Structural Health Monitoring on Ships Using Acoustic Emission Testing

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Abstract

A joint development project has been conducted between a classification society, an AET system and service provider, a global container transportation company and a Trans-Alaskan Pipeline System (TAPS) tanker company. This pilot project examined the viability of acoustic emission technology as a screening tool for surveys and inspection planning. Specifically, in-service AET data were collected for a tanker trading between Alaska and the west coast of the United States and from container ships during voyages through the Pacific and Atlantic Oceans. This project has demonstrated the potential for applying this technology in the identified critical locations on these two types of vessels to more efficiently target surveys and inspections. The acoustic emission (AE) source identification and techniques used to locate the flaw locations and identify the different flaw mechanisms are discussed. This paper also establishes a standard AET procedure, as 1) test plan, 2) AET system installation and checks, 3) data acquisition and analysis, 4) reporting documentation, and 5) follow-up inspection. The results of this feasibility study can be used to support future marine/offshore field tests using AET on structures in operation.

Keywords

Acoustic Emission Testing; Structural Health Monitoring

Introduction

Current industry standards have established a practice of maintaining the life-cycle integrity of ship structures through design, corrosion protection, inspection, maintenance and repair. Periodic inspection and survey play a key role in maintaining life-cycle structural integrity. The primary purpose of inspections is to characterize the condition of the structure so that the risk of structural failures can be assessed and appropriate actions can be taken.

There is a marked trend in the marine industry to continually improve the management of structural integrity, and the shipping industry is taking a more proactive approach by embracing innovation and novel concepts. Real-time structural health monitoring can be advantageous in capturing the current condition of a ship’s structure, providing greater confidence in its structural integrity, reducing inspection/operation costs and offering the potential for life extension. To more accurately monitor and assess the operational condition of in-service ship structures, it is worthwhile to investigate the next generation of monitoring technologies and their ability to detect flaws and corrosion well in advance of failure.

One monitoring tool for providing early warning of flaws is acoustic emission testing (AET), which has been used successfully to detect flaws in marine structures during operation (Ternowchek, S 2012, Wang, G, et al. 2010, Anastasopoulos, A, et al. 2009). AET is used as a global, real-time monitoring, nondestructive testing (NDT) method for the assessment of the structural integrity of large-scale structures with an emphasis on metallic pressure vessels, cargo tanks and offshore structures (Lee, A, et al. 2013).

This paper reports on a joint development project between a classification society, an AET system and service provider, a global container transportation company and a Trans-Alaskan Pipeline System (TAPS) tanker company. This pilot project examined the viability of using acoustic emission technology as a screening tool for surveys and inspection planning. Specifically, in-service AET data was collected for a tanker trading between Alaska and the west coast of the United States and from container ships during voyages through the Pacific and Atlantic Oceans. This project has demonstrated the potential for applying this technology in the identification of flaws at critical locations on these two types of vessels to more efficiently target inspections.

The acoustic emission (AE) source identification and
techniques used to locate the flaw locations and identify the different flaw mechanisms are discussed. Additionally, a standard AET procedure, as 1) test plan, 2) AET system installation and checks, 3) data acquisition and analysis, 4) reporting documentation, and 5) follow-up inspection are established. The results of this feasibility study can be used to support future marine/offshore field tests using AET on structures in operation.

**Structural Health Monitoring for Ship Structures**

The current practice for marine structural surveys generally involves an initial overall visual survey, in which a trained surveyor accesses the structure, focusing on known problem areas and on any noted anomalies. Depending on the type of structure, this overall visual survey may be followed by close-up visual surveys and inspections and the investigation of critical areas using nondestructive testing (NDT) methods (liquid penetrant, magnetic particle, eddy current, ultrasonic inspection, etc.). These surveys are often labor intensive and physically demanding. There has been a significant interest in making surveys safer, faster, and more effective.

Continuous knowledge of the ship’s structural condition is needed to verify the reliability of the structural integrity. With current inspection resource constraints (Demsetz, L, et al. 1996), real-time structural health monitoring can be advantageous in helping survey efficiency (e.g. directing Surveyors to areas of interest, locating new discontinuities, validating repairs, etc.). An early warning system that provides information about crack activity and/or corrosion can reduce unscheduled maintenance and help to avoid catastrophic failure by monitoring the growth of known flaws, and capturing a ship’s structural condition in critical areas.

Although no standard process currently exists for Structural Health Monitoring (SHM), a process (Figure 1) was proposed by Muravin (Muravin et al., 2010) and adopted for the current study. This process is divided into four stages (Procedure Development, Sensing, Diagnosis, and Monitoring).

- **Procedure Development:** A SHM plan is developed based on the collection and analysis of information about: structural design, history of operation, repairs, survey results, applied loads and environmental conditions. In this plan, the critical areas of the structure are identified.
- **Sensing:** Sensors are installed in the identified critical areas and to collect in-service data which is analyzed and used to provide an early warning of structural failures and locate the flaw/defect. For this stage, AET is the proposed NDT method to conduct the structural condition assessment at critical areas and is used as a screening tool for survey planning.
- **Diagnosis:** From the Sensing stage results, the flaws/defects are identified, located, and assessed using close-up visual inspection (CVI), ultrasonic testing (UT), liquid penetrant (PT), magnetic particle (MT), eddy current (ET) and/or other NDT methods.
- **Monitoring:** Monitoring is performed continuously to evaluate flaw development rate and to distinguish between propagating and non-propagating flaws. For this stage, an AET system is proposed for monitoring the growth of flaws.

By locating and identifying flaws as they occur, a monitoring system could potentially yield a large reduction in risk. Additionally, an effective continuous monitoring system should:

- Be readily available to marine and offshore industries
- Provide early detection of flaws and corrosion
- Have limited or no disturbance to operation,
- Support screening tools that assist survey and maintenance planning.

With a track record of successful implementation in other industries, Acoustic Emission Testing (AET) is a potential structural health monitoring tool which can serve as an early warning system for the marine and offshore industries by meeting the above requirements.

**Background of AET**

**AET technology**

Acoustic emissions are the elastic energy waves that are spontaneously released by a material undergoing deformation. The acoustic emission signal reflects the dynamic internal stress redistribution within a material that occurs when an external stress is imposed on a component. The stress can be hydrostatic, pneumatic, thermal, or bending.

AET is a “passive” non-destructive testing method that has been used by the petrochemical industry since early 1980’s, with more than 22 fully accepted codes and standard practices published in ASME, ASTM and API (ASTM E 976-2010, BS 2011, Botten 1989, 1993, Pollock
Acoustic emission is very effective at identifying crack growth and propagation during fatigue tests, as it has been observed that different acoustic emission signal properties, such as cumulative count or energy, increase as the crack-growth rate increases.

In an acoustic emission test (Figure 2), piezoelectric transducers are attached to a structure. These sensors convert mechanical energy such as elastic waves into an electric impulse that is transmitted by wired cables or wireless communication to the AET computer.

It is important to be able to get good coverage of the areas of interest with the minimum number of sensors, without losing sensitivity (ability to detect the activity of interest). Before the structure is stressed or AET starts, an attenuation test (Figure 3) is used to determine the effective distance of the acoustic emission sensors for the given structural system being monitored. In this attenuation test, a series of Pencil Lead Break (PLB) tests are performed for attenuation measurements in accordance with ASTM E 976 (ASTM E 976-2010).

Then, the sensor positions are planned and implemented accordingly to provide complete coverage of the monitoring area. As the structure is stressed, the AET computer collects data. Parameters from each emission are measured and then stored within the system data logger. Data from each sensor is stored on separate channels along with the exact time that the events are detected. These data are analyzed both during and after the test.

For a successful application of AE in the maritime industry, signal discrimination and noise reduction are crucial. Acoustic emission waves can be generated from sources of interest, but are also affected by extraneous signal noise from the environment. Possible AE sources of interest include those that may be a result of crack initiation and/or growth, crack fretting (i.e. rubbing of crack faces as it opens and closes), corrosion, weld discontinuities, and impact. Given the nature of the typical marine environment, there are also other potential AE sources that can produce noise and may be of less interest. These AE noise sources may include fretting of bolts around hatch covers, mechanical friction, weather (e.g. wind, rain, snow), engines/machinery, loose parts (e.g. container tie-down rods on deck), or ship background noise from personnel and general operations (i.e. hosing down the main deck). Identification is critical to the subsequent analysis of AE data in order to discriminate between spurious noise sources and legitimate sources (e.g. cracks). In addition to signal discrimination, the analysis software should also be capable of noise reduction.

Signal discrimination and noise reduction are even more crucial when the AE system is used to detect corrosion activity. This is because corrosion is a very slow process and the signal strength of corrosion activity is not as strong as the one of crack propagation. For the successful detection of corrosion activity using AET, two approaches can be considered. The first approach uses the AE system to measure the emissions due to the electrolytic action between the steel and the oxides forming. In this approach, there is a need for a very quiet environment due to mild signal strength of electrolytic action. The second approach uses the AE system to capture the emissions that are generated as the oxides pop off when the structure is flexed in the tension / compression conditions. In this approach, a thicker oxide can produce stronger signal strength as the oxides pop off.

Another important feature of the AE software is the capability to locate the source of acoustic emission activities. This is achieved by adopting a triangulation scheme which calculates the distance between the origin of a signal and the position of the acoustic emission sensors by measuring the difference in time of signal arrival at each sensor. The speed that the acoustic emission signals travel in the material can be calculated from the material’s properties.

In order to acquire a reliable level of structural flaw detection, an appropriate testing process and analysis procedure for acoustic emission data is essential for the successful AET application.

**Overall Process for AET**

An overview of the steps recommended to lead to a successful AET result is shown in Figure 4 and a brief description of the process for AET is described as follows.

- Plan the Test: Before the test, prior knowledge needs
to be obtained and understood. This includes the test objective, project team selection, structural damage history, structurally critical areas, selection of an AET system, locations of acoustic emission sensors, acoustic emission sensor mounting method, and communication between acoustic emission sensors and AET computer.

- **Install Equipment**: During the installation of acoustic emission sensors and AET system, safety needs to be considered - safety of personnel, watertightness / weathertightness of cable penetrations, and intrinsic safety of sensors, power supply, and other equipment. After the AET system is installed, system checks must be performed using Pencil Lead Break (PLB) to confirm the functionality of sensors, preamplifiers and computer.

- **Collect Acoustic Emission Data**: During the operation, the data acquisition system should record acoustic emission data, operation information, strain information, stress information, etc.

- **Analyze Acoustic Emission Data**: The acoustic emission data could be analyzed in the field or in the office.

- **Create Interim Test Report**: The interim report should identify the areas with acoustic emission activity and recommend follow-up inspection for these areas.

- **Follow-up Inspection**: While AET can effectively identify potential sources of damage and their location in a structure, in order to obtain quantitative results such as flaw size and/or depth, other NDT methods (often ultrasonic testing) are necessary.

- **Monitoring**: The AE system can be installed in a critical area without observed crack as well as in a low risk area with a minor crack. This AE system should be continuously operated and can provide for the structural health monitoring of in-service ships.

- **Take Down Equipment**: Uninstall AET system.

- **Create Final Report**: The final report should identify the areas with acoustic emission activity and evaluate the flaw growth.

**Analysis procedure for acoustic emission data**

The acoustic emission data analysis procedure is critical to the success of the Acoustic Emission Testing. The procedure, shown in Figure 5, includes signature recognition, noise filtering, AE source location and identification of high acoustic emission activity.

![Figure 5: Procedure of Acoustic Emission Data Analysis](image)

In the procedure of noise filtering, the relevant indications are separated from non-relevant indications using the known signatures for structural defects. It has been postulated for many years that different defects would leave unique characteristic signatures (Figure 6) of AE signals (i.e. wave form). These characteristic signatures became a standard tool for Acoustic Emission data interpretation and noise filtering in the 1980’s.

![Figure 6: Unique Wave Form (Signature) for Each Defect](image)

Later, pattern recognition techniques came into use. With these more advanced techniques, the analysis looks for clusters in a multi-dimensional space having the measured features (or derivatives of them) as axes. These techniques...
are powerful but it takes time and special skills to use them. Correlation plots (e.g. energy vs. amplitude, duration vs. amplitude, etc.) are simpler and yet efficient in performing pattern recognition. In Figure 7, a typical correlation plot (energy vs. amplitude) shows five defects at different zones on the plot. Their pattern signatures are obtained through laboratory tests or past experience and expressed by AE amplitude, central frequency, rise time, duration, energy, etc. Using these signatures, explicit criteria can be defined to filter out the non-relevant indications.

**Figure 7: Correlation Plots for Pattern Recognition**

Source location technology employs multiple sensors to determine where the Acoustic Emission signal originated. This has been a major part of Acoustic Emission technology since its early days. Planar location is one of the source location technologies. It is widely used in structural testing and typically applied on plate-like structures. The computed source locations are usually shown as points on a map-like display (y position vs. x position), with the sensor positions and/or structural features displayed in the background. It requires at least three sensors to compute the source location, that is two arrival time differences, together with the wave speed, to compute two coordinates, x and y. Software is readily available for use on closed forms such as cylinders, cones, and spheres, as well as flat plates. Figure 8 shows a typical AE source location plot using four AE sensors. The energy of each AE event in this figure is also shown to classify the intensity of each event (high AE activity).

**Figure 8: AE Source Location**

The evaluation procedure (identify high AE activity) assesses the significance of the relevant indications and leads to the decision of acceptance, rejection or some other kind of decision about what to do next with the structure or component, for example, whether to perform a follow-up survey or inspection.

**Application of AET in a Tanker**

In a previous feasibility study (Wang, et al. 2010), Acoustic Emission Testing (AET) was used to provide early warnings of flaws for a tanker. A 32 year old oil tanker was selected for detecting under deck corrosion and potential cracking in the deck area of the vessel. This tanker was used to transport crude oil from Alaska to the West Coast of the USA. In the oil tanker, there is a loading condition of high stress on the deck. This condition is when the cargo holds are empty and the ballast tanks are full creating a hogging condition. During this condition, the deck is in longitudinal tension with further longitudinal stresses induced by wave action. In this previous feasibility study, this loading condition was used to detect flaws under the deck structure.

**Figure 9: Time History for Strain and AE Events**

(Wang, et al. 2010)

The AE test was installed when the tanker was in dock and had no load or ballast. AE monitoring was started during the loading of the ballast tanks (while the tanker was heading out to sea). Separate data files were generated to enable the evaluation of the ballast loading condition and the voyage conditions. During the voyage, the weather conditions varied from cloudy to rainy to dry and the sea state at the start of the voyage varied from the waves with three feet significant wave height to very calm sea conditions. Figure 9 shows an example of the data acquired. The top plot shows the strain history recorded with the strain gauge installed, and the bottom plot shows events recorded. In these plots, one should note the increase in events corresponding to the increase in stress. Areas that show increases in activity with the increase of hull stress indicate stress-driven mechanisms, which are corrosion and crack growth activated by the sea environmental loads.

With these acquired AE data, the AE sourcing location algorithm was used and three regions were identified and
suspected of corrosion and cracking activities, as seen in Figure 10. From follow up inspection, the map of corrosion was created by automatic ultrasonic testing (AUT) equipment. The results of the AUT plot showed areas of high corrosion consistent with the regions identified by the AE testing.

As a NDT method, AET conducted during the previous study has shown that it is a viable and complimentary technology that can be used for monitoring critical areas on a tanker. Following from this success, a feasibility study using AET for the structural health monitoring on a container ship was also performed.

Application of AET in a Container Ship

A joint development project between a classification society, an AET system and service provider and a global container transportation company was carried out on a 4800 TEU containership. This pilot project’s goal was to examine the viability of acoustic emission technology as a screening tool for surveys and inspection planning.

In this project, the areas of interest for monitoring and inspection during trans-Pacific and trans-Atlantic ocean voyages included: highly critical / stressed areas, areas of known discontinuities (e.g. existing cracks), and locations where historical cracks have occurred. A total of (11) areas were identified for acoustic emission testing (AET) and monitoring, totaling (50) AE sensors, (5) strain gauges, and approximately 2.9 miles of cabling for all sensors. The diagram of areas monitored is shown in Fig. 11.

Attenuation test

Before installing the AE system, a series of Pencil Lead Break (PLB) tests were performed for attenuation measurements in accordance with ASTM E 976 (ASTM E976-2010). These measurements were used to categorize the attenuation of the acoustic emissions. In the PLB tests, the acoustic emission signals were generated by breaking 0.5 mm pencil lead. Three breaks were performed at locations along the main deck with 2ft (0.61m) spacing. The average acoustic emission amplitude of three breaks for each break location is shown in Figure 12. From the PLB test result, the effective distance of each sensor is about 13ft (3.96m) – 15ft (4.57m). Based on this result, it was recommended to implement the acoustic emission sensors with a spacing less than 13ft (3.96m). This will provide adequate coverage of the entire area that is being monitored.

Acoustic Emission System setup

Two AE systems (PC1 and PC2) were installed inside the tunnel on the second deck to monitor main deck structures. Using the PC1 system, nine areas were monitored and using the PC2 system, two areas were monitored. In each area, the main deck structures were
instrumented with two to six R15I Physical Acoustics Corporation (PAC) acoustic emission sensors (Figures 13 and 14). This type of sensor has a 150 kHz resonant frequency with an operation range of 80 – 300 kHz. To explain the configuration of AE sensor array, the positions of the acoustic emission sensors at the hatch corner areas is selected and shown in Figure 13 (P1 area). Four acoustic emission sensors were installed under deck with two sensors at the tunnel (between inner skin and side shell) and the other two sensors inside the engine room (inside the inner skin). All AE sensors were connected to a MISTRAS Sensor Highway II System. This AE system was operated in a passive mode during the whole voyage and loading/unloading processes. All the AE signals were acquired and analyzed to detect crack propagation. In each monitoring area, the setting up of analysis is either a linear or 2D planar array. If the acoustic source is strong enough to hit a minimum of two sensors for linear location or a minimum of three sensors for 2D planar location, the software can calculate the location of the acoustic source. A similar configuration of AE sensor array was arranged inside tunnel underdeck in way of first cargo hold and shown in Figure 14 (P5 area).

**Acoustic emission data acquisition**

Data was acquired using several setups to optimize the data being recorded. Depending on the observable conditions at the time of data acquisition, various front-end setup parameters were used. This was to prevent the contamination of the acoustic emission data by additional AE signals, such as extraneous environmental noise generated by the container ship environment.

In the field test experience, the criteria of front-end filtering are shown as follows:

- Amplitude threshold – a threshold value used for the analysis of AE hit: 40 dB,
- Peak Definition Time (PDT) - the time between the AE hit start and the maximum peak amplitude: 200 μsec,
- Hit Definition Time (HDT) – the time to the end of AE hit: 400 μsec,
- Hit Lockout time (HLT) – A lockout time which starts at the end of the hit during which the AE system does not respond to threshold crossing: 200 μsec, and
- Rise Time – the time between AE hit start and the first peak amplitude: 2 to 500 μsec.

**Acoustic emission data analysis**

After the AE data was acquired with front-end filtering, the AE signal discrimination was executed to get the target flaws (corrosion and crack propagation). Past experience (field and laboratory tests) has established warning criteria of acoustic emission parameters to detect the active corrosion and crack propagation activities. The criterion is shown as follows.

- Amplitude: ≥ 55 dB
- Energy: 10 – 40,000 AE
- Rise time: 2 – 500 μsec
- Duration: 2 – 20,000 μsec
- Centroid frequency: 150 – 350 kHz

With the implementation of the above criterion, the remaining acoustic emissions generated by the active corrosion and crack propagation were analyzed in each main deck area for structural health monitoring.

**Results and findings**

The primary goal of this project was to establish the feasibility of implementing acoustic emission technology on a ship for the purpose of structural health monitoring. In this continuous monitoring study, the acoustic emission testing results were shown and compared with the results obtained in the follow-up inspection. In general, there was no AE activity due to crack propagation for all monitoring areas during the voyages except for micro-crack activity which was observed in Area P1 (port side of hatch corner area).

During periods of harsh weather and heavy seas, it was visually observed that the water splash (due to wave, sloshing water on deck, and rain.) could create an AE signal similar to that of crack propagation. In order to explain the AE activities due to crack propagation and water splash, the testing results in two monitoring areas (hatch corner and forward deck areas) are shown next.

The AET results are displayed in three key formats: 1) Time history of acoustic emission amplitude, 2) Correlation plots of energy vs. amplitude, and 3) AE source location and follow-up inspection.

**Time history of acoustic emission activities**

During the trans-Pacific voyage, the time history of acoustic emission amplitude showed AE activity. Two interesting activities in P1 (hatch corner) and P5 (tunnel in way of first cargo hold) areas were observed and shown in Figures 15 and 16, respectively.
In Figure 15, the activities with amplitude higher than 70 dB (identified as a microcrack activity) as well as high fluctuations of strain were observed randomly over a day. The high AE amplitude activity appeared for a period of a couple of hours then disappeared. After several hours of low AE activity, the high AE amplitude activity appeared again. This may be due to the high fluctuation of strain (high stress range). Given a sufficiently high stress range, the crack propagated and an acoustic emission was produced.

In Figure 16, the activities with amplitude higher than 70 dB were recorded continuously for a half day. From visual observation, this may be due to water splash as the container ship sailed through a severe storm.

Acoustic emission data analysis using correlation plots

The second analyzed acoustic emission data format was the correlation plot of energy vs. amplitude after AE data was filtered. The trend regions in the correlation plots help to distinguish between acoustic emission signals corresponding to crack growth from those generated by mechanical rubbing, such as the fretting between crack faces and other extraneous noises. However, it was challenging to use this correlation plot to distinguish crack growth from water splash since their corresponding parameters are very similar. In the current paper, the correlation plots in Figures 17 and 18 show the microcrack and water splash activities, respectively. It is observed that there is no significant difference between these two plots. In order to further distinguish crack growth flaw, the data format of AE source location was examined to provide more information.

Acoustic emission data analysis using Acoustic Emission Source Location

The third form of analysis performed in this study was AE source location. With the location identification, the flaw locations can be identified within a reasonable region. This information can help the surveyor find the flaw more easily and perform the inspection more efficiently and effectively.

In Figure 19, the AE source location was observed clearly in one spot due to a microcrack at P1 (hatch corner area). Based on this result, this location was focused on during the inspection conducted in the follow-up survey. In Figure 20, the AE source location is observed to be scattered over a large area. This observation indicates that this activity is likely due to water splash activity and is not related to crack growth.
After the acoustic emission data analysis, a follow-up inspection was performed by close-up visual inspection (CVI). A 2” flaw was found about 2 feet away from the AE source location identified (see Figure 21). This discrepancy is likely due to the curvature shape of plate which the current software treats as a flat plate. However, the location was still accurate enough to help the surveyor find the flaw easily. The successful identification and locating of a crack demonstrates the potential effectiveness of using AET as a structural health monitoring tool for the early warning of crack growth in critical areas.

With the identification of the flaw, the next step was to perform the diagnosis evaluation of structural health based on crack location and crack size. Since this detected 2” crack was located at the corner of a hatch corner box and didn’t affect local and global strength, the structural health at this hatch corner area was not affected by this crack. However, the crack growth of this flaw was continuously monitored to avoid crack propagation and potential damage to the main deck.

Conclusions

Continuous AET monitoring technology has the potential to be applied to the structural health monitoring of in-service ships, resulting in both increased safety and economic benefits derived from more efficient surveys, inspections and maintenance. The use of state-of-the-art AET systems, in conjunction with advanced software and internet communications can provide a remote monitoring system for safeguarding ship structural integrity.

In the current paper, a feasibility study investigating the use of AET for the structural health monitoring of ship structures was presented. The main conclusions are as follows:

- AET has been assessed and proved to be a promising tool to detect the crack growth and corrosion activities in the field tests of both a container ship and a tanker.
- Flaws (crack growth and corrosion) were detected by AET and verified in the follow-up survey by close-up visual inspection (CVI) and automatic ultrasonic testing (AUT), respectively.
- The marine environment has a significant amount of extraneous background noise which can interfere with AE data collection. This noise interference was especially prevalent for the container ship. For a successful application of AE in the maritime industry, signal discrimination and noise reduction are crucial. The procedure of AE data analysis in Figure 5 must be conducted to obtain the best quality of AE results.
- From the attenuation test results, it was determined that the effective distance of acoustic emission is about 13 feet (3.96m) for ship structures.

There were also some additional interesting findings in the field test results.

- During the filtering procedure, it was a challenge to discriminate the AE signals generated by crack growth from those generated by water splash (wave, sloshing water on deck, and rain). Based on this paper’s result, the AE source location plot may help differentiate the meaningful crack growth signals from water motion signals. For crack growth, the AE source location was observed to be clustered in a specific area. For water motion, the AE source location was observed to be scattered over a wide area.
- Due to the nature of fatigue damage accumulation, the high AE amplitude activity appeared for a period of a couple of hours then disappeared. After several hours of low AE activity, the high AE amplitude activity appeared again. Based on this observation, continuous monitoring is crucial for AET to obtain the crack growth activity.

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