Structural health monitoring during fatigue of composite marine propellers

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Abstract. Flexible composite marine propeller blades can offer the potential for reduced greenhouse gas emissions as well as a reduction in underwater radiated noise. Nevertheless, their application in the real world is hindered, among others, by unknowns in the fatigue behaviour of these blades. This research assesses the structural health measurements of an experimental campaign wherein a glass-fibre reinforced plastic marine propeller blade was tested under 1½ times the design operational load for 16 million cycles. Acoustic emissions were investigated that were recorded underwater by hydrophones that were placed close by the blade. Approximately 40Gb of AE feature data was obtained, alongside 200+Gb of waveform data. The feature data was filtered to only assess the data pertaining to the hydrophones, with a focus on hit-rate over time and cumulative energy. The results give an insight into the fatigue behaviour of the blade, alongside considerations regarding placement of hydrophones and comparison to other relevant data such as load-displacement histories and visual observations.

Keywords: Acoustic Emission, Hydrophone, Composite marine propeller, Fatigue

Introduction

Flexible composite marine propeller blades can have the potential for reduced greenhouse gas emissions as well as a reduction in underwater radiated noise. Despite their potential, their application in the real world is hindered, among others, by unknowns in the fatigue behaviour of these blades.

To gain more insight into the fatigue behaviour of composite marine propellers, structural health monitoring (SHM) is considered. In composite propellers, there has been a focus on (low frequency) strain measurements, mostly for the sake of validating propeller deflection [1], [2], [3] but also for SHM purposes [4], [5], [6]. The authors consider these methods valuable, but significant changes in strain values tend to show up mostly close to the end-of-life of structures. This makes it extremely difficult to take any proactive measures in operational conditions. Hence a method is desired that can track degradation from an early stage onwards. This can be enabled by acoustic emission (AE) monitoring. Here, the initiation and progression of damage emanate an elastic mechanical wave, called an acoustic emission, that is recorded by nearby AE sensors. Further processing of the AE signals allows for damage location, classification and quantification.

In typical civil engineering structures, AE can be measured using externally bonded sensors. However, in the case of marine propellers, this is not possible as it would cause

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hydrodynamic problems and accelerate wear of the sensor or blade itself. To avoid this issue, the AE sensors can be embedded inside the composite propeller blade [7], [8] or the AE can be measured remotely using hydrophones. The former has the advantage of a measurement close to anticipated damage, whilst the latter is not limited by wiring complexities in the propeller hub.
Hydrophones have been used for AE-based structural health monitoring primarily in the context of mooring systems. Bashir et al. [9] describes ultimate strength testing of submerged synthetic mooring lines that includes AE hydrophones near the mooring line. They classified the obtained AE signals according to their amplitude and frequency content and related these classifications to different stages of mooring line degradation. Riccioli et al. [10] placed a large array of AE hydrophones along a loaded mooring chain and localised and quantified crack progression on the chain links. In the context of AE-measurement of propeller blade material degradation, the authors performed non-destructive AE excitations on a submerged composite marine propeller blade [11]. This included the use of hydrophones as well as embedded sensors and was aimed for feasibility assessment to pave the way for current research on fatigue testing.
This research assesses the use of hydrophones for AE measurement in a composite marine propeller blade loaded in fatigue.
The build-up of the paper is as follows: Firstly, the methodology is explained regarding to the measurement and analysis of AE using remote hydrophones. Secondly, the experiment is described, including the fatigue set-up and the settings of the hydrophones. Thirdly, the results are shown, containing the progression of measurement of AE signals throughout testing and localised over the blade. Thirdly conclusions are drawn from the results, followed by recommendations for future research.

1. Methodology

Acoustic emissions can be generated by damage occurring in a structure. The measurement of AE can reveal insights in the nature, severity and location of damage. To measure AE, sensors can be used that are placed either on the structure, embedded inside it, or placed remotely given that the medium between structure and sensor allows acoustic wave propagation.
In this paper the methodology contains the measurement of these AE signals using remote hydrophones. The accumulation of AE hit events over time can be indicative for the progression of damage, while variations in energy of the AE signals is considered indicative of damage location. This is visualised in Fig. 1.

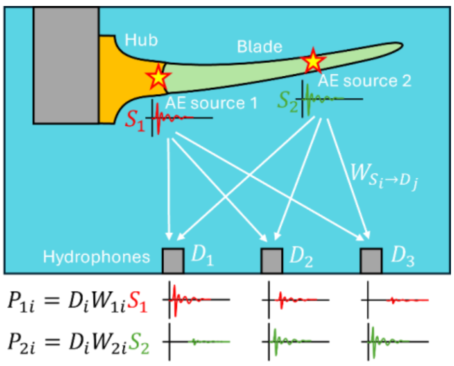

Fig. 1. The propagation of AE sources from the blade and hub towards the

hydrophones. The measurement amplitude P drops as transfer function W represents a larger distance.

In the frequency domain, the measurements from the hydrophones are related to AE source signals as follows:

$$P_{ij} = D_j W_{ij} S_i. \quad (1)$$

Here, S_i is the AE source excitation component at location i, W_{ij} is the wave propagation transfer function from source to (hydrophone) sensor location j, D_j is the sensor electromechanical transfer function, and P_{ij} is the measurement signal.
The energy of a measured AE signal is described in eq. 2:

$$E_{ij} = \beta \int_{t_{ini}}^{t_{end}} P_{ij}^2 \, dt. \quad (2)$$

In this equation t_{ini} and t_{end} are the time stamps related to the first threshold crossing and the last, respectively. Coefficient β is specific to the data acquisition hardware, with resulting energy stored in energy units (EU). With this relation in mind, and assuming the AE sources from different locations have comparable amplitudes, and assuming the hydrophones have comparable sensitivity [11], the energy predominantly captures the effect of wave propagation transfer function W_{ij}. Therefore, the calculated energy can be related to the distance from the source to sensor, i.e. higher energy related to smaller distance. When looking at the cumulative energy over the measurement duration, it can be visualised where on the blade the largest energy was recorded, and this may indicate regions of damage.

2. Experiments

To perform the experiments, a custom set-up was manufactured to accommodate the blade and actuator. The set-up resembles the blade being cantilevered against a stiff HEA30 construction beam assembly, with the actuator (25kN max capacity) being mounted perpendicular to the blade. A photograph of the setup can be seen in Fig. 2.

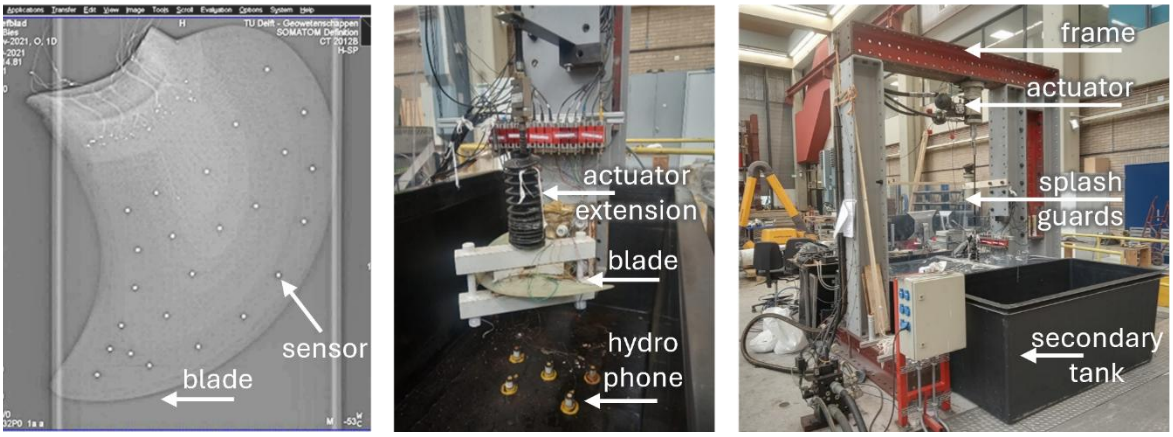

Fig. 2 Assessment of a composite marine propeller blade. The left picture visualises CT-scanning of the blade. In the middle a photograph is shown of the blade in the fatigue set-up, including the hydrophones mounted underneath the blade. The right picture shows the full experimental setup with secondary tank and splash guards.

The load direction and location represent the lumped maximum force acting on the propeller blade during a propeller rotation cycle. The fatigue load amplitude was 1 and 1½ times the loading that the propeller would be experiencing at full ship speed. The load ratio is defined by the minimum experienced load in a propeller rotation, divided by the maximum load per rotational cycle. For the 1½ operational load, this resulted in a 9.4kN to 14.2kN sinusoidal force (at 11Hz cycle frequency).

The blade and part of the set-up were submerged in salt water (with a salinity of 53mS/cm) in order to provide an opportunity to use hydrophones for AE measurement and to investigate the survivability of the embedded sensors in a representative salt-water environment.

In the fatigue setup, 5 hydrophones of type VS150WIC were placed underneath the propeller blade (Fig. 2. middle photograph). The AE recordings were collected at a sample frequency of 2.5MHz using hit-based acquisition available in the Vallen AMSY-6 data acquisition system. A duration-discretisation and rearm time of 250µs was applied, in combination with a 100µs pretrigger period. After measurement, a digital band-pass filter was used, ranging from 25kHz to 850kHz. During fatigue testing, a threshold was variedly set to 50-65dB due to noise and to prevent the data acquisition system from not saving waveforms.

Approximately 40Gb of AE feature data was obtained, alongside 200+Gb of waveform data. The feature data was filtered to only assess the data pertaining to the hydrophones. Events were created based on a time interval of 300µs that had AE measurements from at least two different hydrophones. These events were used in further analysis.

2. Results and discussion

A general overview of the propeller load (F), actuator displacement (S) and equivalent rigidity (F/S) can be seen in Fig. 3.

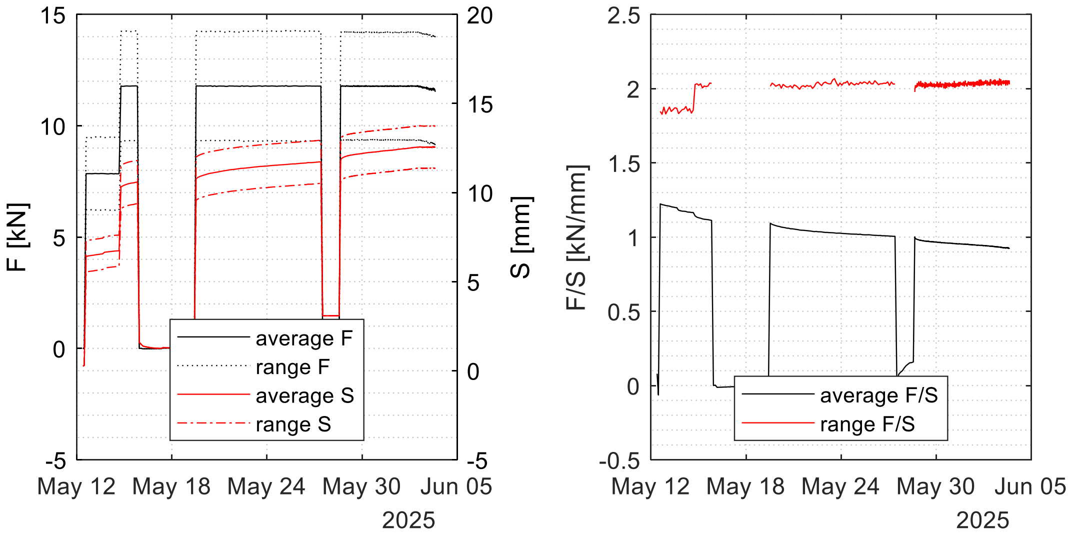

Fig. 3. Left: load and actuator displacement average and range values over time. Right: Load divided by displacement over time for average data and range data.

In the figure it can be noted that over time, for the same loading average displacement increases over time, while the range does not increase. This implies that there is creeping behaviour, but no major stiffness loss due to fatigue. This is confirmed when looking at equivalent rigidity F/S values, where rigidity using the average values dropped, but the rigidity calculated using the range values remained stable. At the start of the experiment, a lower load was applied, coinciding with a lower range-based rigidity. This implies that the blade may have nonlinear stiffness properties.

Regarding AE measurements, mostly at the start of the experiment events were recorded, and these also contained most of the cumulative energy. This may be seen in Fig. 4.

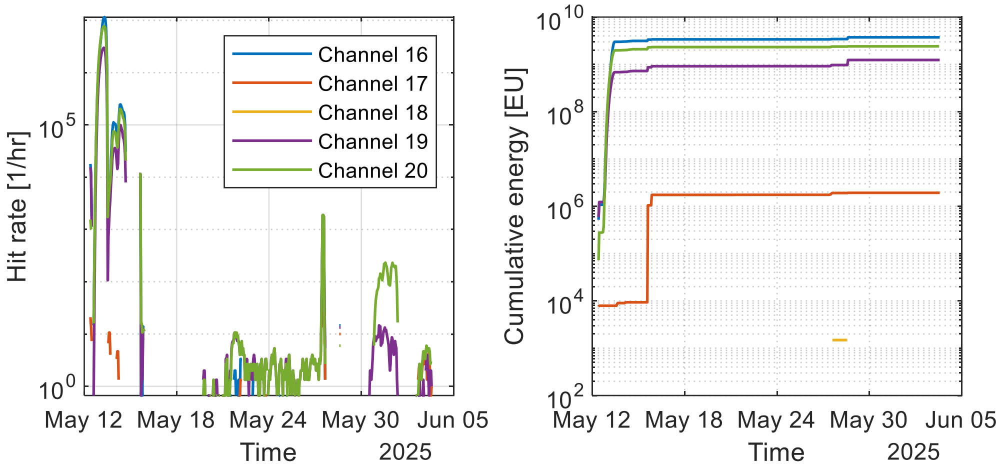

Fig. 4. Left: hydrophone AE hit rate over time. Right: hydrophone AE cumulative energy over time.

The graphs indicate that mostly channels 16, 19 and 20 picked up events, with a lesser amount of events measured by channel 17 and virtually none by sensor 18. After inspection using pencil-lead breaks directly near the sensor, it turned out that sensor 18 was faulty and sensor 17 had reduced sensitivity. On the 27th and 28th of May, the water tank was emptied and refilled, which explains the increase in signals and energy on that date. Furthermore, it should be noted that the AE threshold was set higher during testing, which may influence especially the hit rate results.
To put the results into perspective, the cumulative energy has been projected onto the propeller and compared to visually observed damage (Fig. 5).

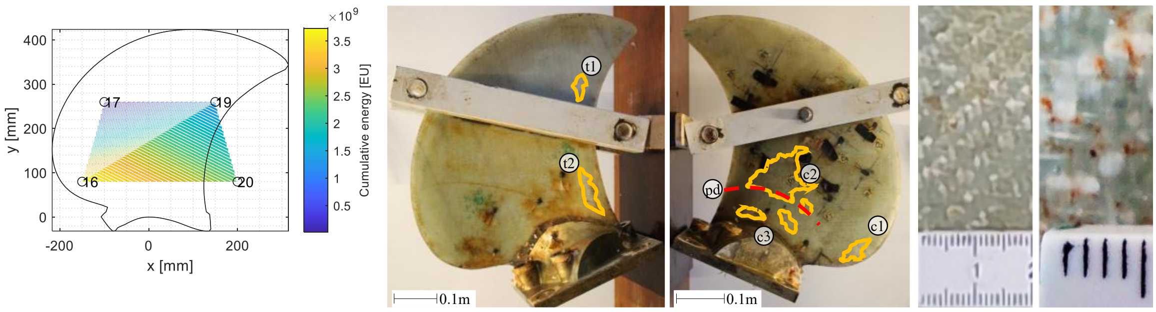

Fig. 5. Left: hydrophone AE cumulative energy at different sensor locations (channel 18 has been left out). Middle: visible damage on the blade surface after 16m cycles of testing. The orange outlined regions mark discolorations due to composite damage, with t1 and c1 being pre-existent. Marker pd describes a ply

drop that aligns with the discoloration c2. Right: Macro photographs of a section within c2. Note the directions of the discolorations in relation to the weave fibre directions, indicating damage.

The photographs in Fig.5. describe locations of discoloration of the composite material. The discoloration is contributed to matrix cracking due to the observation that the discolorations are aligned with the outer layer weave fibre directions. Most of these regions are towards the centre to trailing edge of the blade. Regarding the AE events, the cumulative energy shows a slight preference to channel 16, towards the leading edge, which deserves further analysis[11]. In that light, the results have good potential for further processing as the hydrophone locations with most signals and energy encompass the regions of observed damage.

Conclusions and recommendations

Acoustic emission measurement was performed on a composite marine propeller blade that was subjected to high-cycle fatigue loading. AE monitoring was performed using 5 remote hydrophones. At the end of the test, the blade showed discolorations indicative of matrix damage. The load and displacement histories do not indicate significant degradation. Regarding the hydrophones, it was concluded that these were able to record AE during the fatigue testing. Analysis of hit rate and cumulative energy indicates that potential damage would have taken place early in the experiment, with minor increases afterwards. Recommendations include the performance of time of flight localisation, waveform analysis, and cross-sensor analysis using the data from the embedded sensors, surface mounted sensors as well as other data from strain measurements and posterior CT-scanning.

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