance costs.

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