Modelling of ROV-Operated Disconnectable Mooring Systems in Wave Dominated Environments

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***Abstract*—Floating offshore wind turbines (FOWTs) hold immense potential for unlocking previously inaccessible offshore wind resources, with recent advancements positioning the technology on the brink of commercial success. Central to the success of FOWT projects is the optimization of operations and maintenance (O&M) procedures, particularly concerning mooring system design and the utilization of Remotely Operated Vehicles (ROVs). This paper presents an analysis of mooring line disconnection activities using state-of-the-art ROV technology, focusing on the impact of mooring connector depth with the Arven Offshore Wind Farm serving as a case study. Utilizing a simplified two degree of freedom dynamic ROV model and hindcast metocean data, the study examines the station-keeping ability of an ROV subject to wave perturbations, evaluating the effect of depth on mooring connector operational availability. Results indicate that deeper mooring connector installations substantially enhance mooring connector availability from less than 10 % at 5 m depth to over 90 % at 20 m depth, thereby reducing weather-related delays and improving operational efficiency. Furthermore, a sensitivity analysis on ROV power highlights potential avenues for enhancing accessibility without necessitating mooring design modifications. These findings underscore the importance of integrating FOWT O&M strategies and installation considerations with mooring design at an early stage by accounting for realistic performance of ROV-operated tasks, ultimately contributing to the competitiveness and success in the offshore wind sector.**

***Index Terms*—ROV, Floating Offshore Wind, Mooring, Mooring Line Connector**

I. Introduction

A. Context

Floating offshore wind turbines (FOWTs) have demonstrated their technical feasibility and stand at the threshold of broad commercial deployment. The future progress of FOWTs will unlock previously untapped seabed areas in deeper water than that accessible by traditional bottom-fixed offshore wind installations. In the United Kingdom, the recent ScotWind leasing round has awarded seabed rights for over 19 GW of floating offshore wind projects, outlining an ambitious roadmap for Scotland's development in this sector [1]. Nonetheless, the success of these ventures relies heavily on achieving cost reductions in technology. One promising avenue for cost reduction is in the mooring system, impacting both capital (CAPEX) and operational expenditure (OPEX) [2].

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Fig. 1. Arven Offshore Wind Farm's Approximate Location in Scotland

As depicted in Figure 1, Arven Offshore Wind Farm is a ScotWind site located in a particularly remote location: 50 km east from the Shetland Islands with an average water depth of approximately 122 m [3]. This paper presents an analysis of the availability of the mooring line disconnection system (the proportion of time that the ROV could work on the mooring connector) in this array using ROV technologies, and discusses the implications on the operations and maintenance (O&M) using the Arven Wind Farm as a case study.

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B. Mooring System Design

The mooring system is responsible for the station keeping of a FOWT and keeps the FOWT within a defined region, known as a watch-circle. A typical mooring system is shown in Figure 2, comprising of a combination of chain and synthetic line sections. Chain may be used at both top and bottom to provide abrasion resistance against the platform and seabed respectively, as well as resilience against UV damage, whilst synthetic lines may be used in the mid-section to reduce the cost compared to an all chain system and provide compliance to the system, reducing maximum tensions [4]. The mooring system must occasionally be disconnected from the FOWT platform, for example for the replacement of a failed mooring line, or for the platform to be towed to port. This paper considers the specific process of mooring connection and disconnection by quantitatively assessing the feasibility of employing autonomous or semi-autonomous underwater robots for the task. This study is agnostic to the specific mooring design variables of line length, anchor radius, or line diameter making the findings applicable to a wide range of mooring designs, provided that the exact mooring configuration and, therefore, the length of weather window required for the intervention are accounted for accordingly.

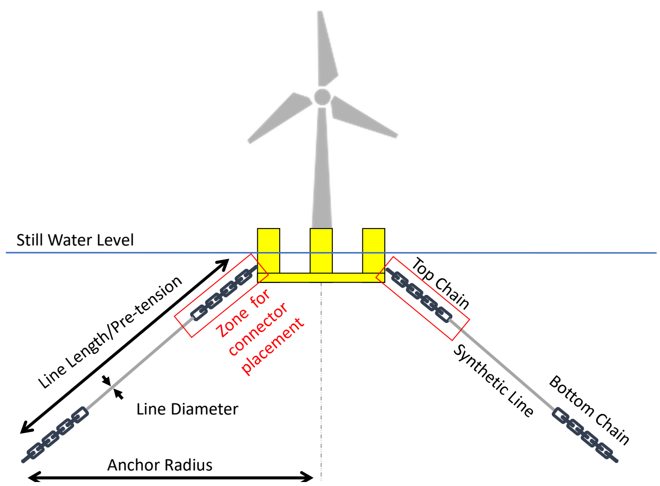

Fig. 2. Typical Mooring Schematic, with indication of the connector location. Adapted from [4]

C. FOWT O&M Strategies

Floating wind provides unique challenges and opportunities for O&M strategies when compared to traditional fixed-bottom alternatives. One of the challenges is that FOWTs tend to be installed in more exposed sites which are characterized by more challenging access requirements and depths exceeding the capabilities of jack-up vessels. Therefore, major component replacement for FOWT platforms represents a particular challenge. Alternative solutions may include floating-to-floating transfer, floating cranes, and self-hoisting equipment. An alternative strategy, unique to FOWTs, is that they can be towed to shore for major component change-outs [5].

The tow to shore strategy has two key advantages compared to offshore maintenance. The most obvious is the reduced requirement for specialised vessels; tug vessels are much more readily available than those equipped for offshore lifting. The other advantage is that it allows for a discontinuous weather windows; the weather window length is required to only be as long as the disconnection operation and length of time to tow the platform to shore - once in port, wave height is no longer a relevant factor (and although wind may delay lifting operations wind speeds are typically lower inshore) – a further weather window would be needed for the reverse operation of towing the platform back to the site and reconnecting it to the mooring system. The possibility of utilising a discontinuous weather window shortens the length of time required to wait to carry out an intervention [6]. However, the tow to shore operation is time consuming and requires multiple vessels for the duration of the tow, which may be lengthy depending on the nearest suitable port access. It can, therefore, be a costly process [7].

In order to enable the tow to shore strategy, as well as to streamline the initial installation, it is necessary for the platform to attach to the mooring line with a connection system that allows for disconnection and reconnection. If this connection system can only be accessed within narrow weather limits, this may increase the time spent waiting on weather and further increase the cost of a tow to shore intervention.

D. Mooring Lines & Remotely Operated Vehicles

Remotely Operated Vehicles (ROVs) are uncrewed underwater vehicles controlled by operators on the surface. These devices may be equipped with cameras, sensors, or manipulators with a variety of possible end-effectors, allowing them to perform various tasks in underwater environments. In the context of FOWT mooring lines, ROVs play a crucial role in inspection, maintenance, and repair operations, as well as in the disconnection of mooring lines [8] [9].

In order to enable the connection and disconnection of the mooring line a mooring line connector would be used. The simplest form of a mooring connector is a shackle, but there are many more complex products available that aim to simplify the connection/disconnection process [11]. Although novel devices are being developed to minimize or avoid the use of ROVs such as the Q-Connect device [12], most connectors require ROV intervention to complete the mooring connection task, such as the Subsea Mooring Connector [13], Buoy Turret Connector [14], Squid [15], or BarMoor [16].

The connection technology may be mounted at the fairlead (the connection point between the platform and the mooring line) or at some point along the top section of the mooring line. As terminations are a weak point that may be susceptible to failure, the designer is likely to co-locate the mooring connector with a change in line material such as where the top chain meets the synthetic line to minimise the total number of line terminations. In any case, a key design variable is the depth that the connection system is mounted. This paper quantifies the advantage of mounting the connection system at deeper water depths. At deeper water depths, the water particles' orbital motion due to wave action is reduced, allowing for better station-keeping operation of an ROV in rougher wave conditions [17]. Therefore, a deeper mooring connection system is likely to be accessible in a wider range of conditions, reducing the time taken to wait for a suitable weather window. However, assuming the connector would naturally be placed at the interface between chain and synthetic line, and because chain is more expensive to manufacture and install than synthetic line, the CAPEX is likely to increase as the mooring connector is installed further from the platform due to the requirement of a longer length of chain. There is, therefore, a trade-off between the accessibility of the mooring connector and the CAPEX.

The feasibility of placing mooring line connection systems at different depths can be assessed by evaluating the station-keeping performance of ROVs during the connection and disconnection tasks. The capability of an ROV to perform closed-loop station keeping control for the purpose of mooring line connection and disconnection tasks is assessed by simulating the dynamic response of a stereotypical ROV subject to large magnitude oceanic disturbances. This analysis provides a sensitivity study of station-keeping accuracy over a diverse range of ocean climates. A metric for the availability of an ROV-operated connector is determined by estimating the proportion of time in which a connector could be operated on at various depths, for the first time offering a feasibility metric for FOWT mooring line connector placement.

II. Method

A. MetOcean Data

Metocean data representing a 20 year data set has been obtained from ECMWF. This dataset is a reanalysis hindcast product, and therefore provides a continuous time series dataset for the specific location of the Arven case study [18]. The data is in hourly time steps, and it is assumed that the conditions within each time step are stationary. The waves are assumed to follow a JONSWAP spectrum which is used to generate an irregular set of waves that represents conditions experienced at the Arven site. Currents have not been included in this analysis as the maximum current flow velocity at the Arven site is small [19].

B. Mobile Under Water Vehicle Modelling

The ROV is modelled following [21] as a neutrally buoyant, 2DoF body. The waves are modelled using linear wave theory (LWT) which estimates the particle motion at different depths; previous validation of using LWT for ROV disturbance was undertaken in [20] and [21]. The ROV is modelled as a floating object with thrusters, which are modelled in the vertical and horizontal direction, each controlled with a PID controller. The magnitude of the force is limited by the power of the motors, which is defined as an input to the model, along with other key variables to define the drag, mass, and added mass of the ROV, which impact the ROV's ability to move towards the target location, see [17]. Key properties of the ROV are shown in Table I. The ROV modelled is a BlueROV, which is relatively small ROV commonly employed for inspection tasks. Depending on the nature of the ROVs involvement in the connection operation, a larger ROV may be required. However, since larger ROVs are typically more powerful and as the response time scales proportionally to thrust and inverse proportionally to effective mass, the final results would likely be similar for a range of ROV sizes.

TABLE I
ROV Key Parameters [22]

Parameter	Value	Unit
Dry mass	11.5	kg
Added mass in X direction	5.5	kg
Added mass in Z direction	14.57	kg
Max thrust per propeller	40	N
Length	0.457	m
Width	0.338	m
Height	0.254	m

To simplify the analysis it is assumed that the ROV can only move in two degrees of freedom and pitch is ignored, the ROV is neutrally buoyant, and off-diagonal added masses terms are disregarded.

The governing dynamic equations are therefore shown in Equation 1 and Equation 2 for the x amd z directions. In these equations v_a and v_r are the absolute and relative velocities of the ROV, m_d and m_a are the dry and added masses, and ρ_f, A, and C_D respectively represent the density of sea water, incident area of the ROV, and drag coefficient of the ROV. Finally T represents the thrust force of the propellers.

$$m_d \dot{v}_{a,x} = \frac{1}{2}\rho_f A_x C_{D,x} v_{r,x}|v_{r,x}| - m_{a,x}\dot{v}_{r,x} + T_x \tag{1}$$

$$m_d \dot{v}_{a,z} = \frac{1}{2}\rho_f A_z C_{D,z} v_{r,z}|v_{r,z}| - m_{a,z}\dot{v}_{r,z} + T_z \tag{2}$$

To determine the maximum extent of ROV motions for each timestep in the dataset without excessive computational effort, the extent of ROV motions was first modelled with a scatter representing a range of different significant wave heights and periods. The maximum extent of ROV motions in every time step of the ERA-5 dataset was then determined through 2D interpolation of the excursion scatter. When generating the scatter, no data was generated for waves with a steepness ratio of 1/7 as these waves would break and therefore do not represent realistic conditions. As a further limit on the model, if the ROV deviates by more than 10 meters from the target location the simulation will end for that sea state. This approach reduces the total time required to run the simulations by stopping simulations that are clearly unsuitable for ROV operation at an early stage.

III. Results

A. Maximum ROV Excursion

The sea states are each modelled for 10-minute periods and the maximum displacement of the ROV is recorded for each combination of significant wave height and zero-crossing period considered. This is repeated for a range of water depths between 5 and 20 m of depth in order to determine the effect of working at different water depths on the motions of the ROV in different conditions.

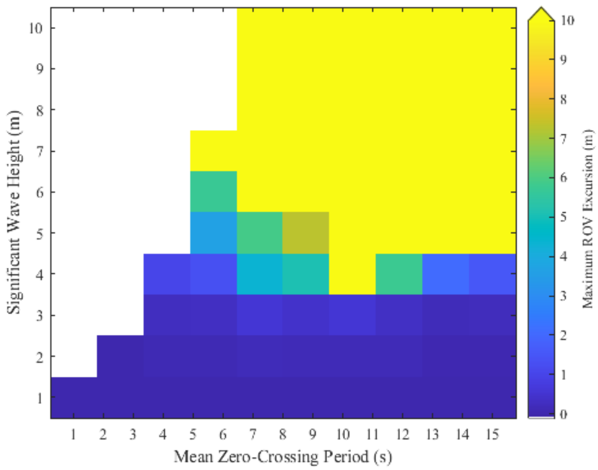

Fig. 3. Maximum ROV excursion in various conditions at 5 m water depth

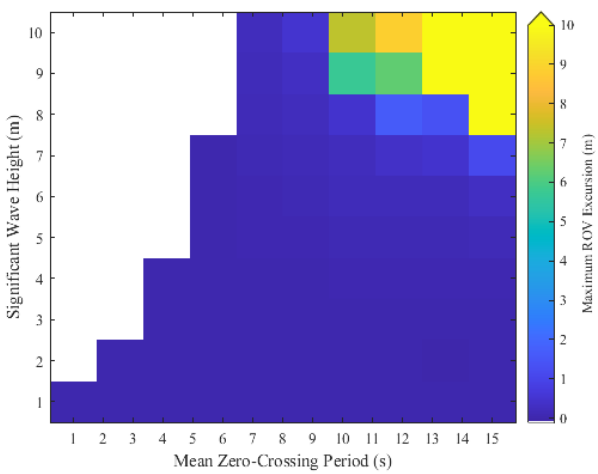

Fig. 4. Maximum ROV excursion in various conditions at 20 m water depth

To illustrate this a heat map is shown in Figure 3, which show the ROV's motion in different wave conditions when it is working at a water depth of 5 m. It can be seen that the motions of the ROV are greater than 1 m in a large range of sea states at this depth; these motions are reduced if the working depth is increased. This is illustrated in Figure 4, which shows the much smaller maximum extent of ROV motions when working at 20 m water depth. It should be noted that the maximum ROV excursions in these figures are capped at 10 m to prevent the figure being dominated by anomalous large excursions in rough sea conditions.

Sea states were run with a single seed, though the maximum ROV excursions are sensitive to the seed. Further work should run all sea states with multiple seeds and take the greatest excursion from each sea state across all seeds to ensure accuracy and reliability of the results.

B. Availability Analysis

An analysis of the availability of the mooring connector has been carried out, where availability is defined as the ratio of hours in which the mooring connector could be operated on by an ROV to the total number of hours in the dataset i.e. the proportion of time that the ROV could carry out work on the mooring connector.

It is assumed that the ROV cannot operate on the mooring connector if there are maximum excursions of greater than 0.1 m. This limit exists because an ROV's manipulator length, and thus it's ability to respond to larger motions, is limited. It's important to note that this threshold value is illustrative and would vary depending on the specific disconnection system and ROV being used. This is visualised in Figure 5 in which an extract of hourly wave height data is plotted alongside the data for the maximum ROV excursions expected in each hour with the threshold value also marked. In this one month extract, the ROV's modelled excursions exceed the threshold value in 22 % of the time giving an availability of 78 %.

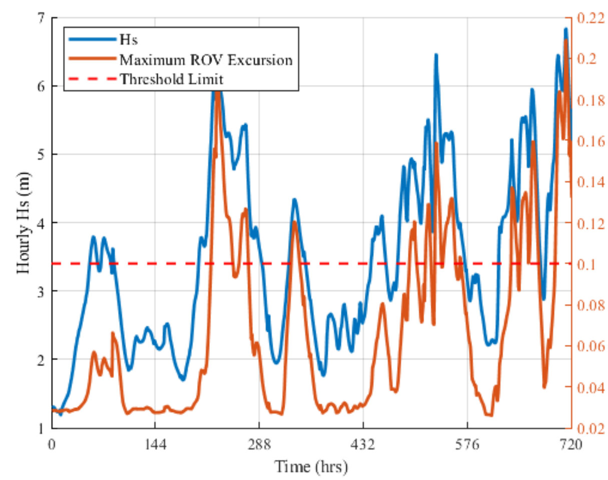

Fig. 5. Extract of hourly Hs and maximum modelled ROV excursions

Two scenarios are considered: one in which only a 1 hour weather window is required, whilst a further scenario is considered in which a 6-hour contiguous weather window is required. The length of ROV weather window required will depend on the specific mooring configuration and ROV as discussed in Section I-B.

Figure 6 shows the availability of the ROV-operated connector in relation to the depth of the mooring line connector, as derived from an analysis of 20 years of hindcast metocean data. This figure depicts the availability of the mooring connector within the prescribed operational limits assuming a 1 and 6 hour weather window requirement.

It can be seen that the deeper the mooring connector is installed, the more conditions the ROV is able to access and

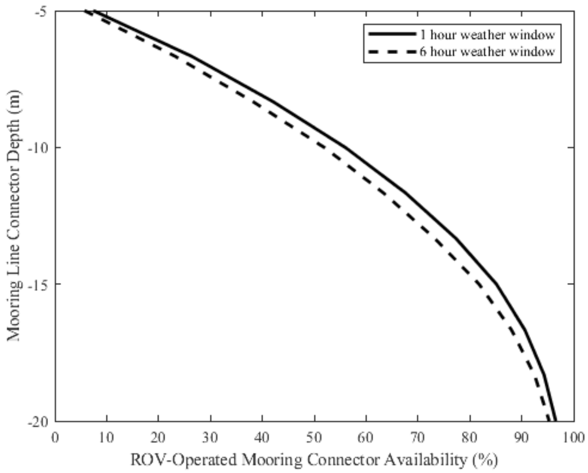

Fig. 6. Mooring connector depth impact on ROV availability

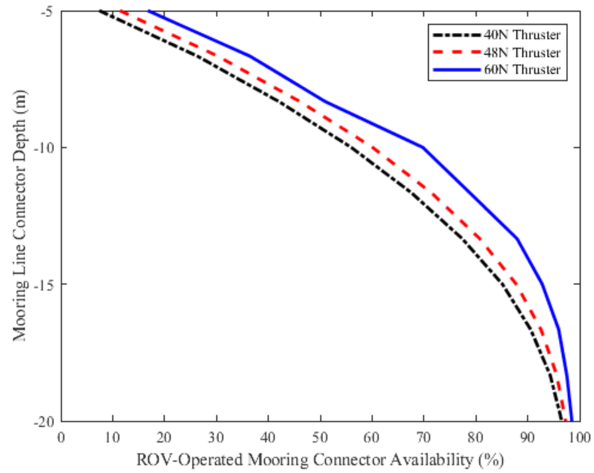

Fig. 7. Comparison of ROV availability with different thrusters

operate on the device, from less than 10 % availability at 5 m depth to over 90 % availability at 20 m. This potentially has a dramatic impact on the time required to wait for an appropriate weather window and would substantially decrease the time spent waiting on weather for a mooring disconnection operation.

Considering the two scenarios presented in Figure 6, the requirement for a longer contiguous weather window does decrease the number of weather windows available and therefore the operational availability, though the impact is relatively small. This is likely because rapid oscillation between calm and stormy weather is relatively unusual. It is notable that the mooring connector depth is a much stronger determinant of the operational availability than the length of the weather window required.

C. ROV Design Adjustments

Though it can be seen that increasing the depth of the mooring connector vastly improves the accessibility of the connector to an ROV, it may not be preferable to place the connector at these deeper depths due to other design or cost constraints. Therefore, a developer may be interested in if the ROV design itself can be changed to increase the availability of the disconnection operation without having to change the mooring design.

A sensitivity study on the ROV power has indicated increasing the power of the ROV can reduce the maximum excursions of the ROV, and increase the number of hours in which an ROV could carry out the disconnection operation as shown in Figure 7.

It should be noted, however, that this study has not considered the increased size and mass that an ROV with larger thrusters may have, which may reduce the benefit seen here. It should further be noted that in some individual sea states the maximum excursions of the more powerful ROV actually increased rather than decreasing. This suggests that a key determinant of the ROV's station keeping ability may be in the control system rather than the power. Therefore exploring more advanced control methods than the PID controller considered in this study may help further improve the station keeping of the ROV and thus improve the accessibility of the mooring connector. Possible approaches involve the explicit inclusion of the disturbance within a predictive controller that forecasts and compensates for future disturbances as successfully demonstrated in [23] and [24].

IV. Discussion & Conclusion

By investigating the impact of mooring connector depth on ROV availability, this paper has shown that deeper installation of a mooring connector can significantly enhance the range of conditions in which disconnection operations can be conducted, though possibly at the expense of increased CAPEX. While deeper installations offer greater operational flexibility, the paper demonstrates diminishing returns at greater depths, where availability becomes less sensitive to depth changes.

To find alternative approaches to increase mooring connector availability, it was shown that adjustments to the ROV power could bring further improvements in accessibility, offering developers alternative strategies for enhancing operational performance without necessitating changes to mooring designs, though it was suggested that greater improvements could be had by improving the ROV control method.

These findings underscore the importance of integrating O&M technology into early stage design considerations of FOWT projects, ultimately contributing to their overall success and competitiveness in the offshore wind energy sector.

Future research could explore additional factors such as mass and size of the ROV as well as the control function, influencing ROV performance. This research could further inform strategies for optimizing FOWT design and O&M procedures.

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