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Underwater acoustic emission monitoring – Experimental investigations and acoustic signature recognition of synthetic mooring ropes

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ABSTRACT

Mooring ropes are essential components of offshore installations, and synthetic ropes are increasingly preferred because of their favourable cost to weight ratios. In-service condition of these materials is traditionally monitored through costly visual inspection, which adds to the operating costs of these structures. Acoustic Emissions (AE) are widely used for condition-monitoring in air, and show great potential underwater. This paper investigates the AE signatures of synthetic mooring ropes subjected to sinusoidal tension-tension loading in a controlled environment, using a large-scale dynamic tensile test rig. With a linear array of 3 broadband (20 Hz to 50 kHz) hydrophones, four main signatures are identified: low-to high frequency, low-amplitude signals (50 Hz to 10 kHz), low-amplitude broadband signals (10 kHz to 20 kHz), high amplitude signals (10 Hz to 48 kHz) and medium-amplitude signals (500 Hz to 48 kHz). These AE types are related to different stages of rope behaviour, from bedding-in to degradation and failure. The main findings are that the failure location and breaking load can be identified through the detection of AE. The occurrence of high amplitude AE bursts in relation to the applied tensile load allows the detection of an imminent failure, i.e. prior to the failure event. These initial results indicate that AE analyses can enable the integrity of synthetic mooring ropes to be monitored.

1. Introduction

Most floating offshore structures need mooring systems, in order to provide a restoring force to counteract the effects of wind, wave and current loads. As operations move into more challenging marine environments (e.g. deeper waters or wave-energy generation), the offshore industry has repeatedly expressed concerns about the frequency of mooring line failures [1], potentially resulting in high cost mooring designs. Steel chain and wire rope have conventionally been used, but contemporary designs often feature synthetic polyester ropes which typically have a lower submerged mass per unit length, a lower cost per unit length and the potential to reduce peak loadings [2,3]. Mooring ropes will be subject to variable loads throughout their lifetime, affecting their operational properties (i.e. stiffness and damping) and potentially inducing fatigue [4]. For the most critical assets (e.g. oil platforms), regular inspection with submersible vehicles is still the tool of choice for condition-monitoring, despite its known limitations [1] and the latest guidelines recommend full replacement of ropes every few years [5]. Direct inspection is not easily carried out in more challenging environments, for example in the energetic conditions suited to Wave Energy Converters (WECs) or in the strong currents favoured for tidal turbines [6]. Mooring costs correspond to more than 10% of the capital cost of a typical WEC installation [7] and regular visual inspection with submersible vehicles would further affect the costs of marine renewable energy production, especially when scaled up to the dense arrays now planned. Several mooring monitoring systems have been developed such as MOORASSURE, Inter-M Pulse, Load Cell Tension and Inclination Monitoring [8]. Other monitoring methods include steel catenary riser inclination/vibration, tendon tensions, fibre optic strain gauges, mooring winch vendor and pull tube monitoring [9]. However, the reliability of most existing monitoring techniques has not be proven and most are only capable of detecting the failure but not the degradation of the mooring lines [8,10].

Remote monitoring of mooring condition using Acoustic Emissions (AE) is an attractive option and, it should be possible to monitor a large variety of mooring structures at once, for a much lower cost. Condition Health Monitoring has long used AE in air, for a variety of systems and application such as AE monitoring of wire ropes [11,12]. Acoustic waves propagate better in water, being less

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attenuated over larger distances, and recent work showed WEC signatures could be distinguished up to 200 m away [13]. AE from mooring ropes needs to be separated from other noises associated with device operation (e.g. the Power-Take Off system of a WEC), maintenance (e.g. supply or repair vessels) and environment (wind, weather and waves, mostly) [14]. In the case of WECs, this is exacerbated by the fact that mooring connections can significantly affect energy absorption and production [15], potentially changing the acoustic signature from surface waves. It is therefore extremely important to understand the exact acoustic contributions of mooring ropes to the soundscape, in particular as they approach failure.

This article focuses on polyester ropes, as they are potentially an enabling technology for cost-effective mooring systems [3]. Polyester ropes are preferable over steel ropes as certain materials and constructions display greater compliance which can lead to a reduction in peak loadings. Their operational characteristics are however complex, often with time-dependent viscoelastic and viscoplastic behaviour [16]. For the purpose of this study three samples of a typical rope material and construction were tested in the controlled environment of the large-scale dynamic test rig DMaC (Dynamic Marine Component, University of Exeter), under a variety of loads typical of marine operations (Section 2). Their Acoustic Emissions were monitored with 3 broadband hydrophones and specific signatures were identified in spectrograms (Section 3). The time-of-arrival localisation of specific AE is linked to the physical processes of degradation and failure (Section 4). This Section also identifies which characteristics can best be used at sea, focusing on the application of this technique to Wave Energy Converter mooring system monitoring. The concluding remarks are presented in Section 5.

2. Experimental testing

Underwater acoustic testing has been carried out to study the AE of synthetic fibre mooring ropes. The aim of the testing was to detect the release of acoustic waves or energy in response to applied loading regimes, informing remote monitoring options for reliability and durability assessment of polyester ropes.

2.1. Samples

The rope type chosen for the experiments was a 12-strand double-braid polyester rope with a nominal diameter of 24 mm. The rope has six right-hand laid strands and six left-hand laid strands that produce a torque balanced rope. It is a double-braided rope with a core enclosed by an outer braid cover. The internal and external core construction are both laid in a braided assembly. This 12-strand double-braid rope construction offers high strength and very good abrasion resistance and as such is well suited to MRE mooring applications [3].

Acoustic testing was carried out on three polyester rope samples from the same manufacturer's batch, referred to as R1, R2 and R3 in the following sections. The three samples were eye-spliced in order to connect them into the test rig using mooring shackles. The total eye-to-eye length of the three spliced ropes before loading was measured to be R1 = 3.53 m, R2 = 3.60 m, R3 = 3.62 m. The rope sample properties are given in Table 1 as stated by the manufacturer [17]. Fig. 1(a) provides a schematic of the construction of double braided rope and Fig. 1(b) shows the photograph for internal core and outer cover of the rope.

Table 1
Rope properties & specification [17].

Material	High tenacity polyester multifilament fibre
Construction	12 strand double braid
Nominal diameter	24 mm
Nominal mass in water	0.13 kg/m
Minimum breaking force	129 kN

2.2. Test facility and tensile load profile

The DMaC facility is a purpose built test rig that can replicate the forces and motions that components are subjected to in offshore applications. The rig can test component specimens of up to 5 m in length (with up to 1 m extension) and has the capability of carrying out immersed component testing. The linear actuator and the headstock allow the dynamic testing of large scale components in a fully-controlled environment by applying realistic motion and load time-series [18].

All three rope samples were subjected to similar tensile cyclic loading regimes with the objective to progressively increase the maximum load until failure. Before applying tensile cyclic loading, bedding-in was carried out for all three rope samples. The bedding-in procedure was specified using the rope MBL as outlined in [16]. However, due to time constraints a shortened procedure was specified with shorter load-hold durations. A twenty minute bedding-in time interval comprising hold and ramp cycles lasting twenty seconds with a minimum and maximum load of 5 kN and 20 kN respectively was used. The time series plot for bedding-in cycles is given in Fig. 2(a). It is acknowledged that the samples may not have been completely bedded-in after this process.

The rope samples were subjected to sinusoidal load cycles, oscillating between the minimum and maximum loads indicated. The minimum loading was set to 5 kN, whilst the maximum loading was stepwise increased from 30 kN until rope failure. An example time series plot for cyclic loading of between 5 kN and 90 kN is shown in Fig. 2(b). The cyclic loading was increased linearly in order to study the acoustic emission for all regimes. Rope sample R1 was tested with slightly larger step-sizes to identify loads of increased acoustic release. Rope samples R2 and R3 were tested with smaller incremental steps to provide a different load increment. Initially, the rope sample R1 was subjected to load cycles with a time period of 40 s, and this was later increased to 60 s for rope sample R2 and R3 to minimize the background noise caused by the test rig. Table 2 summarizes the individual test cycles experienced by each rope sample.

2.3. Acoustic set up

In order to carry out underwater acoustic testing of polyester ropes, a linear array consisting of three hydrophones was installed inside the DMaC test rig. Two of the sensors were SQ26-08 Cetacean cylindrical shaped directional hydrophones and the third was a ball-shaped JS-B100-C4DS-PA Integrated Acoustic Sensor. Table 3 summarizes the specifications for both types of hydrophones used. The two cylindrical hydrophones were placed at the two ends of the rope samples close to the splices ('Headstock hydrophone' and 'Z-ram hydrophone') and the third ball hydrophone was placed at the centre of the rope samples ('Centre hydrophone'). The hydrophones were placed at equal distances (i.e. 1.6 m) along the rope in order to cover the entire length of the rope. A schematic of this configuration and photographs of the mounted hydrophones are shown in Fig. 3.

The test rig was filled with fresh water and the rope samples were submerged 10 cm deep. The hydrophone array was placed at a distance of 10 cm next to the length of the rope and at the same depth in the water. The hydrophones were enclosed in a wire cage to protect them from damage. Similarly, the cables of the hydrophones were passed through PVC pipes for protection. The pipes were filled with self-expanding foam to avoid them acting