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Non-Contact Acoustic Emission Monitoring of Corrosion in Mooring Chain Links

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Abstract. This paper highlights an experimental investigation for monitoring of corrosion-induced damage in mooring chain links using non-contact Acoustic Emission (AE) technique in submerged conditions. Accelerated corrosion experiments were performed on a large-scale mooring chain sample retrieved after operation offshore. Ultrasound signals were continuously measured using two arrays of underwater AE transducers placed on two perpendicular planes at a fixed distance from the chain links. The variation and evolution of AE parameters have been analysed as a function of testing time. Corrosion-induced AE sources have been localized on the 3D geometry of the tested links in the water tank. The results suggest that corrosion-induced ultrasound signals can be detected and monitored using non-contact AE transducers underwater.

Keywords: Acoustic Emission; Corrosion; Damage Detection; Damage Localisation; Mooring Chain.

1. Introduction

Mooring systems are key parts of floating energy production units, such as floating offshore wind turbines (FOWT), floating photovoltaic (FPV), and floating production-storage-offloading units (FPSOs). Corrosion is considered among the main degradation mechanisms that affect the structural integrity of mooring chains [1]. Detailed integrity assessment of these structures can be challenging due to their difficult-to-access locations, waves, surface conditions, and weather conditions, etc.

Acoustic Emission (AE) is a passive ultrasound method and is widely recognized for monitoring corrosion damage [2]. AE technique can allow to detect, localise, and characterize corrosion damage by continuously measuring the transient stress waves (i.e. AE event) generated by the rapid release of energy from localised sources on the material surface [3]. Corrosion-induced AE sources can be characterized by their specific properties, such as amplitude, energy, counts, etc. [2]. The breakdown of thick oxide films (in high-temperature water) is a significant and highly energetic source of AE [4]. The evolution and implosion of

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hydrogen gas bubbles (due to the cathodic reaction in acid solutions) are the other primary sources of AE during the corrosion process [4]. Although associated with the lowest energy level, dissolution of metal and breakdown of thin passive film are additional potential sources of AE [4]. Recently, the authors have investigated the detectability of AE signals during the corrosion (and corrosion-fatigue) process in small-scale specimens using non-contact AE transducers [5-6].

This paper presents a feasibility study of detecting, localising, and monitoring corrosion damage in full-scale mooring chain links using non-contact AE measurements. Large-scale accelerated corrosion experiments have been performed on a mooring chain sample retrieved after operation offshore. Ultrasound signals were continuously measured using two arrays of underwater AE transducers facing the chain from two perpendicular planes at a fixed distance from the chain links in a water tank. A source localisation algorithm for the corrosion-induced ultrasound signals has been implemented. The results have been projected on the 3D model of the chain surface. The AE parameters extracted from the measured signals have been analysed as a function of testing time. The paper has been organised as follows. The methodology is described in Section 2. Description of the experiments is given in Section 3. Results are presented and discussed in Section 4, followed by conclusions in Section 5.

2. Methodology

For a submerged steel specimen subject to corrosion, Fig. 1, schematically shows the ultrasound wave propagation path with an array of non-contact AE transducers.

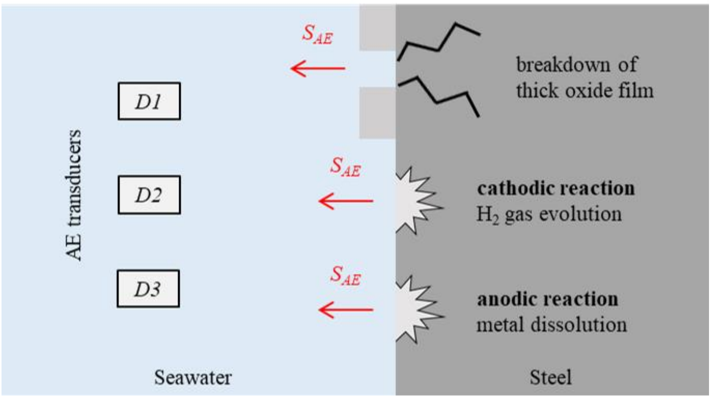

Fig. 1. Schematic illustration of the wave propagation path in submerged steel specimen with an array of non-contact AE transducers.

Corrosion-induced ultrasound waves can propagate from the steel surface through the seawater medium as pressure waves (constant speed of sound). Wave components with sufficient energy to overcome attenuation and geometrical spreading can reach the array of ultrasound transducers. Each signal P_i, measured by the *ith* transducer, can be described in the frequency domain as the convolution of the source signal S_{AE} with the transfer function of the propagation media and the sensor, as in

$$P_i = D_i W_w S_{AE} + N_i , \qquad (1)$$

where W_w is the propagation (transfer) function of water, and D_i is the transfer function of the *ith* sensor. N_i refers to the background noise and the neglected components of the ultrasound wave.

2.1 Detection and Identification of Corrosion Damage using Non-Contact AE

Parametric analysis of the AE signals [2] is considered in this study to investigate the feasibility of detecting and monitoring corrosion damage in mooring chain links using non-contact AE measurements. Damage-induced ultrasound signals have been continuously recorded using two perpendicular arrays of AE transducers throughout the test. The analysis covers the entire duration of the test.

The total number of recorded AE signals is calculated for each sensor in the perpendicular arrays of AE transducers. The total number of AE signals can provide insights into the most active areas on the chain surface.

The cumulative number of AE signals and the AE hit-rate (defined as the number of recorded burst-type signals per unit time) are calculated as a function of testing time to assess the evolution of the corrosion damage. Considering the nature of the AE signals, every relevant AE event can indicate the onset of a new damage zone, the growth of an active corrosion pit, and/or the occurrence of secondary corrosion-induced degradation processes. The evolution of the cumulative number of AE signals can provide information about the evolution of the corrosion damage. The AE burst hit-rate can provide indications of the damage growth rate (i.e. corrosion rate).

2.2 AE Source Localisation

The AE source localisation approach in this study employs the triangulation principle [7]. For every AE event, the differential time-of-flight at each sensor is obtained from the waveforms using the Akaike Information Criterion (AIC) [8]. A search domain is defined utilizing the surface of the chain links. Minimization of the error between the predicted and measured differential arrival times over the domain is performed to estimate the source location. A maximum allowable error value is additionally used as a quality criterion to improve the reliability of the source localisation.

For coupled arrays of AE transducers facing the chain links from perpendicular planes, the participation of a minimum of 4 sensors is considered. Once all the AE events are localised, a cumulative inverse error function (ε) is defined for visualization of the most probable location of the AE source, as in

$$\varepsilon = \sum_{k=1}^{N} \alpha_k \beta_k e_k^{-1}(x)\,, \tag{2}$$

$$\beta_k = \begin{cases} 0, & \forall e_k > \bar{e}_k \\ 1, & \forall e_k \le \bar{e}_k \end{cases}\,, \tag{3}$$

where N is the total number of localised AE events and $e_k^{-1}(x)$ is the inverse of the error function, i.e. objective function, defined over the search domain. α_k is the normalization factor limiting the values of $e_k^{-1}(x)$ between [0,1]. β_k is a binary coefficient that selects only the events that satisfy the localisation error threshold.

The scheme described above has been numerically implemented by discretizing the search domain. A 3D model of the chain surface obtained with 3D laser scanning has been used for this purpose.

3. Experiments

Accelerated corrosion experiments have been performed on a large-scale mooring chain sample to assess the feasibility of detecting, localising, and monitoring corrosion damage in large-scale submerged steel structures using non-contact AE transducers.

3.1 Experimental Setup

A dedicated experimental setup was designed and fabricated to apply accelerated corrosion on a large-scale mooring chain sample submerged in natural seawater. Fig. 2 (left) shows a schematic illustration of the setup and equipment.

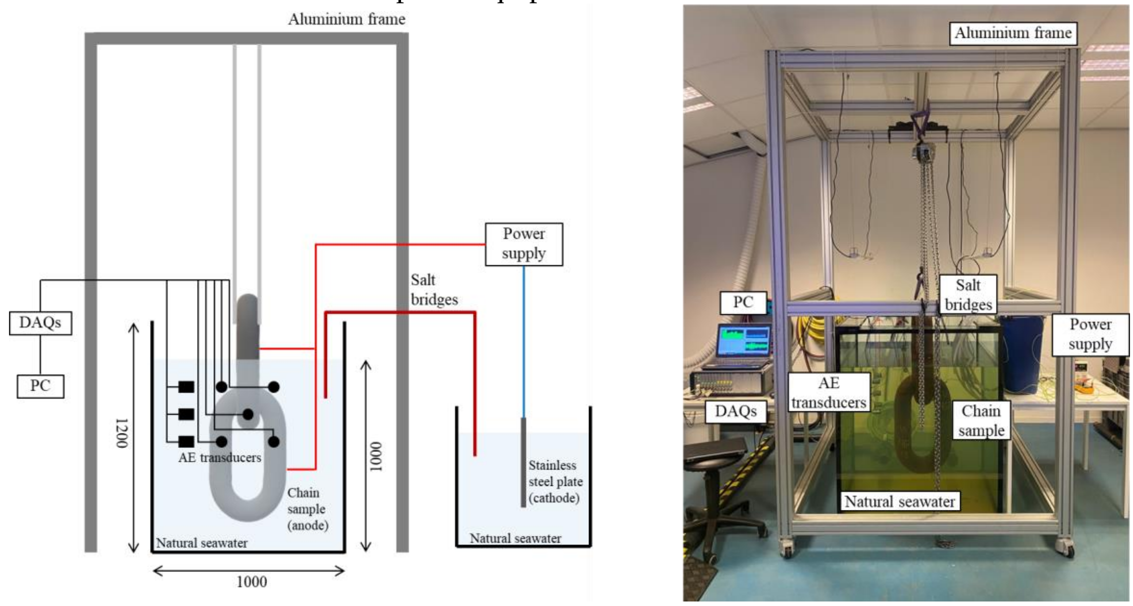

Fig. 2. Schematic illustration of the large-scale corrosion experimental setup (left), and large-scale corrosion experimental setup with submerged mooring chain sample (right). Dimensions in mm.

Fig. 2 (right) shows the fabricated test setup. An aluminium support frame was used to accommodate the 2-link mooring chain sample in the 1000x1200x1000mm^3 glass tank. The chain sample was submerged in a natural seawater volume of 1000x1000x1000mm^3. The chain sample consists of a segment of a used studless R4 chain with a nominal diameter of 136 mm.

3.2 Accelerated Corrosion Process

The corrosion process was accelerated through galvanostatic anodic polarisation. A direct current has been imposed to accelerate the corrosion process with the positive pole connected to the submerged mooring chain sample (i.e. anode) and the negative pole connected to a stainless-steel plate (i.e. cathode). Direct current power supply (i.e. 36 V and 5 A) has been deployed. Both anode and cathode have been submerged in natural seawater to ensure sufficient (and realistic) electrical conductivity. The cathode was positioned in a separate water container to prevent contamination of the main anode water volume by OH- (hydroxyl) ions produced during cathodic reactions. A total number of about 15-20 salt bridges have been placed between the two water volumes. The chain sample was subject to an accelerated corrosion process for about 187 hours using an anodic current level of 0.25 A.

3.3 Data Acquisition, Management, and Quality Control

To collect and record the ultrasound signals generated during the corrosion process an AMSY-6 Vallen data acquisition (DAQ) system and ten watertight piezoelectric AE transducers (VS150-WIC-V01, with an integrated preamplifier, gain of 34 dB) were employed [9]. Watertight co-axial cables connected the piezoelectric AE transducers to the DAQ system. Fig. 3 schematically shows the layout of the AE transducers. A fixed distance (equal to 300 mm) was kept between the vertical axis of the chain sample and the two arrays of AE transducers using two sensor holders (400x400mm^2 acrylic plates with a 7x7 grid of holes 50 mm equally spaced). A sampling rate of 2,5 MHz was used to record the AE signal waveforms (with a total sample length of 4.096 points).

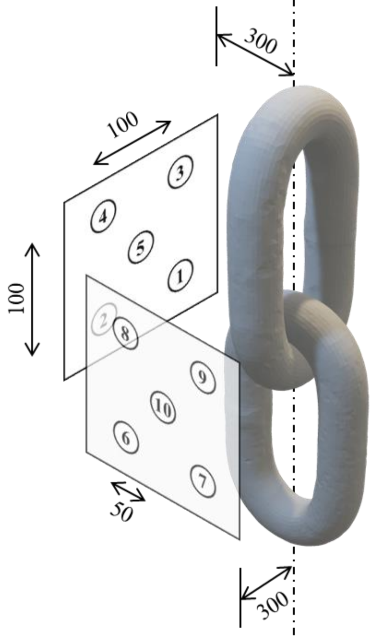

Fig. 3. Schematic illustration of the layout of the AE transducers. Group 1 includes sensors 1-5. Group 2 includes sensors 6-10. Dimensions in mm.

Pencil lead break tests (according to ASTM E976-15 [10]) on the submerged surface of the chain links were performed to check the proper functioning of the AE measurement system and to verify the localization algorithm before testing.

The maximum measured noise level in the laboratory was about 27 dB. The acquisition threshold was set to 30 dB. The recorded ultrasound signals have been pre-processed using a signal-to-noise ratio filter of 10 dB to separate potential damage-induced signals from possible background noise (i.e. continuous-type signals).

4. Results and discussion

Experiments described in Section 3 were performed and the methodology for the data analysis described in Section 2 was applied.

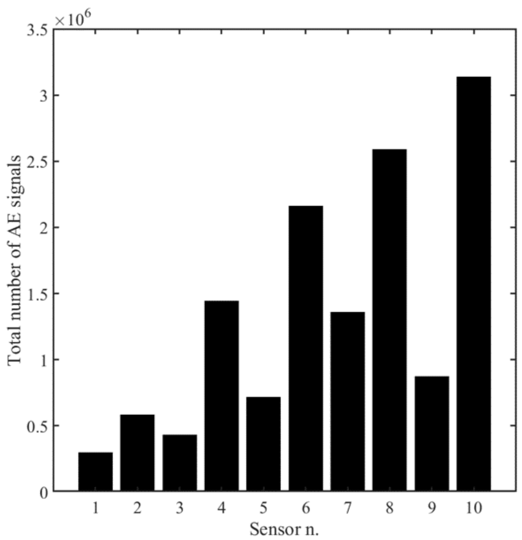

Fig. 4. Total number of AE signals measured by each sensor.

Fig. 4 shows the total number of AE signals measured by each sensor in the perpendicular arrays. When combined with the AE sensors layout in Fig. 3, it can be inferred that most of the acoustic activity seems to be generated from the side of the links facing sensor group 2. Sensor 10 shows the maximum number of signals recorded (with 3.1×10^6 signals) followed by sensors 8, 6, and 4. This may indicate active AE sources in the part of the upper link towards sensor group 2 and facing sensor group 1. Sensor 1 displays the lowest number of AE signals recorded (with 0.3×10^6 signals) followed by sensors 3 and 5. This seems to suggest relatively low acoustic activity on the opposite side of the chain links.

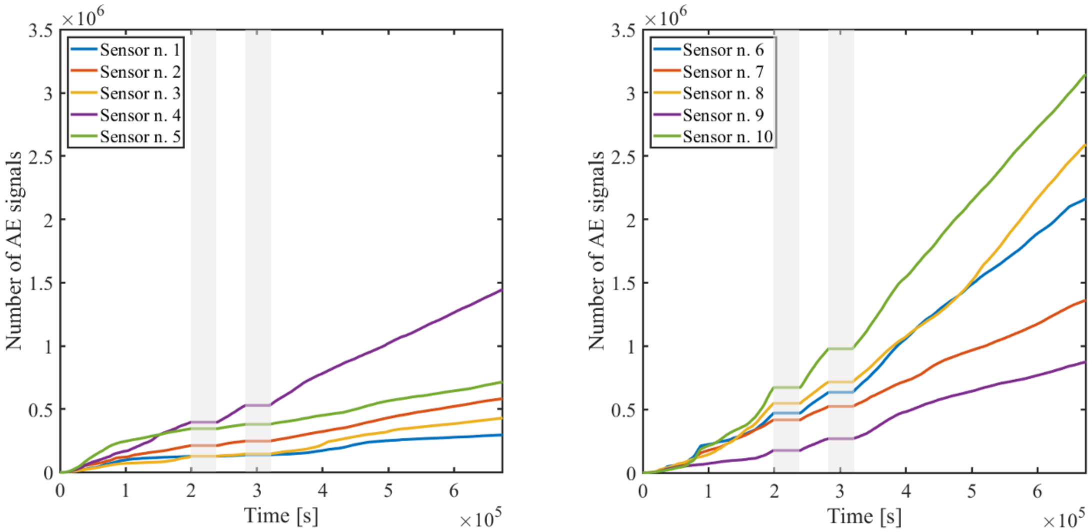

Fig. 5. Cumulative number of AE signals measured by each sensor. Grey areas indicate the periods where measurements are not available.

Fig. 5 shows the cumulative number of AE signals recorded by each sensor in the perpendicular array. Among the sensors in group 1, sensors 1-3, and 5 seem to follow a similar trend throughout the experiment. After 1×10^5 seconds their curves show a constant and similar slope. Sensors 4 and 6-10 show a similar but steeper trend characterised by a constant slope of the curve (throughout the test) possibly indicating constant rate of the degradation process.

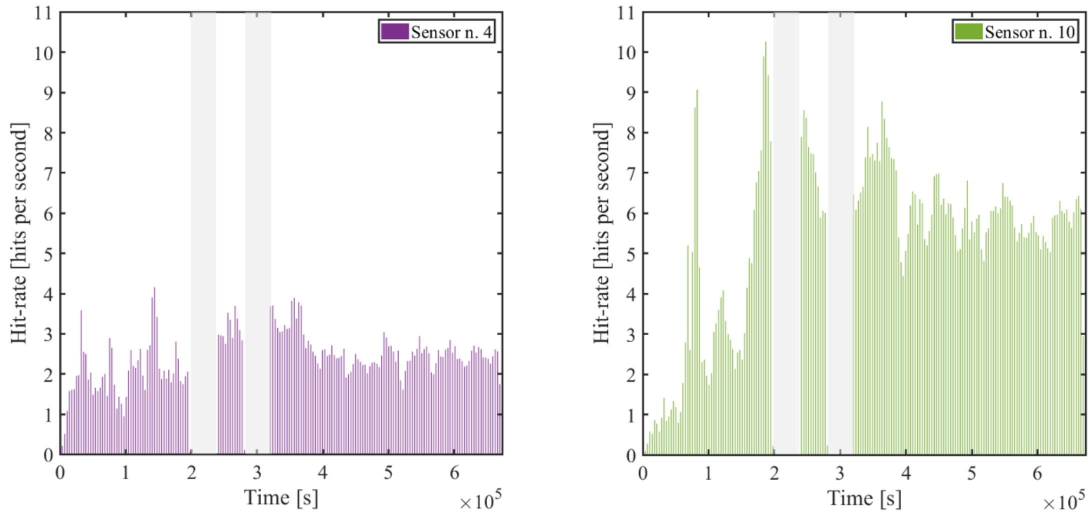

Fig. 6. AE hit-rate measured by the most active sensor in each perpendicular array.

Fig. 6 shows the AE hit-rate recorded by the most active sensor in each perpendicular array. Although the two sensors differ in the value of AE hit-rate (i.e. 3-4 hits per second) similar variations can be noticed. Sensor 4 measures 2-3 hits per second between 0 and $2x10^5$ seconds (Fig. 6, left). Sensor 10 shows an increasing trend in AE hit-rate reaching 8-9 hits per second by the end of the same period. After $2x10^5$ seconds, sensors 4 and 10 seem to measure a relatively stable AE hit-rate of 2-3 and 6-7 hits per second, respectively.

Damage-induced ultrasound signals have been localised using the two arrays of AE transducers facing the chain links from perpendicular planes. Results of the AE source localisation were projected on the 3D geometry of the chain links in the form of a localisation map. The AE source localisation map has been calculated using the procedure described in Section 2, and calculated over the grid points for each localized event recorded during a testing time of about 5 hours (between $4.9x10^5$ and $5.1x10^5$ seconds). The grid has a uniform spacing of 10 mm in x, y, and z directions. The speed of sound in water is considered to be 1500 m/s at 20^o C. A maximum allowable error (between the predicted and the actual differential arrival times of the wave) of 10 μs has been used.

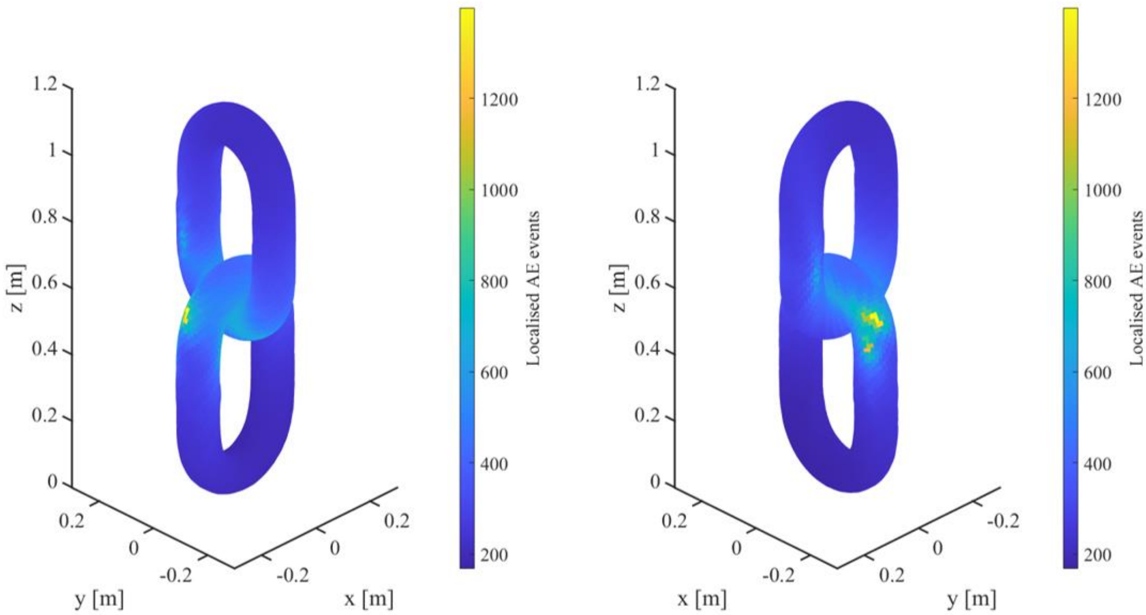

Fig. 7. Localisation map of AE sources calculated for a testing period of 5 hours.

Fig. 7 shows the localisation map for a selected period of the test duration. The AE source localisation map reveals one zone as the most acoustically active. This activity ranges from 1200 to 1300 localised AE events, resulting in a rate of localised AE events of 240-260 events per hour. An average of about 200 localised AE events is reported for the rest of the chain links surface.

5. Conclusions

Large-scale corrosion experiments were performed to assess the feasibility of detecting, localising, and monitoring corrosion damage in mooring chain links using non-contact Acoustic Emission (AE) technique. A 2-link mooring chain segment was subjected to accelerated corrosion while submerged in natural seawater. Ultrasound signals were continuously measured using two arrays of 5x AE transducers placed at a fixed distance from the chain and facing the specimen from perpendicular planes.

Parametrization of the AE measurements was used to monitor the acoustic activity induced by the corrosion process. The total number of AE signals highlighted the most active areas in the chain links. The cumulative number of AE signals displayed distinct activity patterns for two groups of AE sensors. Both the groups show a constant slope of the curve, possibly indicating a constant rate of the degradation process. The AE hit-rate of the two most active sensors in the two perpendicular arrays show high similarity, likely induced by the same AE sources. The AE hit-rate confirmed a relatively stable rate of degradation.

A 3D source localisation algorithm for corrosion-induced ultrasound signals was successfully implemented. Results of the AE source localisation were projected on the 3D model of the chain surface in the form of a localisation map. The AE source localisation map revealed the most acoustically active zone on the chain surface with 1200-1300 AE events localised in five hours of testing (i.e. 240-260 AE events per hour).

The present study suggests that corrosion damage can be effectively monitored using non-contact AE transducers. Further work will be performed to extend the localisation approach to the entire duration of the experiment. The findings presented in this investigation can also serve as the basis for future possible corrosion damage prognosis in mooring chain links using non-contact AE technique.

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