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Synthetic rope responses in the context of load history: Operational performance

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ABSTRACT

The utilisation of synthetic mooring ropes for marine renewable energy (MRE) devices is a recent occurrence. Despite current use in the offshore industry, MRE mooring components are typically subjected to highly dynamic loads, necessitating the detailed characterisation of operational and long-term component performance for lifecycle analysis and operations management. To address the uncertainties associated with synthetic mooring components in this application, tension experiments have been conducted on nylon 6 parallel-stranded rope samples at IFREMER, France and the University of Exeter, UK under the consortium MERiFIC (Marine Energy in Far Peripheral and Island Communities). Measurements are reported from harmonic loading tests with different initial bedding-in levels used to investigate the influence of load history on the immediate dynamic properties of the rope. Two irregular load regimes were also applied based on mooring tensions recorded by the South West Mooring Test Facility (SWMTF). Datasets are provided to facilitate the development of rope modelling tools. For the load regimes studied it was found that the operational performance of the rope is strongly influenced by the instantaneous load-strain characteristic. This study provides unique insight into the stiffness and damping properties of synthetic rope in the context of loading regimes relevant to MRE devices.

1. Introduction

Due to favourable performance characteristics and an inherent ability to reduce peak mooring loads, there has been an increase in the use of synthetic ropes made from materials such as HMPE, polyester, nylon and aramid for the station-keeping of offshore equipment over the past two decades (da Costas Mattos and Chimisso, 2011; François et al., 2010; Chailleux and Davies, 2003). This has led to a number of testing programmes which have primarily been carried out by the oil and gas industry and the development of certification guidelines and standards, such as those produced by Bureau Veritas (2007), International Standards Organisation (2007), Det Norske Veritas (2010) and American Bureau of Shipping (2011). Marine renewable energy (MRE) devices are a new field of application requiring the development of robust and economical mooring systems. It is likely that the synthetic materials currently used for existing offshore equipment will feature in the mooring systems of MRE devices (Ridge et al., 2010) and recommendations have been produced to pre-empt the shift from conventional technologies (e.g. The Carbon Trust/DNV The Carbon Trust, 2005). Acting as a point of reference, these guidelines are based on recommendations made for the station-keeping of large offshore equipment and their applicability is questionable for the mooring systems of smaller structures, such as floating tidal turbines and wave energy converters (WECs) due to differences in mooring system footprint, load regimes, mass distribution, water depth and expected environmental conditions. For example large floating platforms, such as those used for fossil fuel exploration and extraction tend to be located in water depths much greater than WECs (up to 3000 m for spar platforms). Although the mooring system designs are broadly similar (i.e. catenary or taut-leg geometries), large manned platforms are designed with natural periods which avoid the expected first-order wave periods of the area, enabling the platform to remain on station and operate safely. Excitation by longer period, second-order wave forces may be permitted if levels of component fatigue cycling are acceptable. In contrast WECs are designed so that the natural periods of one or more modes of motion correlate with the expected wave energy periods in order to maximise the level of energy absorbed for a given location. This can result in highly dynamic device responses which are directly coupled to the response of the mooring system. Given this context significant uncertainties exist about the application of synthetic ropes for MRE devices and it is essential that the operational and long-term performance of mooring components is quantified to enable predictions to be made regarding fatigue life and capacity to

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withstand extreme loads (Johanning et al., 2006). The mooring response will be influenced by the physical properties of components within the system (mass, geometry, axial stiffness and damping) (Johanning et al., 2007; Fitzgerald and Bergdahl, 2008) as well as other loading mechanisms (i.e. viscous drag and added mass). Whilst ultimate strength and axial stiffness have been quantified for the loading regimes and rope constructions relevant for large, slow-moving equipment (e.g. Banfield et al., 2000; da Costas Mattos and Chimisso, 2011; Davies et al., 2011), material and structural damping are usually not reported. As part of a dedicated component testing program involving the collaboration of L'Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) and the University of Exeter, as part of a MERiFIC (Marine Energy in Far Peripheral and Island Communities) consortium, the axial stiffness and the damping of several parallel-stranded nylon 6 rope samples are quantified in the context of the operational mooring loads that could be experienced by MRE devices. Nylon has been selected due to its compliant properties which may be utilised to reduce peak mooring loads (Ridge et al., 2010). In this study, harmonic and irregular loading regimes are used to determine the average performance of new rope samples with investigations made on the influence of load history on time-averaged and time-varying performance. In a forthcoming publication rope conditioning will be investigated, with comparisons made between the dry and wet performance of the new rope samples and also the loading behaviour of an aged rope sample utilised on the South West Mooring Test Facility (SWMTF). It is the intention of the present study to provide experimental data that can be used to reduce uncertainties regarding the performance and reliability of nylon mooring ropes, enabling the design of economical mooring systems and facilitating the development of guidelines and standards which are more applicable to MRE devices (e.g. IEC-TS 62600-10 Ed.1.0, IEC, 2013).

In the next section the experimental equipment used in this study is outlined. The loading regimes applied to the rope samples are then defined in the context of mooring tension measurements recorded by the South West Mooring Test Facility (SWMTF). The experimental method and analysis techniques adopted are then summarised. In Section 3 results are presented from harmonic load tests involving three new rope samples subjected to different bedding-in levels. To further investigate the effect of load history on sample performance, irregular load tests based on SWMTF mooring tension measurements are presented in Section 4.

2. Experimental approach

2.1. Equipment used at IFREMER and the University of Exeter

The synthetic rope studied has a parallel-stranded subrope construction comprising multi-filament nylon 6 fibres, with a minimum break load (MBL) specified by the manufacturer of 466 kN. The rope comprises seven subropes surrounded by a non-load bearing jacket, resulting in a cross-sectional diameter of 0.044 m (Fig. 1a). Three samples were supplied by the manufacturer pre-spliced with an eye-to-eye distance of approximately 5 m. These ropes form the upper 20 m of the three catenary mooring lines used on the South West Mooring Test Facility (SWMTF; Fig. 1b) which was designed and is operated by the University of Exeter. Located in an average water depth of 30 m in Falmouth Bay, the lower sections of each mooring line comprise chains and a drag anchor. On the surface is an instrumented buoy which includes a digital GPS unit (10 Hz sampling rate) and a multi-axis inertial ‘MotionPack’ (20 Hz sampling rate) as well as a digital compass and sensors to measure temperature, wind velocity, wind direction and salinity. At each mooring limb attachment point, tensions are simultaneously recorded at a sample rate of 20 Hz by a three-axis load cell in addition to an axial load cell. Current velocities in the water column and surface elevations are recorded at 2 Hz using a seabed-mounted 4-beam Acoustic Doppler Current Profiler (ADCP) located nearby. In this paper only the tension measurements recorded by the axial load cells are reported. Further details regarding the SWMTF can be found in Johanning et al. (2011).

The rope samples were subjected to several loading regimes in dry conditions using the 100 Tonne hydraulic test machine at IFREMER. This machine has the capability of testing samples up to 10 m long in quasi-static and dynamic conditions (e.g. Davies et al., 2011, Fig. 1c). Extension of the free length of the sample was measured (sample rate: 2 Hz) over a distance of 1.1 m using a draw-wire transducer (ASM Sensors: WS10-375-R1-L10) clamped to the rope, at least 0.25 m clear of the end terminations and splices. Loads applied to the sample and hydraulic piston displacements were also recorded at a sample rate of 2 Hz. Additional tests to replicate irregular tension time-series measured by the SWMTF and faster harmonic oscillation periods were also conducted using the DMaC (Dynamic Marine Component) test facility at the University of Exeter (Fig. 1d). The facility includes a hydraulically powered tailstock for the application of user-defined loads (harmonic and irregular time-series). Although not utilised in this study, a hydraulically powered headstock provides an additional three degrees-of-freedom (roll, pitch and yaw) for applying bending and torsional loads (Johanning et al., 2011). For this machine, extension of the free length of the sample was measured using a draw-wire transducer (Applied Measurements: WS12-1000-R1K-L10-SBO-M12) at a rate of 50 Hz. Hydraulic piston displacements and applied loads were also recorded at a sample rate of 50 Hz. Due to the occurrence of signal noise, extension measurements were filtered using a low-pass Butterworth filter with a cut-off frequency of 1.5 Hz. A comparison between the IFREMER test machine and the DMaC test facility is provided in Table 1.

2.2. South West Mooring Test Facility load measurements

In order to replicate loading conditions in the laboratory that are relevant to the mooring systems of buoy-like MRE devices, the rope samples were subjected to load regimes defined in the context of mooring line tensions measured by the SWMTF between March 2010 and September 2011 (Fig. 2a). During this first deployment a range of load and load rates were recorded by the axial load cells, the extremes of which are represented by tension time-series measured in calm (Fig. 2c) and mild-storm (Fig. 2d) conditions. In calm conditions ($H_s \approx 0.36$ m, $T_p \approx 4.1$ s, average water depth 32.5–33 m from ADCP measurements) the average tension for Lines 1–3 was 3.77 kN, corresponding to 0.8% of the rope MBL. During mild-storm conditions ($H_s \approx 2.67$ m, $T_p \approx 7.5$ s, average water depth 31.9–32 m) much larger loads were measured, with an average tension of 5.97 kN. In the plotted time-series the majority of loads are low amplitude and in the range of 0–4% of the rope's MBL, in which the stiffness of the rope is highly non-linear (Flory et al., 2004). A notable snatch load of 0–52.2 kN (0–11.2% MBL) occurred during the mild-storm interval for Line 1 at 02:09:55, providing insight into the survivability of the system during the application of a short duration, high magnitude load. This event does not directly correspond with a large wave peak, instead it is due to the dynamic response of the buoy and the mooring system. Although severe, analysis of the axial mooring loads measured during the first SWMTF deployment indicates that a peak load of this magnitude was an isolated event, with most loads lower than 8% MBL (Fig. 2b; details of the identification method used are outlined in Weller et al., 2012).