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**Publication date**
2021

**Document Version**
Final published version

**Published in**
Proceedings of the 13th Symposium on High-Performance Marine Vehicles, HIPER '21

**13th Symposium on**

**High-Performance Marine Vehicles**

# HIPER'21

**Tullamore, 13-15 September 2021**

Edited by Volker Bertram

# Applying a Needs Analysis to Promote Daughter Craft for Year-Round Access to Far-Offshore Wind Turbines

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**Abstract**

*Service Operation Vessels (SOVs) are purpose-built maintenance vessels that provide high accessibility to far-offshore wind turbines, but they lack multitasking capabilities. Its daughter craft (DC) is a valuable asset for unplanned maintenance in the summer when it can operate safely, but it is often not deployable during rough weather conditions. The main research question is: What are the deficiencies of current DCs, and how can these access vessels be modified to operate year-round at far-offshore wind farms? The results show that the current DC's deficiencies lie in its current operational requirements. Also, performance in oblique waves is currently riskiest since that is when there are higher vertical accelerations or a combination of vertical and lateral accelerations. Furthermore, wave steepness has significantly more effect on accelerations than wave height. Lastly, future DC designs should be focussed on stable seakeeping performance during transfers rather than high-speed transit. An analysis into the seakeeping performance of four prototypes showed that it is feasible to increase the transfer requirement from $H_s \leq 1.5$ m to $2.0 \text{ m} \leq H_s \leq 2.5$ m. The catamaran type DCs have a high potential to realise year-round accessibility to far-offshore wind farms due to their resulting performance in oblique wave conditions.*

## 1. Introduction

With the known negative effects linked to the use of fossil fuels, it is becoming increasingly important to switch to cleaner energy. Among many alternatives, wind farms are one of the most environmentally feasible solutions to reduce greenhouse gasses when the entire lifecycle is assessed, *Guezuraga et al. (2012)*. *Walsh (2019)* reports that offshore wind farms in Europe are moving farther from shore. This is because operators want to attain stronger and more stable wind resources, and due to depleting locations near the shore.

However, this trend makes it more challenging and expensive for wind farm operators to provide service. The harsher weather conditions require offshore wind turbines to be maintained more frequently than those situated onshore. Also, both the weather and the distance complicate the process of accessing wind turbines. *Shafiee (2015a)* describes that the availability of offshore wind farms is in the range of 60% to 70%, while for onshore wind farms, it is typically between 95% to 99%.

### 1.1. Problem definition

The main adverse effect of the remoteness of far-offshore wind farms is the increased transit times from ports, which decreases the time available for maintenance tasks and causes fatigue in technicians. A common solution is to work from an offshore-based hub, such as a Service Operation Vessel (SOV). SOVs are used primarily for calendar based (preventive) maintenance. This minimises the need for unforeseen (corrective) maintenance but does not eliminate it. When an unforeseen event occurs, an SOV is often occupied and cannot reach the defective turbine fast enough. So, the problem is that SOVs are not flexible enough to carry out corrective maintenance next to preventive maintenance, and that does not benefit wind farm availability.

Other access vessels can assist in the event of unforeseen events by transporting technicians from the SOV or the shore. But with farms moving farther from shore, each solution becomes impractical for reasons such as limited weather window, longer transit times and cargo capacity, making them less suitable to access defective far-offshore turbines. In short, the accessing capabilities of smaller vessels are insufficient for far-offshore wind farms. If both problems persist, O&M operators will not be able to repair a (sudden) turbine malfunction in time, leading to turbine downtime and high revenue losses.

### 1.1 Goal

The overall goal of this study is to improve accessibility to (defective) far-offshore wind turbines. Based on the stated problems, (i) SOVs require new or improved subsystems to increase their multitasking capability and (ii) its daughter craft (DC) shows the most potential to do so. Hence, this study aims to confirm that DCs are the system-of-interest based on their capabilities and deficiencies and determine what is required to resolve them. This is done by applying a Needs analysis, which is part of the Systems Engineering approach by *Kossiakoff et al. (2011)*, and consists of four steps: Operations Analysis, Functional Analysis, Feasibility Definition, and Needs Validation. These steps start from section 4.

## 2. Scope of stakeholders

This study considered the stakeholders identified by *Ahsan et al. (2018)*, who have a high interest in and high power to influence the far-offshore activities: wind farm owners/investors, the turbine supplier, the vessel supplier, and the O&M operator's technicians. Either of the two first stakeholders can also take on the additional role of O&M operator, whose primary interests are preserving turbine availability, minimising costs and ensuring turbine accessibility. However, the two remaining stakeholders can have conflicting interests with the O&M operator. First, the vessel supplier may require engineering and design costs that the O&M operator is unwilling to pay. Second, it is paramount that the technicians can work in a safe environment. Their safety imposes lower and upper limits to vessel performance and, thus, accessibility. The TU Delft is an external stakeholder with high interest in such a project since they wish to encourage and contribute to the energy transition but has low influence because they are not involved in how business is done.

## 3. State-of-the-art access vessels

Accessibility is defined as the fraction of time when safe access to wind turbines is achieved, *Shafiee (2015b)*. To understand where the need for a new system comes from, it is first necessary to be familiar with current access methods in offshore O&M.

SOVs are best suited for calendar-based maintenance due to their large weather window; access is possible up to $H_s \leq 3.0$ m. Their ability to accommodate 25-40 technicians onsite for extended periods makes them more efficient due to reduced transit time. They are primarily used for preventive maintenance but will be used for corrective maintenance if necessary.

Some SOVs are fitted with a DC. These are ship-based vessels used to send technicians to wind turbines for corrective/preventive maintenance or to prepare the wind turbine before the SOV arrives. However, these vessels are currently only operable in the summer due to their smaller weather window. Existing DCs have been designed to transfer at $H_s \leq 1.5$ m since that is predominantly observed in their current operational area, i.e. at wind farms situated closer to shore.

Crew Transfer Vessels (CTV) are similar to DCs but are much larger and port-based vessels. These are used to cover the entire range of maintenance strategies. However, they are more suitable for offshore wind farms located not far from the shore to limit transit times and avoid motion sickness. In literature, they are occasionally mistaken for a DC. This study adheres to the following distinction: a CTV is an independent vessel that always heads back to port at the end of the day while a DC is dependent on its mothership, which launches, recovers, and stores it.

A Service Accommodation and Transfer Vessel (SATV) combines the capabilities of CTVs and SOVs. They can also remain offshore for (less) extended periods, which reduces transit times and can cover the entire range of maintenance strategies because they are meant for smaller wind farms.

Lastly, helicopters are the only non-seaborne access vessel at an O&M operator's disposal. They are not limited by metocean phenomena but are mainly used for urgent corrective maintenance.

## 4. Operations analysis

This section defines the deficiencies in current systems and operational objectives of the new system.

### 4.1. Operational area

This study is limited to offshore wind farms located in the North Sea because most are currently located there. The focus lies on the wind farms where offshore-based hubs (i.e. SOVs) are considered useful, but accessibility has become an issue because they are either occupied or not fast enough to take care of unplanned events. So, their operational area represents the operational area of the DCs. Two criteria were used to select the wind farms.

The first criterion is the distance from shore. This plays a significant role when selecting a vessel because they must have sufficient range to reach and operate at these wind farms. *Phillips et al. (2013)* estimated that the most cost-effective distance to implement offshore-based hubs, i.e. SOVs, is 35 nm (65 km) from the port.

The second criterion is the number of wind turbines. An SOV can visit approximately six scheduled turbines per day. With a yearly weather window of 90% an SOV can then be scheduled to service nearly 2000 turbines per year. *Krause and Stead (2017)* estimated that offshore wind turbines need to be visited 15 times per year for both scheduled service and troubleshooting. In that case, wind farms with at least 120 turbines are expected to properly occupy an SOV, which is this study's benchmark.

There are three wind farms in the North Sea that meet these two criteria: Hornsea One, Gemini and East Anglia Three. For conciseness, this paper will solely focus on the weather data from Hornsea One.

### 4.2. Operating conditions

Whether a turbine is accessible depends on the access vessel's ability to navigate the ongoing weather conditions. Specifically, wind speed, significant wave height and wave steepness predominantly affect vessel seakeeping, *MaTSU (2001)*. It should be noted that the performance of a majority of vessels is characterised by significant wave height. However, since these phenomena all interact and influence each other, it is doubtful whether a vessel's operability can be determined using a single parameter, *MaTSU (2001)*. Because of the interaction, experience shows that vessels still occasionally fail during conditions they were designed to handle. Here, wind speed was acknowledged but will not be considered a design criterion due to its minimal and indirect influence on the vessel and crew.

#### 4.2.1. Significant wave height

Significant wave height ($H_s$) is defined as the mean height of the highest one-third of waves and is a popular design criterion to determine a vessel's operational limit, *MaTSU (2001)*. Fig.1 shows the cumulative occurrence of significant wave heights measured over 21 years at Hornsea One. This wind farm observed $H_s \leq 2.5$ m for 90% of the time annually. Furthermore, the occurrences differ throughout the seasons: 90% of waves in the summer are $H_s \leq 2.0$ m, while this increases to $H_s \leq 3.0$ m in the winter. Overall, this graph gives an initial impression of how often a range of significant wave heights is likely to occur. It is ultimately used to determine the theoretical weather window.

#### 4.2.2. Wave steepness

While $H_s$ is a more popular parameter to determine a vessel's operational limit, *MaTSU (2001)* considers wave steepness to be a better indicator because it determines the force upon a fixed or floating structure, how it will behave and when waves are likely to break. Like $H_s$, wave steepness is linked to its location. Table I is a wave scatter diagram of the waves measured at Hornsea One. It indicates how many waves correspond to a specific combination of $H_s$ and peak period ($T_p$). Where there is no data implies that waves will break due to steepness.

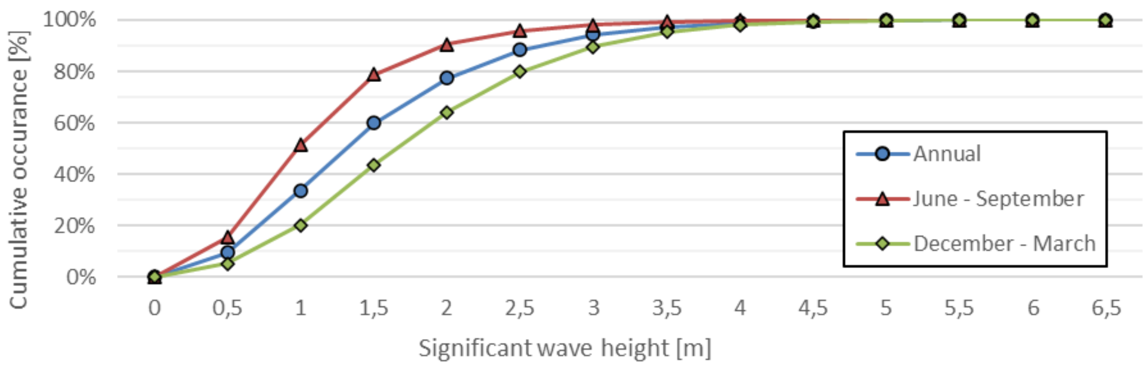



Fig.1: Measured wave data at Hornsea One (adapted from *Stavenuiter (2009)*)

Wave steepness (S) is defined as the ratio between $H_s$ and wavelength (λ). However, wavelengths were not included in the used weather database. According to *Antão and Soares (2016)*, the wavelength can be calculated from the dispersion relation given in Eq.(1).

$$\lambda = \frac{gT^2}{2\pi} tanh\, \frac{2\pi d}{\lambda} \qquad (1)$$

Where, *g* is the gravity acceleration, *T* is the wave period, and *d* is the water depth. Deepwater assumptions are applied since the ratio between wave heights and water depth is relatively large, which means that $\frac{2\pi d}{\lambda} \gg 1$ , *Gerritsma (n.d.)*. Inserting the simplified Eq.(1) into the definition for wave steepness gives Eq.(2). Applying Eq.(2) to the values in Table I shows that the majority of waves have S = 0.03 and that waves will mostly break when S > 0.05.

$$S = \frac{H_s}{\lambda} = \frac{2\pi H_s}{gT^2} \qquad (2)$$

Table I: Scatter diagram of sea states at Hornsea One (adapted from *Jiao et al. (2018)*)

| Hornsea 1 | | Significant wave height (Hs) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 | Sum |
| Peak period (Tp) | 2.5 | 86 | 1 | | | | | | | | | 87 |
| | 3.0 | 718 | 10 | | | | | | | | | 728 |
| | 3.5 | 2885 | 203 | | | | | | | | | 3088 |
| | 4.0 | 5677 | 3910 | 9 | | | | | | | | 9596 |
| | 4.5 | 3624 | 9684 | 569 | | | | | | | | 13877 |
| | 5.0 | 3345 | 9069 | 6245 | 84 | 1 | | | | | | 18744 |
| | 5.5 | 2852 | 4963 | 9668 | 2379 | 33 | | | | | | 19895 |
| | 6.0 | 2149 | 3690 | 5111 | 7415 | 1115 | 13 | | | | | 19493 |
| | 6.5 | 1867 | 3368 | 3847 | 4671 | 4040 | 422 | 1 | | | | 18216 |
| | 7.0 | 1466 | 2871 | 3038 | 2923 | 2596 | 1847 | 91 | | | | 14832 |
| | 7.5 | 934 | 2114 | 2235 | 2120 | 2136 | 1526 | 860 | 104 | | | 12029 |
| | 8.0 | 954 | 2307 | 1749 | 1792 | 2157 | 1610 | 702 | 315 | 69 | 2 | 11657 |
| | 8.5 | 894 | 2223 | 1531 | 1025 | 921 | 1408 | 619 | 151 | 66 | 36 | 8874 |
| | 9.0 | 501 | 982 | 882 | 601 | 471 | 654 | 732 | 236 | 44 | 17 | 5120 |
| | Sum | 27952 | 45395 | 34884 | 23010 | 13470 | 7480 | 3005 | 806 | 179 | 55 | 156236 |

No data here because waves break due to steepness

| Steepess value |
|---|
| 0.01 |
| 0.02 |
| 0.03 |
| 0.04 |
| 0.05 |
| ≥0.06 |

### 4.2.3. Prominent wave directions

The wind turbines of the reference farms have the boat loading oriented such that vessels encounter head waves the most. This is because head waves are generally considered to induce the lowest responses. This is also beneficial because the chance of large roll motions is then minimised. Besides head waves, there are other wave directions that are then encountered most frequently. For Hornsea One, there are mainly head, beam and following waves.

## 4.3. Deficiencies

The SOV's large weather window makes them ideal for upholding scheduled maintenance. However, its primary deficiency is its capacity to provide maintenance for unforeseen events due to its low response time. The SOV often cannot travel to a turbine far away because they are restricted by safety regulations that state that the operator must reach a turbine within an hour when an emergency occurs, and technicians need rescuing or medical treatment. SOVs can be equipped with DCs to increase their multitasking capability for unforeseen events. But DCs have a much smaller weather window. With offshore wind farms moving farther from the shore, the rougher weather conditions and sea states will continue to restrict operators from utilising DCs because they lack performance, especially during the winter season. CTVs have better access performance than DCs and are faster than SOVs. However, since they operate from the port, the vast distances make them ill-suited for far-offshore applications. SATVs are unsuitable because their functions are similar to that of an SOV, making them obsolete if an SOV already operates there. The main deficiency of helicopters is that it is not able to transport many technicians (usually 3-6) and cargo (usually less than 100 kg), *Hu et al. (2019)*, especially large components which the seagoing vessels are better capable of transporting.

## 4.4. The daughter craft is the system-of-interest

Solutions should be sought in increasing the SOV's multitasking capability. This could be achieved by improving one of the SOV's existing subsystems, and the system-of-interest is the DC because:

- DCs are already useful in the summer when weather conditions are calmer.
- DCs have a relatively cheap day rate compared to SOVs (around €500, which is included in the SOV's charter rate of roughly €25.000 per day), so they are more accessible for a redesign.
- DCs are included in the charter rate; it is more convenient and efficient to use the already paid vessels instead of hiring another access vessel.
- Altering a CTV to fit on and work from an SOV technically classifies it as a daughter craft.
- Even at lower speeds, the DC will reach the turbine faster than a CTV at top speed.

Since DCs are SOV-based, their overarching objective is to increase the multitasking capability of the SOV assigned to far-offshore wind farms. These far-offshore locations are characterised by wave conditions that are expected to induce extreme responses from existing DCs. So, the DC's operational objectives are deficiency driven. Based on the weather data from Hornsea One and the DC's deficiencies, the main operational objective is "Allow access in $2.0 \text{ m} \leq H_s \leq 2.5 \text{ m}$". This applies to both the transit and transfer phase, but it is mainly an enhanced objective with respect to the original transfer requirement since existing DCs are already required to transit in $H_s \leq 2.5$ m with 25 knots.

Also, different phenomena are present during high-speed transits and zero-speed transfers. This makes it hard to optimise a system towards both access phases. However, it was determined that 25 knots should no longer be required as a design speed. Instead, it should become the desired top speed because the (SOV-based) DCs are always closer to their destination than port-based access vessels.

# 5. Functional analysis

The second step of the Needs Analysis establishes whether there is a feasible and technical approach to design a system that could meet the operational objective. The DC's enhanced objective is essentially about improving seakeeping. *Beukelman (1986)* states that a ship's behaviour in a seaway primarily depends on its speed, main dimensions, and proportions. The second point of interest is the underwater hull form parameters and the weight distribution, especially for fast semi-planing ships. A majority of these points can be traced back to the hull, making that the DC's component-of-interest.

### 5.1. Seakeeping analysis method

The analysis method is shown in Fig.2 and is similar to the approach by *Tan (1995)*. The sea spectra were defined using weather data, described in section 4.2, and three existing DCs were replicated digitally. The resulting seakeeping performance (for heave, roll and pitch) at the bow transfer point was obtained by applying Strip Theory through the software MAXSURF Motions. Evaluating the results and the original operational requirements leads to a design assessment and operator guidance. Note that the DCs were compared to each other based on ship performance priorities and not operational criteria. The operator guidance segment does not include operability plots but rather demonstrates which DC works best, given the set of responses to certain conditions. Also, since this step analyses existing DCs, the design assessment feedback will be applied in section 6; where a reflection on the original DC will lead to new DC designs.

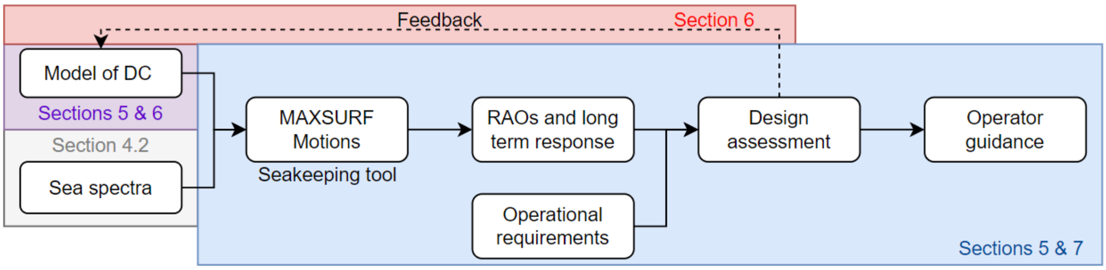



Fig.2: Seakeeping performance analysis method (Adapted from *Tan (1995)*)

#### 5.1.1. Applicability of Strip Theory

Strip Theory is a linear, frequency domain approach to study seakeeping. In essence, it converts the three-dimensional underwater hull into two-dimensional sections or strips, each of which has associated local hydrodynamic properties (added mass, damping and stiffness), which contribute to the coefficients for the complete hull, *Lloyd (1998)*. In this case, it is expected to overestimate the resulting motions because it neglects the effects of three-dimensional flow, viscosity and nonlinearities, *Tezdogan et al. (2014)*. Nevertheless, as argued by *Keuning and Pinkster (1995)*, the linear approach may be justified for the sake of comparison.

This is not the only way to study seakeeping, but the main advantage is that this method requires significantly less computation time to produce seakeeping predictions compared to 3D methods. It is especially useful for including seakeeping in the early design analysis of alternatives and calculating mission operability, *Smith and Silva (2017)*. Note that the reference DCs are not in an early design stage, but the method is deemed valid for this study since it uses mock-ups that will be compared.

#### 5.1.2. Daughter craft models

Mock-ups of a small, medium and large existing DCs were created with lengths of 10, 13 and 16 m, respectively. These three were chosen to gain an insight into the capabilities of a range of DCs currently available. These models were inspected visually and deemed to have a good resemblance to the confidential line plans. Still, the results may deviate slightly from the actual motions of these vessels since these mock-ups were not optimised through iterations. This is acceptable as these models serve to study (hard chine) monohull behaviour in high waves. An example of one of the mock-ups is shown in Fig.3.

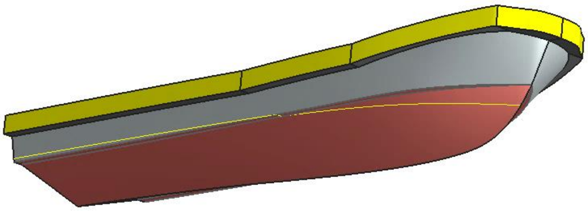


Fig.3: Mock-up of medium DC

### 5.1.3. Input parameters

The radii of gyration were specified for roll, pitch and yaw. These are often estimated as a percentage of the beam and length. The default settings in MAXSURF Motions correspond to widely accepted values, namely 0.35B, 0.25L and 0.25L, *Journée and Massie (2001)*, respectively. These values were left unchanged since the real values were unknown.

The vertical centre of gravity depends on, among others, the location of the installed machinery, equipment, fuel and number of passengers. Based on existing data, the vertical centre of gravity averaged around 1.4 metres for all DCs.

Motion damping occurs because the oscillating hull radiates energy away from the ship in the form of waves, *Lloyd (1998)*. For most motions, Strip Theory makes a decent estimation of the damping factors based on (potential) wave damping while neglecting the minimal viscous effects, *Journée and Massie (2001)*. However, viscous effects dominate the roll motion, while wave making is only a small portion of the total roll damping coefficient, *Journée and Massie (2001)*. So, the total roll damping coefficient ($\upsilon$) must be specified to include viscous effects. The DCs were assumed to have a total roll damping coefficient within the range of 0.15 and 0.20.

Possible wave angles ($\mu$) were grouped into five headings: following, stern-quartering, beam, bow-quartering, and head waves; $\mu = 0°$, $\mu = 45°$, $\mu = 90°$, $\mu = 135°$ and $\mu = 180°$, respectively. The groups are still expected to give a complete impression of the resulting motions.

The JONSWAP spectrum was used to specify the wave spectra needed to simulate the various (irregular) sea states of the North Sea. Seven wave spectra were set up, which are based on current requirements and the weather conditions found at the reference farms, see Table II. The labels were established using the spectra characteristics.

The first spectrum (denoted by 10-3) resembles common and calm weather conditions; when it is generally safe to use DCs. In addition, there are three pairs of spectra, each with a specific significant wave height: (i) $H_s$ = 1.5 m; the current transfer requirement for DCs, (ii) $H_s$ = 2.0 m; the objective's lower boundary, and (iii) $H_s$ = 2.5 m; the objective's upper boundary. Of the pairs, the first spectrum represents the steepest condition, and the second represents the most common for that wave height.

Table II: Simulated wave spectra

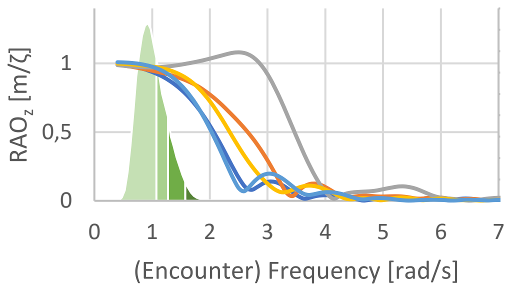
| **Spectrum label** | **10-3** | **15-6** | **15-3** | **20-5** | **20-3** | **25-5** | **25-3** |
|---|---|---|---|---|---|---|---|
| Significant wave height [m] | 1.0 | 1.5 | 1.5 | 2.0 | 2.0 | 2.5 | 2.5 |
| Peak wave period [s] | 4.5 | 4 | 5.5 | 5 | 6.5 | 5.5 | 7 |
| Steepness [-] | 0.03 | 0.06 | 0.03 | 0.05 | 0.03 | 0.05 | 0.03 |

## 5.2. Seakeeping assessment

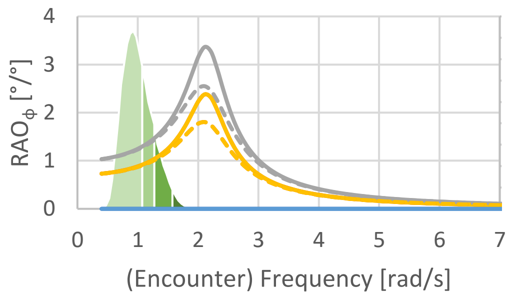
This section discusses the resulting motions and accelerations that can be expected from the reference DCs. This is presented as Response Amplitude Operators (RAOs) and long-term responses to (wind) waves. For conciseness, only the medium DC's graphs are shown here since it is referred to in later sections, but all results will be discussed. The green-shaded histogram represents the common frequencies observed at the reference wind farms. For an in-depth explanation, see *Brans (2021)*.

### 5.2.1. Resulting Response Amplitude Operators

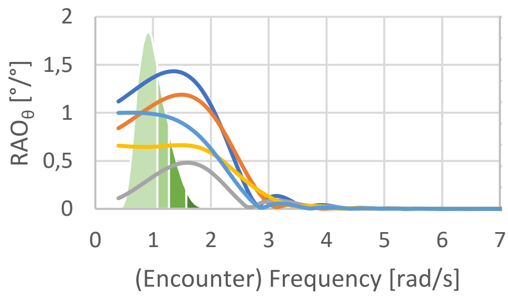
RAOs are transfer functions that show how the vessels are likely to respond to waves at sea. Each motion has its own graph due to different mass, damping and stiffness coefficients, *Bentley Systems (2014)*. They are also independent of the significant wave height, *de Jong (2011)*, because the heave RAOs were made non-dimensional against wave height, and the roll and pitch RAOs against wave slope. Here, the encounter frequency is the same as the wave frequency due to zero-speed. Fig.4 shows the results.




a) Heave




b) Roll




c) Pitch

Fig.10: RAOs of medium DC

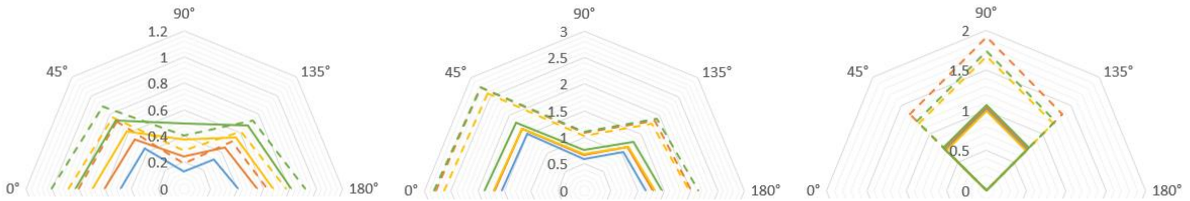
For heave, the DCs have good performance. There is a small peak resonance in beam waves, but all of the DCs' natural frequencies are situated outside the common frequencies range. So, the chance that DCs will experience heave resonance in beam waves during transfers is insignificant. In the event that there are beam waves travelling with $\omega \approx 2.5$ rad/s, the large DC will experience the highest responses.

For roll, the response amplitudes of each DC are similar to one another; i.e. their maximum responses are more or less equal. This is logical since all three DCs were given the same roll damping coefficients. Most importantly, the graphs show how $\upsilon = 0.20$ leads to lower responses, which would be beneficial during transfers. Also, the natural roll frequency of the small DC is approximately $\omega_n = 1.7$ rad/s. This is within the range of the common frequencies, but the chance that these waves will occur is meagre. With $\omega_n = 2.1$ rad/s and $\omega_n = 2.4$ rad/s, the medium and large DC, respectively, have less chance to experience resonance. Note that the response induced by stern-quartering waves is similar to the bow-quartering waves due to zero-speed.

For pitch, following waves will induce the largest pitch rotations. This is because the flatter stern is less suited to pierce waves compared to the bow. Also, all resonance peaks are located quite within the range of expected encounter frequencies. But those of the medium and large DCs are closer to the frequently observed wave frequencies. So, although the small DC has the highest amplitude, the natural frequencies of the medium and large DC make them more unfavourable.

### 5.2.2. Long-term responses to waves

The graphs in this section are comprised of the responses to the wave spectra given in Table II. Together, the results show how the DCs respond to wave conditions that are observed throughout the year. Each set of results corresponds to $\upsilon = 0.15$ since the results for $\upsilon = 0.20$ were similar. The polar graphs display the absolute motions and accelerations at the bow for all wave directions and spectra. Here, only the graphs for the medium DC are shown.




(a) (b) (c)

Fig.5: RMS absolute responses of medium DC; (a) Vert. motion, (b) Vert. accel., (c) Lat. accel.

The vertical motions at the bow, Fig.5a, show how much the bow moves. It includes all (three) motions and depends on the wave spectrum and incoming angle. The highest motions are induced by head and following waves. Also, higher wave heights increase the motion, while wave steepness increases the motion further. There is little difference between the three DCs. Fig.5b shows that the highest vertical accelerations at the bow are caused by following and stern-quartering waves. Also, steeper waves will increase the accelerations, while a varying wave height seems to have relatively less effect. In addition, the results for the "highest" steepness give an impression for the maximum observable accelerations. This is because steeper waves do not exist due to wave breaking. Thus, accelerations are not expected to exceed this limit either. When the motions are compared between DCs, they are reduced for the medium and large DC. But the medium DC achieves the lowest accelerations in beam waves. Fig.5c shows the lateral accelerations at the bow of the medium DC. The large DC has comparable lateral accelerations in all wave directions, but the small DC has the lowest accelerations overall. Again, steeper waves increase the accelerations, while a varying wave height has relatively less effect.

## 5.3. Main observations

### 5.3.1. Performance at zero speed

Following, stern-quartering and beam waves induce the largest accelerations. In contrast to the studies on vessels with a forward speed, the RAOs and long-term responses show that head waves seem to cause the least or relatively fewer excitations when all (three) motions are considered. Thus, it is smart to position the wind turbine's boat landing to ensure these vessels encounter head waves the most. But as discussed in section 0, waves from other directions are not significantly less likely to occur.

### 5.3.2. Effect of wave parameters

The wave steepness seems to increase the DC's responses more than higher wave heights. This makes sense looking at the rotational RAOs from section 05.2.1. These are made non-dimensional against wave slope, which is a function of wave frequency, directly related to the wave period. So, the higher the slope, the higher the response of the DC. This is also logical considering that an infinitely long wave with any wave height will give minor pressure changes and low accelerations. Therefore, the combination of wave period, i.e. wave steepness, and wave height, should be considered, rather than wave height alone, when deciding whether it is safe to deploy DCs.

### 5.3.3. Motions to be improved

Based on the RAOs of these reference DCs, the roll motion shall be prioritised for improvement since it is the riskiest motion when there are oblique waves. Looking at the long-term responses, then there are sometimes low vertical accelerations, but lateral accelerations are high. After that, pitch is prioritised due to its performance in waves from the aft. Heave will be investigated last. So, modifications will be made based on the prioritised motions. For example, if a modification to improve heave will undermine the roll response, it will not be implemented.

## 6. Feasibility definition

In the third step, a system's feasibility is defined by how compatible it is with its interfaces which can impose constraints. The interfaces included here are the SOV and the technicians. Technically, the wind turbine is also an important interface. Although it is a highly relevant interface during transfers, it is not considered here because it has more to do with fender type and material, which are excluded from this study.

### 6.1. Size and weight constraints

The DC must be stored on the SOV. Although minimal changes are considered allowed, the general arrangement of any SOV imposes limits to size and weight and will be heavily included to guide the prototype's design.

The ESVAGT FARADAY was selected as the reference SOV to determine size constraints because the SOV's superstructure does not surround its current DC. Fig.6 is a sketch of the surrounding area and includes notable systems. In short, there is no room for a DC to expand in length because the fast rescue craft cannot be placed elsewhere. There will be room in the width if the deck-crane and DC's davit are moved towards to centreline. Deducting the space needed for the DC's davit leaves roughly 7.5 m available in the width.

When the DC is being launched or recovered, the SOV's davit lifts the DC by its hook. This means two things for the DC: (i) it must have the structural integrity to be lifted by its hook, and (ii) its total weight must be within the current davit's lifting capacity of 14 t, https://www.redrock.no/portfolio/a-frame-davit-rda/.

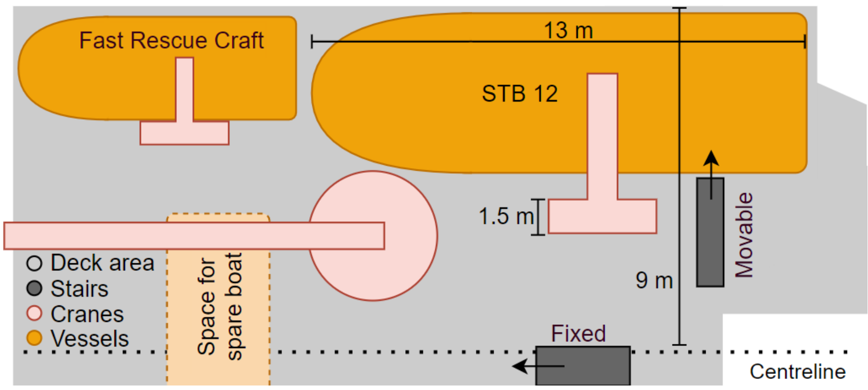


Fig.6: Sketch of available deck space on ESVAGT FARADAY

### 6.2. Habitability constraint

An operable DC will be able to reach the turbine and stay there, but a habitable vessel will have limited excitations to allow the technicians to transfer safely to the wind turbine. If a vessel is mainly operable, the motions are within an acceptable range for the vessel itself, but a wrongly timed move could cause injury to the technicians. So, because human comfort and safety have a crucial role in a DC's operability, habitability will define the limits as to how a vessel should respond to waves.

*Phillips et al. (2015)* state that there is little experience and consensus for the limits of vessel motion for transfers but point out that the vertical and horizontal acceleration limits should at least be lower than the values for transit. Specifically, they suggest that the thresholds at the wheelhouse should be 0.5 m/s² for vertical acceleration, 0.4 m/s² for horizontal acceleration and predominantly zero at the transfer point. It is uncertain how feasible these values are in practice, especially for the relatively small DC that cannot guarantee a low frequency of slip in high waves. Therefore, this study does not consider the proposed thresholds as a constraint but as a goal.

### 6.3. Physical characteristics of prototypes

Many solutions have emerged from extensive research in the field to improve seakeeping performance. To summarise, seakeeping can be improved by:

(i) modifying the hull dimensions and proportions, *Tan (1995), Keuning and Pinkster (1995,1997), Özüm et al. (2011)*,

(ii) applying a more suitable hull type or bow shape, *Belga et al. (2018), Jupp et al. (2014), Keuning and Gelling (2007), Keuning et al. (2001)*),

(iii) adding stabilisation devices, *Tan (1995), Yang et al. (2019), Irkal et al. (2019), Liang et al. (2017)*.

However, this study excludes stabilisation devices because analysing their influence requires other and higher fidelity methods. Furthermore, these can be added later in the design process.

Ultimately, two different hull types were selected to be tested, namely a monohull and a catamaran. Furthermore, two versions of those two hull types were generated to understand the effects of changing certain parameters, especially since most of the modifications are based on results obtained for (much) larger vessels. These prototypes were made based on the priority to improve roll motions, as stated in section 5.3.3. The new DCs and their characteristics are summarised in Table III. Note that no attempt was made to seek optimum designs in this step because the aim was establishing the feasibility to meet the set of operational objectives, *Kossiakoff et al. (2011)*. Furthermore, all new DC models were fitted with an Axe bow to reduce heave and pitch motions. So, the difference between Monohull 1 and the parent hull, for example, is not only due to the decreased metacentric height (GM). Still, the following analysis will isolate the effects of all the modifications.

## 7. Needs Validation

The resulting performance is evaluated against measures of effectiveness (MOE). The transfer thresholds (given in section 6.2) were deemed too idealistic to be feasible, especially for far-offshore wind farms that frequently observe rough weather conditions. So, the new DCs are evaluated against the parent hull, whose performance (shown in section 5.2) represents the MOE. The results were obtained using the same method described in section 5.1.

### 7.1. Response Amplitude Operators

Table III: Physical characteristics of DC models

| | **Parent hull (Medium DC)** | **Monohull 1 (M1)** | **Monohull 2 (M2)** | **Catamaran 1 (C1)** | **Catamaran 2 (C2)** |
|---|---|---|---|---|---|
| **Main differences** | NA. | Smaller GM | Larger beam | New hull type | Small clearance |
| **Bow shape** | Sharp bow | Axe bow | Axe bow | Axe bow | Axe bow |
| **Waterline length** | 12.39 m | 13 m | 13 m | 13 m | 13 m |
| **Waterline beam** | 3.68 m | 3.67 m | 4.27 m | 7.10 m | 4.70 m |
| **Demihull width** | NA. | NA. | NA. | 1.60 m | 1.60 m |
| **Draught** | 0.85 m | 1.22 m | 1.22 m | 1.41 m | 1.41 m |
| **GM** | 1.92 m | 0.80 m | 1.90 m | 11.83 m | 3.38 m |
| **LCB** | 5.58 m | 5.49 m | 5.69 m | 6.248 m | 6.248 m |

| | | | | | |
|---|---|---|---|---|---|
| **Weight** | 13.49 t | 12.60 t | 15.43 t | 20.36 t | 20.36 t |
| **Symbol in graphs** | | | | | |

The effectiveness of the DCs was analysed by normalising the area under their RAOs with respect to that of the parent hull, Figs.7 to 9. This gives a better indication of how the RAOs change in certain wave conditions. Note that an effectiveness level under 1.0 indicates a better performance than the parent hull because the RAO area is lower. Although all five waves directions were studied, only the results for beam waves are shown here for conciseness. All results can be found in *Brans (2021)*.

### 7.1.1. Heave

Compared to the parent hull, the monohulls' natural frequencies (i.e. resonance peaks) in beams waves moved closer to the peak of common wave frequencies. This shift is presumably due to the Axe bow since the response from M1 and M2 are similar. So, the Axe bow seemed to have changed the secondary parameters such that natural frequency is lowered. Still, according to Fig.7, which shows the level of effectiveness, their absolute responses are generally similar to that of the parent hull; only at higher frequencies is there a notable improvement compared to the parent hull.

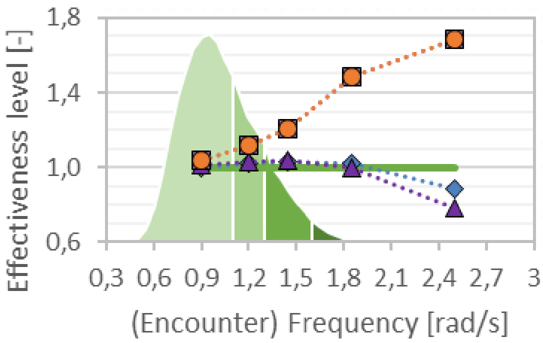



Fig.7: Effectiveness of heave in beam waves

Also, the new monohulls perform poorer than the parent hull in waves from the aft. The catamarans show a much larger resonance peak at their natural frequency in beam waves. Although it is positioned outside the range of expected encounter frequencies, Fig.7 shows how the heave response to beam waves is always higher than the parent hull and the new monohulls. The same goes for the other wave directions. In short, all DCs match for the first range of frequencies. As the frequencies rise, the catamarans show the poorest performance while the monohulls are mostly comparable to the parent hull.

### 7.1.2. Roll

The roll damping coefficient of the catamarans was calculated to be $\upsilon = 0.20$. So, the effectiveness was evaluated for this value. The monohulls have the same resonance amplitude as the parent hull. However, M1 has a lower natural frequency than the parent hull and M2. So, it is presumed that the shift is due to a lower GM and not the Axe bow. Moreover, it is fairly in the range of wave frequencies expected to occur often, which is a considerable disadvantage. Fig.8 confirms this: M1 matches the rest of the DCs in the first frequency range but is the worst at other common frequencies. So, M1 would be ill-suited to use at Hornsea One, where beam waves frequently occur. The roll response from M2 is similar to the parent hull. Besides a slightly decreased amplitude after the resonance peak, the roll RAOs are unaffected by a wider beam. The resonance amplitude from both catamarans is significantly lower than the parent hull: C1 and C2 reduced the amplitude by roughly 50% and 18%, respectively. Moreover, C1's natural frequency shifted farther from the frequency spectrum's peak, while C2 shifted closer to it. So, C1 is most effective in reducing the roll motions in all (oblique) wave directions, especially in beam waves.

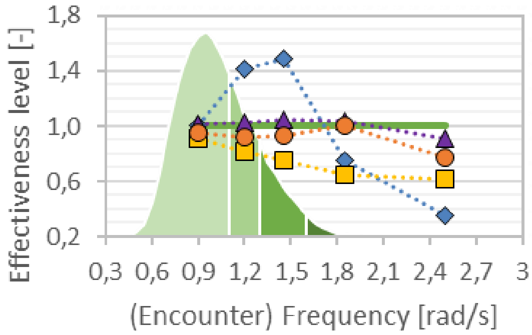


Fig.8: Effectiveness of roll in beam waves

#### 7.1.3. Pitch

The pitch response from both monohulls is nearly identical to that of the parent hull. Fig.9 confirms this for the common frequencies and most wave directions. This was anticipated since modifying the Axe bow and shifting the LCB are known to have little effect on pitch. The LCB of M1 even moved backwards, but the (negative) effect is not large. Also, it seems that the positive LCB shift of M2 was not large enough for there to be a notable reduction.

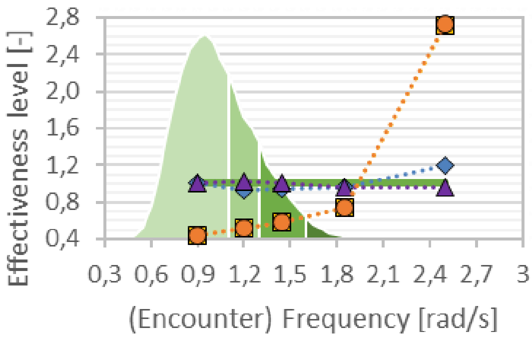


Fig.9: Effectiveness of pitch in beam waves

The natural frequencies of the catamarans shifted farther from the frequency spectrum's peak. According to *Gutsch et al. (2020)*, this is what lowers vessel motions. So, although the absolute pitch response in stern-quartering waves is higher than the monohulls, the natural frequency shifted to a more favourable position. Furthermore, the resonance amplitude in following waves was reduced as well. It seems that the catamarans' LCB was moved forward enough for it to (positively) affect pitch. Fig.9 shows that catamarans performed best in beam waves, except in the high (but uncommon) frequencies. They also performed best in following and stern-quartering waves. Only in waves from the front did they perform slightly worse than the monohulls for all frequencies. Considering that head waves occur the most due to the boat landing's orientation, catamarans would then not immediately be the vessel of choice.

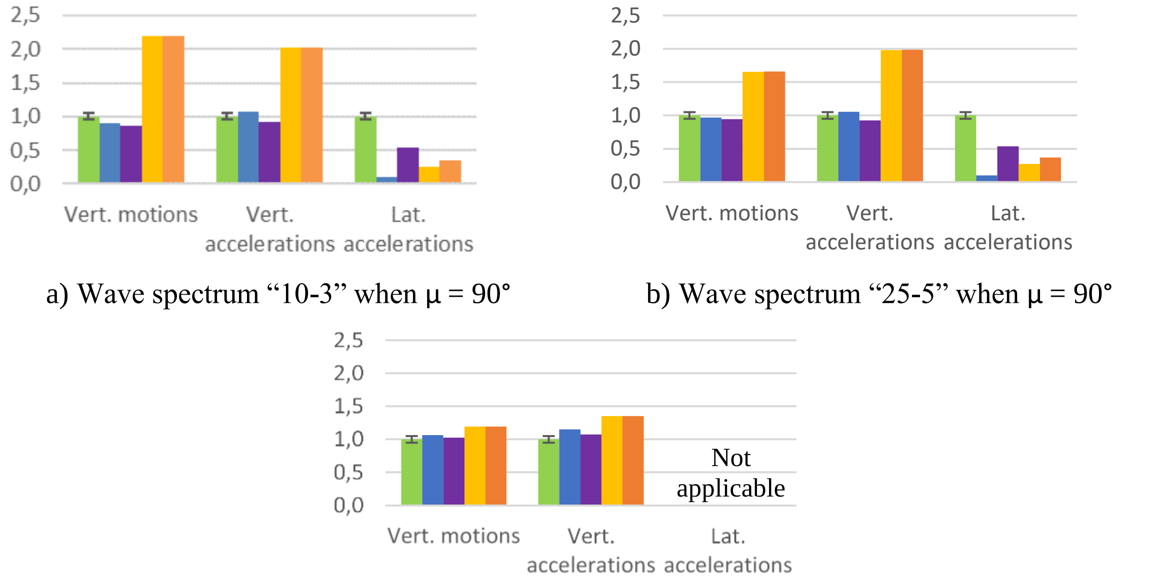
### 7.2. Long-term response

Fig.10 shows the prototypes' effectiveness in terms of vertical motions and accelerations and lateral accelerations. Table III defines the colour codes. For conciseness, it only contains results from three wave conditions.

#### 7.2.1. Vertical motions and accelerations

The monohulls have nearly identical responses to the various wave spectra. Just like the parent hull, the highest response is induced by head and following waves. The catamarans show larger motions for all wave directions. This alone does not indicate that the catamarans are less safe, but the accelerations are higher as well. However, their accelerations in longitudinal waves are very similar to the monohulls.

The difference found here corresponds to the results found by the RAOs; the catamarans also had a higher response to quartering and beam waves compared to the monohulls.




a) Wave spectrum “10-3” when μ = 90°

b) Wave spectrum “25-5” when μ = 90°

c) Wave spectrum “25-5” when μ = 180°

Fig.10: Long-term effectiveness

### 7.2.2. Lateral accelerations

In this case, the parent hull has the largest accelerations. The lowered GM of M1 significantly reduces the lateral accelerations to near-zero levels, and at first glance, this is the ideal response. This reduction was expected because a smaller GM leads to a smaller righting arm, which slows down the roll period. However, an analysis into static stability showed that the GM of M1 is so low that it will already tend to capsize at a heeling angle of 15°-20°. So, M1 is deemed unpractical and will not be promoted for far-offshore use. M2 has the same GM as the parent hull and a wider beam. The accelerations were cut in half, but a wider beam was not as “effective” as a lowered GM. This corresponds with the conclusions by *Gutsch et al. (2020)*. Both catamarans also have significantly reduced accelerations. Those of the quartering waves are even reduced with a greater scale. C1 has the lowest accelerations among the two, so the larger clearance is more effective in lowering the lateral accelerations; the same conclusion was drawn for the RAOs.

## 7.3. Overview of best-performing daughter craft

This section summarises the results in Table IV by presenting which model performed the best for various seakeeping parameters. Specifically, three points were considered to determine which DC (type) is most useful at the reference farms: the most prominent wave directions (section 0), the notion that the response should be as low as possible (to meet the ideal seakeeping criteria for transfers given in section 6.2) and the estimation of their intact stability (excluded in this paper).

In short, the monohulls are suitable if only head waves are considered. Once other wave angles are included in the analysis, catamarans start to outperform the monohulls. The new monohulls also had poorer transverse stability than the parent hull. Still, there are occasions when the catamarans are slightly inferior, i.e. heave and vertical responses. However, these DCs were simulated to be floating freely. The heave results could perhaps improve when the interaction with the boat landing is included in the analysis.

Table IV: DCs best suited for combinations of seakeeping and wave direction

| | Head | Beam | Stern-qtr. | Following |
|---|---|---|---|---|
| **Heave RAO** | Monohulls | Monohulls | Parent hull | Parent hull |
| **Roll RAO** | Not applicable | C1 | Catamarans | Not applicable |
| **Pitch RAO** | Parent hull and monohulls | Catamarans | Catamarans | Catamarans |
| **Vertical bow response** | Parent hull | Monohulls | Monohulls | Monohulls |
| **Lateral bow response** | Not applicable | Catamarans | Catamarans (matched threshold in common steepness) | Not applicable |

## 8. Conclusions

The seakeeping performance of existing DCs was analysed to determine where the deficiencies lie and what could be done to resolve them. The first notable deficiency of current DCs stems from their operational requirement to transfer in $H_s \leq 1.5$ m. As a result, DCs will have a low accessibility rate in areas frequented by higher significant wave heights, which undermine their value for far-offshore applications. The second deficiency is that they are required to achieve a high speed of 25 knots in transit when the emphasis should be laid on safe transfer conditions. This is due to their closer proximity to the wind farm than port-based O&M access vessels. For existing DCs already under a charter-contract, it is recommended to refit them with motions stabilisation devices to improve their seakeeping performance at zero-speed. For future DCs meant to operate far offshore, this paper recommends requiring them to be able to access wind turbines in $2.0 \text{ m} \leq H_s \leq 2.5$ m to realise year-round access while considering the effects of wave steepness. Various combinations of solutions were analysed to establish the access requirement's feasibility while focusing on the transfer phase. No prototype had improved responses in all conditions. But overall, the prototypes outperformed the parent hull for a majority of conditions. Moreover, the catamaran DC have a high potential to realise year-round accessibility to far-offshore wind farms due to their performance in oblique waves. Lastly, it is believed that accessibility can be improved further if the wind turbine facilitates the daughter craft during transfers. But this solution is more suited for wind farms still in the development phase.


## Acknowledgements

This work was performed as part of the MSc thesis for the lead author, *Brans (2021)*. The thesis was performed in Marine Technology at Delft University of Technology and the authors would like to acknowledge both Delft University of Technology and Siemens Gamesa for their support of this research.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