Physical testing of a non-linear active damper developed for offshore renewable energy

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The ambitions of large-scale offshore renewable energy deployment can only be realised if technological and logistical challenges are resolved to reduce the levelised cost of energy. The effective station keeping during device lifetime is a significant challenge that can be addressed through innovation in mooring systems. To increase confidence in the performance of the innovative components and systems prior to field deployment, lab based physical testing must be conducted.

The Intelligent Mooring System (IMS) is an innovative non-linear component that is designed to provide active control over the load response of the mooring system to reduce peak loads. To improve the seaworthiness of the system, design changes were made and the resulting IMS is composed of a braided Dyneema sleeve housing an internal accumulator. This paper characterises the static and dynamic load response of the improved design through physical tests conducted at the Dynamic Marine Component test facility.

Results indicate that the initial internal pressure is the primary driver of the IMS stiffness profile relative to the water/air ratio. A comparison between the quasi-static and dynamic stiffness characterisation shows that quasi-static stiffness provides a good first-estimate for individual configurations. While the Dyneema fibre displays a hysteretic behaviour for loading and unloading, it improves the strength of the IMS by 47% compared to the previous Vectran build.

The presented stiffness curves of the IMS can be used in conjunction with available offshore renewable energy system models to demonstrate the effectiveness of including the IMS in the mooring system to reduce peak loads. Future work includes the field demonstration of a scaled prototype at the U.S. Navy Wave Energy Test Site in Hawaii.

***Keywords*—Non-linear mooring component, Performance characterisation, Physical testing.**

I. Introduction

MOORING system design in offshore renewable energy readily adopts components and standard guidance from conventional industries such as oil and gas to provide the required structural integrity and station-keeping capacity. Designing a robust mooring system that can withstand peak loads results in a conservative system design that can be marked with a high capital expenditure. If peak loads can be mitigated, the cost of mooring systems and associated structural elements can be significantly reduced.

To achieve mooring load reduction, Intelligent Moorings Limited has developed a non-linear active damper, the Intelligent Mooring System (IMS). A range of design improvements have been achieved throughout the product development phase aimed at reducing the number of mechanical moving parts. The resulting IMS is a large diameter braided sleeve encapsulating a hydraulic reservoir. It is regarded as an active damper as its stiffness can be tuned dynamically in operation in response to wind and wave conditions, as well as allowing multiple pre-configured responses to loading thresholds. This ability to change the load-extension curve in operation also allows tuning of the mooring system, potentially reducing platform motions through variable pre-tension without replacing the mooring system.

The IMS displays non-linear stiffness behaviour, where it has an initial soft/elastic response followed by a stiffer response for higher elongations. This is due to a combination of adiabatic processes and non-linear volume change. The resistance to extension is provided by the pressure in the flexible hydraulic reservoir: as the braid extends, the internal bladder reduces in volume causing an increase in internal pressure. This provides a means of storing energy from loading events to reduce the tension developed in mooring lines. Consequently, the initial

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elastic response and further extension are limited by the action of the hydraulic resistance.

Currently developed to Technology Readiness Level (TRL) 5, the IMS will be installed at the top end of mooring lines for large floating platforms. The number of units and length of the IMS will be decided based on the site-specific loading conditions. Previous numerical investigations [1] have replaced the top 2% of the conventional line with the IMS for different mooring systems to simulate the load reduction potential.

Whilst essential innovative aspects have been proven through analytical assessment [1, 2, 3, 4] and physical testing [5, 6, 7] in previous projects, this paper presents further development of the innovation as the IMS prepares for commercialisation in the offshore renewable energy sector.

Previously, physical demonstration has been conducted for an IMS device with a different build: it was composed of a Vectran braid sleeve housing an internal fluid filled bladder. This was additionally attached to a 20 litre gas charged accumulator to allow for fluid transfer to the accumulator when the internal pressure in the bladder increased. The unstretched braid length was 0.67 m. Quasi-static and dynamic tests were conducted with various pre-charge pressures to quantify the influence of pre-charge on bladder stiffness. Table I summarises the difference between the previous test campaign [6] and the campaign presented in this paper.

TABLE I
COMPARISON OF TEST CAMPAIGN 1 WITH PREVIOUS TEST CAMPAIGNS AS PRESENTED IN [6].

Feature	Harrold et al [6]	Feature
Braid material	Vectran	Dyneema
Braid length (m)	0.67	1.0
External accumulator	Yes	No

Previous testing [6] showed that the bladder displayed non-helical deformation due to the presence of the end caps. It was also found that the hydraulic properties showed good agreement between the predictions and measurements. Three 'pre-charge' configurations were tested where the internal system pressure was 163 kPa, 252 kPa and 310 kPa to characterise the non-linear tension-extension behaviour of the IMS. The system was also exposed to dynamic loading with cycle periods of 60, 30, 20, 15, 12, 10 and 8 seconds at each pre-charge pressure. The dynamic performance showed good agreement with the quasi-static performance for the Vectran braid.

As a result of the break testing of the Vectran sample, the following three failure mechanisms were identified:

- Braid end cap failure
- End cap bolt failure
- Braid section failure

II. TEST SET-UP

A. IMS prototype

The IMS device for this test campaign, as shown in Fig. 1, is designed as a fully sealed length of hollow braided Dyneema rope around a bladder with varying ratios of water and air. The unstretched length of the braid is 1.0 m and the diameter is 0.16 m. The extension of the braided rope under tension leads to a contraction in the braid diameter, resulting in a volumetric reduction of the bladder. Since the whole system is pressurised and fully sealed, this leads to the compression of the gas (air) inside.

Fig. 1. IMS prototype for performance testing.

B. Test facility

The IMS unit was tested at the Dynamic Marine Component Test Rig (DMaC) at the University of Exeter for two weeks between 19/10/2020 to 30/10/2020. DMaC, pictured in Fig. 2, is a tensile test machine that can replicate the dynamic loading and motions experienced by components, including mooring systems, in offshore conditions. One end of the rig consists of a linear hydraulic cylinder that can apply tension and compression forces to replicate the heave, whereas, the other end can apply forces in 3 degrees of freedom, namely roll, pitch and yaw to represent x- and y-bending or torsion forces.

Fig. 2. DMaC test facility showing headstock (far-end) and tailstock (near-end).

DMaC has a stroke length of 1 m and can apply tensile forces up to 200 kN and 450 kN under dynamic and static conditions, respectively. The actuation of the rig can be controlled in displacement or force mode. For this test campaign, the tests were run in displacement mode.

Three measurements were taken during each test: force, elongation and pressure. For the tests reported here, these were simultaneously logged at a sample rate of 50 Hz. An industrial pressure sensor with a full scale accuracy of <±0.25 based on the best fit straight line method is used.

DMaC provides the capability to test components in a submerged environment to ensure that the tests are representative of the intended application, therefore, this test campaign was conducted with the IMS submerged in freshwater.

The quantity of water and air in the IMS was administered through a single inlet/outlet at the tailstock end of DMaC. To avoid pressure build up and rupture of the bladder, a pressure relief valve was also included in the set-up with a rating of 600 kPa as shown in Fig.3.

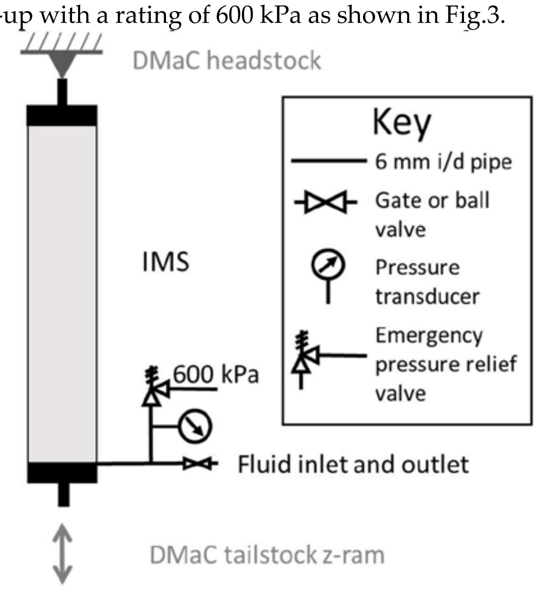


Fig. 3. IMS test set-up at DMaC.

C. *Sample preparation*

At the outset of the test campaign, limits for pressure, force and elongation were identified in order to avoid pre-mature failure of the IMS. These were calculated based on previous testing [6]. It was determined that the device must only be operated within a 30 kN load limit, half the minimum breaking strength of a single Vectran unit estimated at 60 kN. Similarly, the pressure limit was determined at 350 kPa for all tests and the elongation limit was set at 40%.

The sample initial internal pressure was set to the required values via a pump and the readings from the pressure sensors were monitored throughout this process to ensure accuracy. The total fluid in the system for each configuration was topped up through the same inlet using standard fluid measurement equipment. Each top-up required removal of existing air in the system.

The IMS was subjected to a standard bedding-in procedure at the outset of the test campaign to condition the rope to a known, repeatable state, as described in Section B3.1 in ISO/TS 19336:2015 [8] for fibre ropes.

The standard describes the bedding-in process with respect to the Minimum Breaking Load (MBL). However, the MBL of the IMS with Dyneema braid was not known, therefore, extra caution was exercised during the bedding-in process. The IMS was pulled to 0.3 m and held under this load for 30 minutes followed by 100 cycles between 0 m to 0.2 m at 30 s period.

III. Methodology

The following characterisation studies are conducted to suitably configure the IMS for field deployment:

- Study 1: Braid characterisation
- Study 2: Stiffness characterisation
- Study 3: Break test

D. *Braid characterisation*

In order to fully characterise the braid, braid angle and circumference measurements were also taken in addition to the standard readings of force, elongation and pressure. These readings were recorded manually by extending the IMS single unit in 0.05 m intervals and using a measuring tape and protractor to record the circumference and braid angle at the centre as indicated by the markings in Fig. 1. This characterisation practice was performed for Configuration 1 with initial internal pressure of 100 kPa and no water in the system.

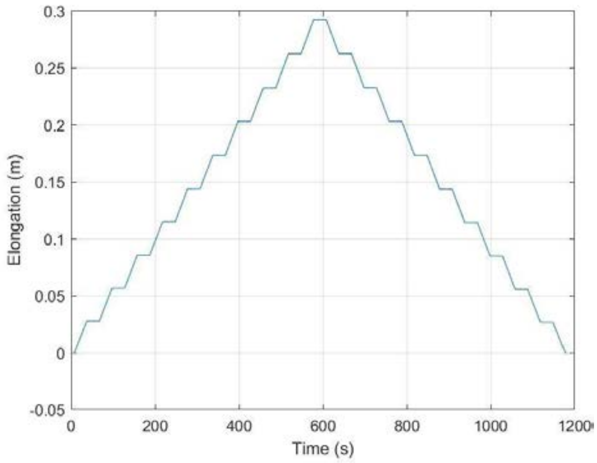
E. *Stiffness characterisation*

Study 2 was distributed into a two-step approach, where the first step was a manual jog of the IMS to ascertain the safe operation of the system to determine the dominant safety limit and associated force and elongation measurements. In the second step, these force and elongation measurements were used to design the quasi-static and dynamic tests for each configuration to ensure safe completion of tests without pre-mature failures.

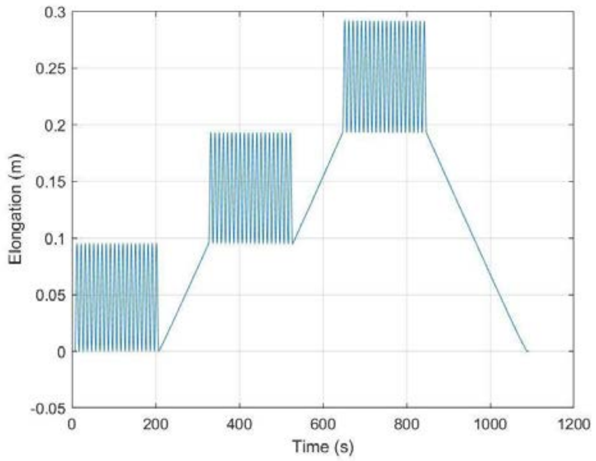
Study 2 was conducted for a number of IMS configurations, where the IMS configuration was

TABLE II
IMS single unit configurations for the test campaign

Configuration	Water (ml)	Water/Air ratio	Pressure (kPa)
1	0	0	100
2			200
3	2000	0.1	100
4			200
5	4000	0.2	100
6			200
7	6000	0.3	100
8			200
9	8000	0.4	100
10			200
11	10000	0.5	100
12			200



(a) Quasi-static



(b) Dynamic

Fig. 4. Example input elongation time series for (a) quasi-static and (b) dynamic stiffness characterisation tests.

determined by the water/air ratio and initial internal pressure. Water/air ratio of 0 to 0.5 was investigated and configurations with initial internal pressure of 100 kPa and 200 kPa were tested as shown in Table II.

The manual jog for stiffness characterisation was conducted by an incremental increase in the extension of the IMS until one of the safety limits was achieved. For configurations with initial internal pressure of 100 kPa, this was usually the extension limit of 40% whereas for the initial internal pressure of 200 kPa, pressure was the limiting factor.

After determining the maximum safe extension of the IMS for each configuration through the manual jog, quasi-static testing was conducted. The braid extension was increased in 30 s intervals and the IMS held at each extension for 30 s. Fig. 4a shows the input extension time series for Configuration 11 (initial internal pressure: 100 kPa, water/air ratio: 0.5) as an example.

For each configuration, the system was then loaded dynamically for 3 extension intervals of 0-10%, 10-20% and 20-30%. 20 cycles were applied at each extension interval at a range of cycling periods from 4 s to 30 s. For Configurations 9, 10 and 11 the final extension interval at 20-30% was not applied to reduce the risk of premature failure.

Fig. 4b shows the extension time series for Configuration 11 with a cycling period of 20 s.

F. *Break test*

The break test was conducted on the IMS single unit at Configuration 12 (Table II) where the initial internal pressure was 200 kPa and the water/air ratio 0.5. The braid was slowly and continuously extended until it started to show damage and then failed completely.

IV. RESULTS

This section presents a summary of the results of the test campaign where the performance of the Dyneema braid and internal accumulator are characterised through a series of tests.

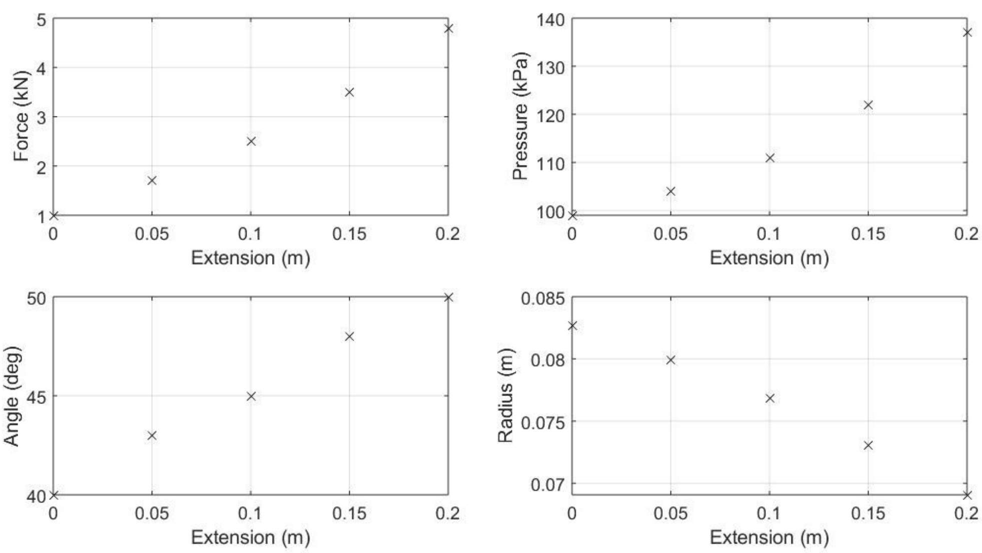


Fig. 5. Braid characterisation for Configuration 1 with a water air ratio of 0 and 100 kPa initial internal pressure.

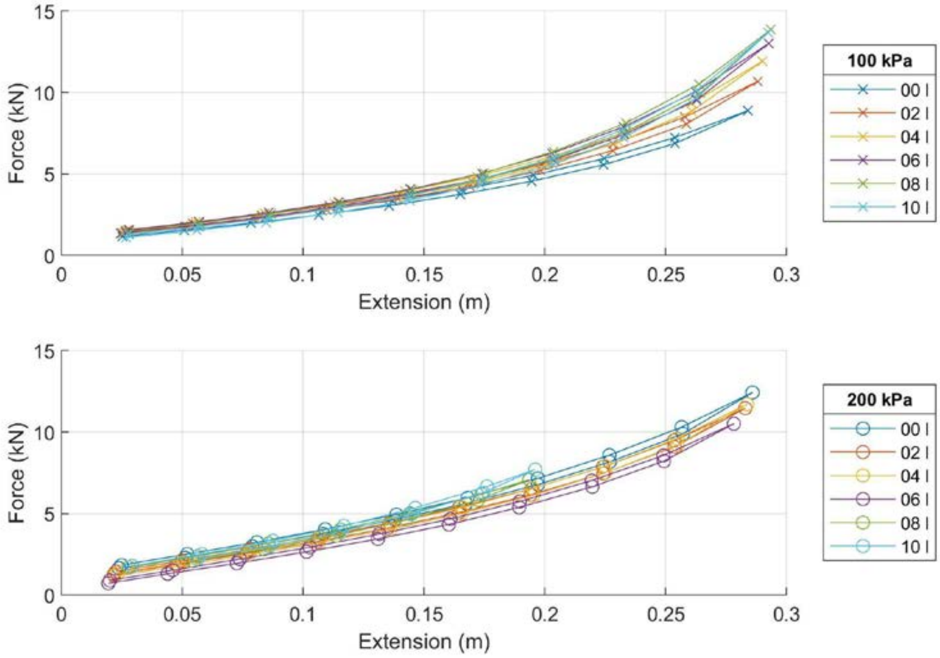
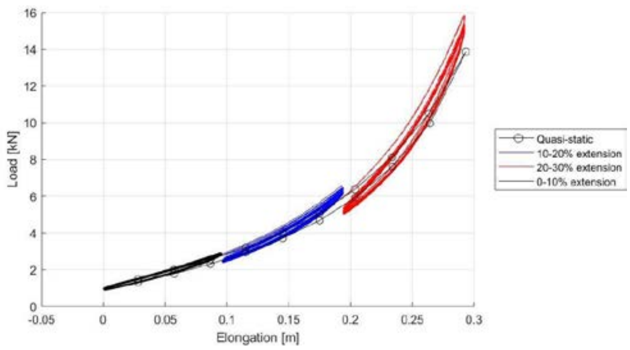


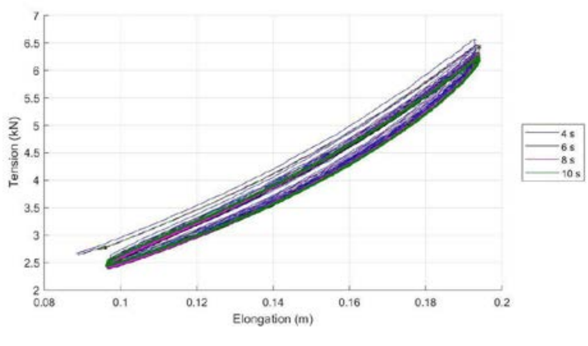
Fig. 6. Quasi-static load-extension profile for the various IMS configurations.

G. Braid characterisation

The resulting force, braid angle, internal pressure and braid radius can be seen in Fig. 5. It can be seen that as the braid undergoes extension, the braid angle increases whereas the braid radius at the centre decreases. This leads to a volumetric reduction causing an increase in the system internal pressure due to compression of air. As the air is compressed further, the hydraulic resistance increases leading to the non-linear behaviour displayed by the IMS.



(a) Quasi-static and dynamic



(b) Dynamic at different cycling frequency

Fig. 7. Comparison of tension-extension profile between (a) quasi-static and dynamic testing as well as (b) dynamic testing at a range of cycling periods

H. Stiffness characterisation

Fig. 6 shows the quasi-static stiffness profile for the tested configurations. For each configuration, the load-extension plot for extension and retraction is seen which displays a hysteretic behaviour. It can be seen that for the initial internal pressure of 100 kPa, the system elongation is the primary limiting factor, whereas this was not achieved for the 200 kPa configurations. Instead, these configurations were extended until they reached the pressure limit.

A comparison of the quasi-static profile of the IMS to the dynamic analysis is conducted and Fig. 7a shows the resulting comparison for Configuration 9.

In order to investigate the influence of cycling period on the dynamic performance of the IMS, Figure. 7b shows the 10-20% extension of the IMS for cycling periods of 4 s, 6 s, 8 s and 10 s.

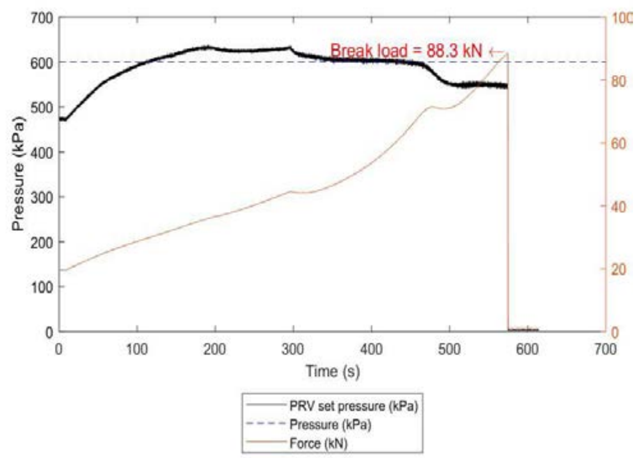


Fig. 8. IMS break test time series for the force and internal pressure.

It can be observed that for the investigated periods, the IMS does not show considerable variation in its dynamic performance when the cycling frequency is changed.

I. Break test

The MBL of the single unit IMS with Dyneema braid was determined at 88.3 kN as seen in Fig. 8. The figure shows that two small peaks were observed in the tension profile of the IMS; at 300 s and 480 s during the break test. The first is due to the escape of water as the set pressure on the relief valve was achieved. The second peak can be attributed to the loss of air which led to a larger loss in pressure. The pressure profile in Fig. 8 shows these dips due to the pressure relief valve (PRV) settings.

The IMS break test showed that the bladder, end plate bolts and clamps were intact. A circumferential braid failure was observed.

V. Discussion

The single unit tests presented in this paper establish that the improved IMS design also displays a non-linear stiffness behaviour similar to the previous Vectran build. The IMS response characteristics are seen to be dependent on the IMS configuration that depends on two primary variables: water/air ratio and initial internal pressure. It was found that the initial internal pressure was the primary driver of the stiffness profile relative to the water/air ratio. Therefore, a larger envelope of stiffness profiles can be achieved by adjusting the internal pressure of the IMS instead of the water/air ratio. Therefore, the functionality of the IMS to tune its stiffness based on the prevalent sea state will largely depend on the control of the internal pressure. A more compliant IMS with lower internal pressure will be suitable for normal sea states to reduce structural mooring loads, however, a stiff configuration with high internal pressure can provide effective station-keeping during storm conditions.

A comparison of the dynamic and quasi-static testing shows that the quasi-static tests slightly underestimate the stiffness of the IMS for some configurations. The characterisation curves from the quasi-static tests can be used to define the stiffness profiles in numerical simulations of full-scale offshore wind systems to identify the load reduction potential of the IMS. Existing software tools do not provide the capability of including dynamic characterisation curves, therefore, quasi-static characterisation can be used as a good first estimate.

The difference between dynamic stiffness results for different cycling periods is minimal for the investigated periods between 4 s and 30 s. This can be attributed to the small range of extensions used for dynamic testing. Cycling periods do not show considerable effect for a 10% extension range for different levels of extension, however, a larger effect can be observed if the cycling range is increased to 30% extension. For future testing, lower cycling periods and larger extension ranges must be investigated to see significant differences in the stiffness profile during dynamic testing.

The new IMS build is more compact and has fewer moving parts that improves its seaworthiness and reduces the maintenance requirements. The robustness of the system has been improved as the bladder, end-plate bolts and clamps remained intact during testing. A new failure mode has been observed during testing as the braid experienced a circumferential failure. Furthermore, the IMS single unit with Dyneema build has a minimum break load of 88 kN relative to 60 kN for the Vectran build tested in previous test campaigns.

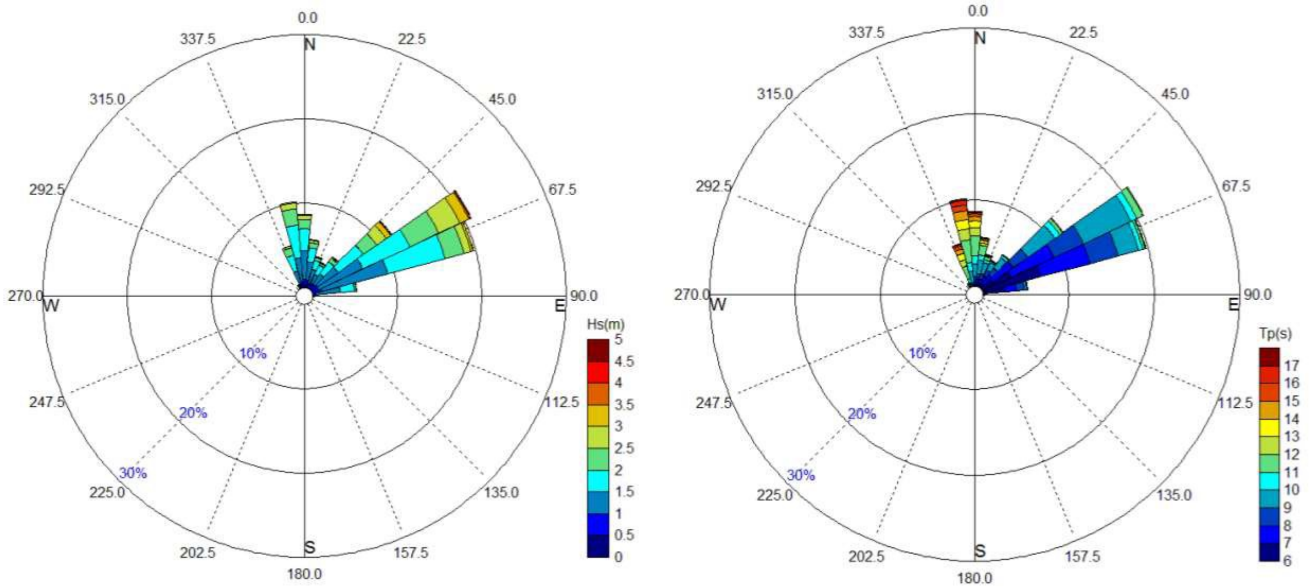


Fig. 9. Rose plot of (a) significant wave height and (b) peak period at the Wave Energy Test Site based on Waverider records from November 2012 to October 2013 [16].

VI. Further Work

Based on the results of the physical testing, planned further work includes site-specific coupled modelling and system integration with floating platform design requirements. The IMS will be designed, built and tested for field demonstration at the U.S. Navy, Wave Energy Test Site (WETS) located offshore at the Marine Corps Base (MCB), Hawaii in Oahu's Kaneohe Bay. [9].

WETS has three pre-permitted, grid-connected berths within 2 km of shore with primary mooring, submarine power and data cable [10]. It provides the opportunity to test components and systems in a partially sheltered, open-water location at TRL 5–7 and is currently configured for testing point absorbers and oscillating water column devices. Previous deployments at WETS include the Northwest Energy Innovations Azura [11], Fred Olsen LifeSaver [12] and C-Power SeaRAY [13], whereas, planned deployments for 2021 include the Oscilla Triton-C [14] and OceanEnergy OE35 [15].

The wave climate at the WETS site is composed of swells from the Pacific and wind waves from the northeast with average wave heights in the 1-3 m range and wave period in the 6-10 s range. The occurrence, magnitude, and direction of the wave height and period is shown in Fig. 9 as investigated by [16].

The deployment of the IMS at the WETS site provides an opportunity to test a design that is suitable to meet quarter scale loads for platforms supporting the NREL 15 MW reference turbine. The planned field tests will increase the TRL of this mooring technology, demonstrating the operational performance of the IMS system.

VII. Conclusion

The presented performance characterisation curves of the IMS can be used in conjunction with available models of offshore renewable energy devices for individual deployment sites. This will quantify the expected peak load reduction achieved by including the IMS in the mooring system. In practice, the IMS configuration will be such that it provides the required strength to withstand environmental and turbine operational loads whilst providing necessary compliance to reduce the platform loads. The site- and platform-specific loads will be determined by conducting analysis similar to that described in previous studies [1, 4].

The demonstration testing has shown that the safety limits used for this test campaign were highly conservative, therefore, future testing can benefit from the results of the break test to define suitable safety envelopes. Future testing involves laboratory testing of an IMS with multiple units attached in parallel to understand their performance. Additionally, the range of dynamic tests must be increased including higher initial internal pressure settings to identify the range of possible stiffer response of the system.

The planned field demonstration testing offers a subsequent technology development towards a higher TRL, de-risking the innovation ahead of commercial use in offshore renewable energy projects.

Acknowledgement

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