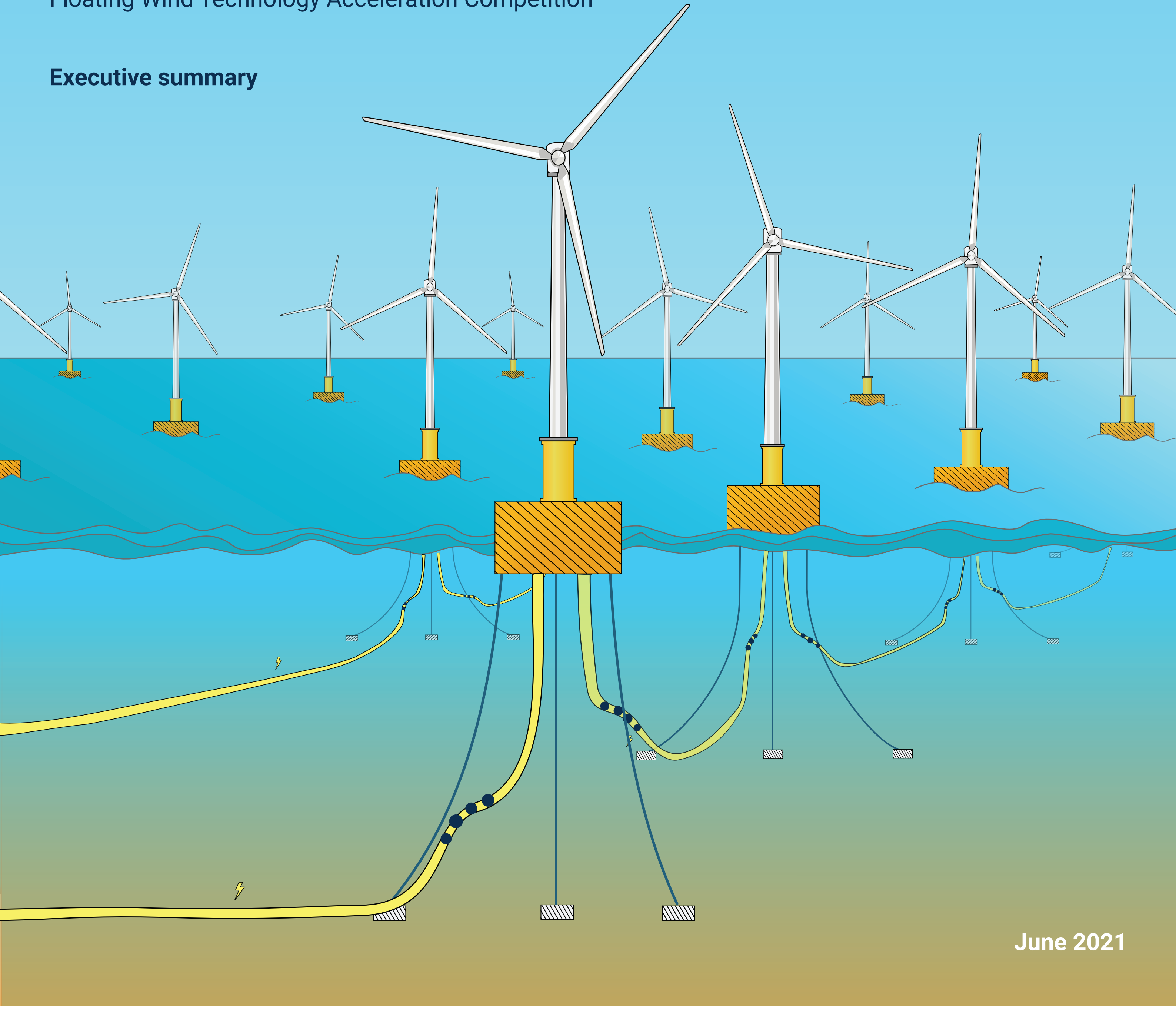
CARBON TRUST

Condition Monitoring of Floating Wind Mooring Lines

Floating Wind Technology Acceleration Competition

Executive summary



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Final Report: Executive Summary

Remote monitoring combined with digital-twin methods can eliminate or reduce subsea inspections of mooring systems on floating offshore wind turbines, yielding significant cost-savings.

Introduction

A consortium of Fugro, AS Mosley and the University of Strathclyde were awarded a grant as part of the Floating Wind Technology Acceleration Competition, administered by the Carbon Trust with funding from the Scottish Government. The project was titled: Condition Monitoring of Floating Wind Mooring Lines.

The purpose of the work was to demonstrate a remote monitoring approach for a Floating Offshore Wind Turbine (FOWT) to track mooring line fatigue as an enabler for a risk-based inspection regime. To be cost-effective, the monitoring system considered only robust and reliable sensors that can be mounted on (and preferably within) the floating hull, namely: accelerometers, gyroscopes and satellite positioning. The resulting position and motion signals were converted to mooring line tension cycles using transfer functions generated from a simulation model of the FOWT that characterised its response in various wind and wave conditions. Mooring line fatigue was calculated using the industry-standard S-N Curve method but also using a new peridynamic method, which gives a comprehensive assessment of fatigue damage progression. Tracking fatigue over the whole life of the FOWT, allows subsea inspections to be targeted to only when (and if) necessary. The elimination of unnecessary subsea inspection yields significant cost-savings as well as reduced health and safety exposure.

Simulation and Mooring Line Tension Cycles

A simulation model of the Hywind Scotland 6 MW FOWT design was created to simulate its response to a variety of environmental conditions. The simulation response was tailored to match the measured Hywind Scotland response as closely as possible using the available design information.

A method of calculating the mooring lines tensions was demonstrated based on virtual sensor packages measuring FOWT motion and position. Excellent correlation and fatigue matching were obtained at the mooring line connections versus tension extracted directly from the simulation (see Figure 1). Typical correspondence for fatigue was within 10%, which is very good for fatigue tracking and excellent verification of the project methodology.

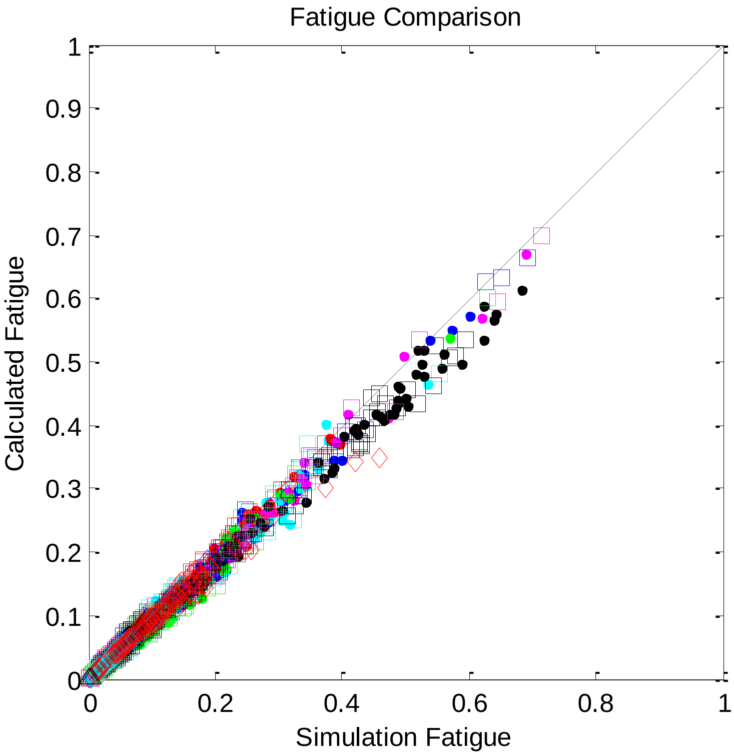

Figure 1: Comparison of Calculated (Motion-Derived) Fatigue versus Simulation Fatigue

The sensor packages considered during the verification phase were relatively low-cost and included MEMS-based accelerometers and gyroscopes as well as a commercially available satellite positioning receiver. The analysis demonstrated that the noise performance of such units was more than adequate to determine fatigue rates in the mooring lines. For example, the motion-derived tension cycles were lower noise than subsea load cells installed in the Hywind Scotland mooring lines.

A sensitivity study of differing wind and wave directions as well as increasing significant wave height suggested that a lookup table of motion-to-tension transfer functions should be derived from simulations with 10° compass direction intervals and 3 m significant wave height bins. This is shown to give accurate fatigue predictions.

The analysis method was applied to a limited set of field data recorded on one of the Hywind Scotland FOWTs. The mooring line tensions were calculated from the FOWT rotations (i.e. pitch) and horizontal position for comparison against measured tension readings from six load cells installed in the mooring lines at the connection to the hull. The overall correspondence was broadly correct but significantly less accurate than was obtained using the simulation data sets. The reasons for the divergence are believed to be as follows:

1. There are no accelerometer or vertical position signals in the Hywind Scotland published data set. These would capture a significantly higher proportion of the loading on the mooring lines.
2. The accuracy of the Hywind Scotland GPS package (giving horizontal position only) is quite poor; several data sets are subject to excessive spurious noise, which made them unusable.

3. The noise performance of the Hywind Scotland load cells is not sufficient to capture the dynamic content of the signal except for very large motions at low-frequency hydrodynamic modes and (marginally) at the wave frequency. There is excess noise on Bridle 5 (Hywind Scotland notation: Line 2, Bridle 2), which made it unusable.
4. The simulation model used idealised anchor positions. This modifies the response of the floating hull and how the loads are distributed between the mooring system components.
5. The Hywind Scotland design includes active control of the one or more hydrodynamic modes of the floating hull. Control of this type is designed to minimise fatigue in the mooring and should, obviously, be expected to influence the floating hull response quite strongly. Exact details of the control system are not available.
6. The blade pitch controller in the simulation model is a generic representation as the actual details are not available. This governs how the floating hull responds to changes in wind speed (including gusts).

The method of using floating hull motion and position to infer mooring line tensions has been shown to give excellent results within simulation studies. This approach utilises low-cost, reliable and robust instrumentation that can be maintained while avoiding expensive and difficult to service subsea equipment such as load cells.

Conclusive validation of the method using data sets from Hywind Scotland was not possible due to limitations in the monitoring system and available data. To develop this methodology further, it is recommended that a dedicated monitoring system to the specification outlined in this report is deployed on a floating wind turbine with the full data set available for processing.

Key findings of this work were that the monitoring system should:

- Record accelerometer signals from the FOWT.
- Include vertical motion and position.
- Utilise high-accuracy (“differential”) satellite positioning to minimise spurious data.

Anomaly Detection

Anomaly detection of mooring failure scenarios and events was also demonstrated using the monitoring system. By processing the measured signals continuously, problems with the mooring system can be identified in a timely manner – safely and remotely. To demonstrate this, simulations were performed for four identified failure scenarios or events that are relevant to operation of a FOWT. These were:

- Trawler snag loading
- Mooring line anchor slippage
- Broken mooring line bridle
- Loss of floater ballast

The data was processed in real-time in segments of 10 minutes to reduce the measured time series data to an appropriate and manageable set of statistics. By looking for deviations in FOWT position, inclination and dynamic response from predictions of the simulation model – essentially adjusting for prevailing wind and wave conditions – anomalous behaviour of the FOWT was accurately identified. All the selected failure scenarios could be confirmed.

Peridynamic Fatigue Analysis

A peridynamic fatigue analysis was conducted on a mooring line component (a triplate) to determine the fatigue life under typical load cycles and how fracture would progress. This was shown to provide not just accurate predictions of the formation of fatigue cracks but also where and how they would progress to failure. Peridynamic fatigue analysis can predict all three phases of fatigue failure: crack initiation (phase I), crack growth (phase II) and final failure controlled by quasi-static crack growth (phase III). The peridynamic fatigue model was validated by considering results from a plate with an existing crack problem to the results of a cyclic load test. To demonstrate the capability of the peridynamic fatigue model, the fatigue analysis of a triplate (which is a component of the Hywind Scotland mooring system) was performed under constant and variable amplitude loading conditions. A complete picture of fatigue damage evolution from crack initiation to final failure was obtained. Detailed information like this will be an important input into a risk-based inspection methodology: knowing what and where to look for fatigue failure will greatly assist in targeting any subsea inspection work that is deemed necessary.

The peridynamic fatigue model is a new and alternative method for fatigue analysis of structures. Conventional S-N curve methods can only provide information about fatigue life, which typically corresponds to the point of fatigue damage initiation. Since peridynamics can capture all three phases of the fatigue damage process, it can provide more accurate information and decrease the level of conservatism. Moreover, the information that peridynamics provides is much more beneficial for a digital twin system since operators will be able to see when and where damage starts and how it propagates. As such, it is a useful input into any inspection process of the mooring lines as the failure pattern to look for.