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A study of the towing characteristics of a semi-submersible floating offshore wind platform

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Abstract. A robust pipeline of floating wind energy has emerged with a general trend of projects becoming larger, further from shore, and placed in increasingly energetic seas. The installation process for these farms involves the pre-assembly of components onshore or in sheltered waters before towing the platform to the operational location using tugs. It can be expected that such marine operations will be repeated in reverse at the time of decommissioning. The cost and safety of these operations will be influenced by the tugs used, towing speed, the local metocean conditions, the platform/turbine characteristics and other factors. This paper investigates the hydrodynamic characteristics of a large semi-submersible floating offshore wind turbine (FOWT) under tow. The motions of the FOWT are analysed using a numerical tool and validated using a towing test. A framework is proposed for the assessment of FOWT towing operations. Various limiting factors have been identified and the hydrodynamic performance of the system has been evaluated using the framework.

1. Introduction

Towing operations represent a critical phase of the floating offshore wind farms (FOWFs) construction process. They were required during the installation of the existing FOWFs such as the Hywind Scotland, Kincardine and Windfloat Atlantic projects [1]. Despite the importance of these activities, the planning of towing operations currently primarily relies on the experience of the captain of the towing vessel whilst any of the modelling and planning tools for these critical operations usually rely on the general recommendations and standards developed for offshore structures [2]. When numerical models are used to assist with this process, they are typically not optimised for the very large, top-heavy FOWTs. Since many floater designs that vary in size and geometry have been developed, it is important to analyse the towing behaviour of these FOWTs individually, until FOWT-specific rules of thumb or standard industry practices are developed. This need for bespoke towing planning and optimisation tools for FOWFs is increasing in importance as they will roll out with large-scale deployments which are further from shore, and in areas where weather windows are likely to be reduced, compared to traditional bottom-fixed offshore wind farms.

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This paper presents a framework that can be used to analyse the towing operations of fully-assembled FOWTs. A sequential approach, influencing and restricting factors and guidelines for FOWT towing are explained with the help of the presented framework. An experimental study and results that were used for the analysis of a basic towing operation are also presented.

2. Framework for analysing the towing characteristics of a floating offshore wind turbine

FOWTs vary in shape and size and the geometry of the platform will affect the towability of the fully-assembled FOWT system. Therefore, it is important to analyse each floater separately before commencing towing operations. In this section, a framework is presented to analyse the towing operation of a FOWT (see Figure 1). This framework can be used to check the feasibility of towing a FOWT at a particular draught and speed.

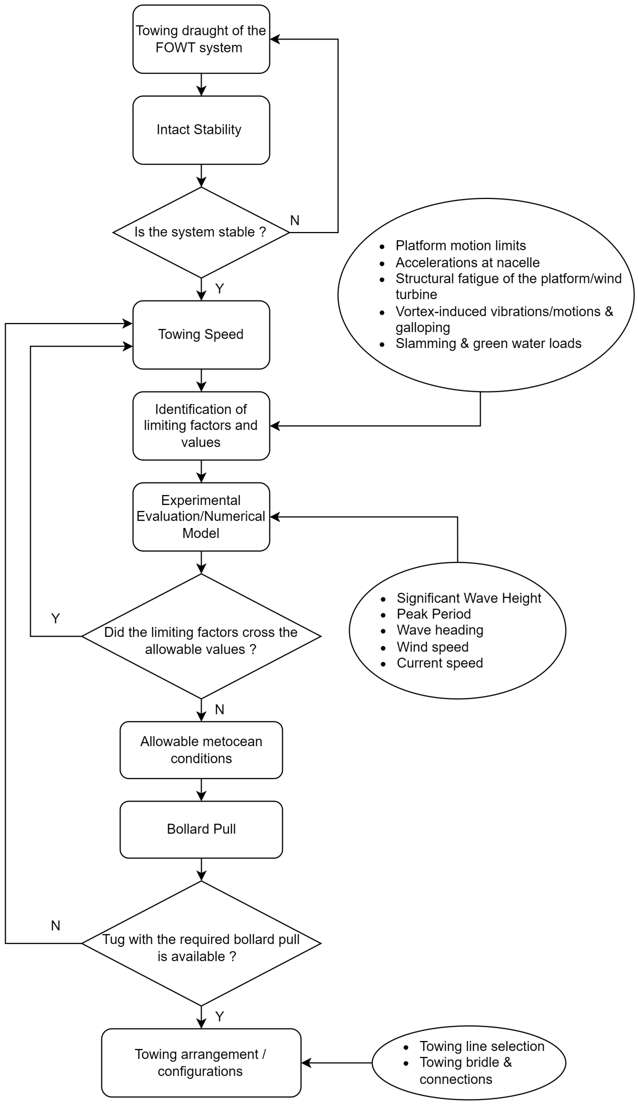

Figure 1. Framework for analysing towing of FOWTs

The first step is to check the intact stability of the FOWT at the given draught of interest. Collu et al. [3] have defined the stability requirements of FOWTs during towing operations. A minimum GM (metacentric height) of 2 m is recommended during tow-out. The static range of stability should not be less than 15 degrees and the area under the righting moment curve is to be 1.4 times more than the area under the wind overturning moment for safe towing [4]. The towing point should be positioned in such a way that the heeling moments are minimised. The maximum inclination angle, under total heeling moment, should remain below 5 degrees and under half-towline pull, should remain below 2 degrees. Furthermore, the distance between the maximum static draught and minimum water depth should be higher than 2 m or 10% of the static draught (whichever is lesser).

Det Norske Veritas (DNV) has set the limiting conditions for motions and accelerations in DNV-ST-N001, standards for marine operations [2]. Wind turbine OEMs (Original Equipment Manufacturers) have defined acceleration limits at the nacelle for operation and survival conditions. There should be sufficient freeboard at the bow to minimise damage from slamming and green water loads [5]. For long tow durations, fatigue checks should be performed for the platform as well as the wind turbines. Local areas prone to fatigue damage should be identified prior to towing and fatigue life should be assessed. The fatigue life should be higher than the entire tow duration including waiting times. For offshore structures like FPSOs (Floating Production Storage and Offloading), the hull girder strength, structural connections, local plating strength etc. are recommended to be checked [5] and this can be adopted for FOWTs also. The fatigue damage check of the structural connection between the topside and hull is also recommended by DNV [2], similarly, the connection between the tower and transition piece/platform should be checked in the case of FOWTs.

Vortex-induced motions and vibrations (VIM&VIV) are also phenomena that can affect towing operations, especially spar-type platforms and semi-submersibles with cylindrical columns [6]. These phenomena have been observed on slender oil & gas structures and were studied extensively in the past decades and this knowledge is transferable to FOWT towing operations also. VIM&VIV are strongly non-linear phenomena and no well-established analysis methods exist, but fair predictions and analyses can be made using CFD (Computational Fluid Dynamics) and model testing [6]. One of the factors that trigger VIV is the Reynold's number [6], which is a function of speed, so towing speeds that can induce VIV should be avoided. Fishtailing is another phenomenon which should be considered while choosing the towing configuration.

A numerical/analytical model built using a suitable available hydrodynamic tool can be used to test the response of the FOWT system under various metocean conditions like significant wave height, peak period, wind speed, current speed etc. The limiting values associated with the various limiting factors and phenomena should be identified and the towing operation should be analysed numerically to find if those values are exceeded during towing in those metocean conditions. Two approaches can be followed to determine the performance of the system during the voyage:

- **Scatter diagram approach**: In this approach, for each environmental condition in a scatter diagram, the towability is determined. Based on the seasonal probability of occurrence of each entry in the scatter diagram, the feasibility of the tow can be determined. This approach is justifiable for short-distance tows.
- **Voyage approach**: In this approach, the environmental conditions along the route are derived from a hindcast time series. The above-mentioned evaluation is applied for each condition during the voyage. This reveals whether the voyage is feasible or not depending on the starting date/time of the year in the hindcast time series.

A systematic iteration of different draughts and speeds using the framework can be used to find the optimum towing draught, speed and bollard pull for a towing operation. This process requires numerous iterations to find the optimum towing characteristics, which is a lengthy and complex procedure. This method consists of:

- Determination of the least draught at which the FOWT system is statically stable. The lightweight draught (zero ballast) is the least possible draught and this is to be taken as a starting point.
- Once the draught is calculated, the towing speed is to be determined. Initially, a low towing speed (eg: 0.5 kn (knot)) is applied and then slowly raised to higher speeds.
- The various limiting factors and the permissible values are identified.
- A numerical/analytical model is built using a suitable hydrodynamic tool and the system is tested in various metocean conditions.
- If the limiting values are not exceeded during the voyage, the bollard pull can be calculated and suitable tug(s), towing line and towing arrangement can be selected. Special care should be given to check towing stability and chances of fishtailing.

To demonstrate the usage of the framework an experimental study with a high draught and speed was performed and analysed. Focus is given to testing a particular towing speed and draught and assessing the bollard pull requirements rather than using the complete framework, which is a complex process as mentioned before. A simplified numerical model using a hydrodynamic analysis tool is used to calculate the motions and accelerations of the platform and is validated using the experimental results. Using the model, the performance of the system in various wave headings and irregular wave conditions is derived.

3. Model, experimental setup and testing procedure

The platform used for the study was a semi-submersible floater designed by CENER, Spain, as part of the INNWIND Project [7]. The platform is coupled with an NREL 5MW wind turbine [8]. The aluminium model was constructed at a scale of 1/50. The geometry details (see Figure 2) and main particulars (see Table 1) of the FOWT system are described below:

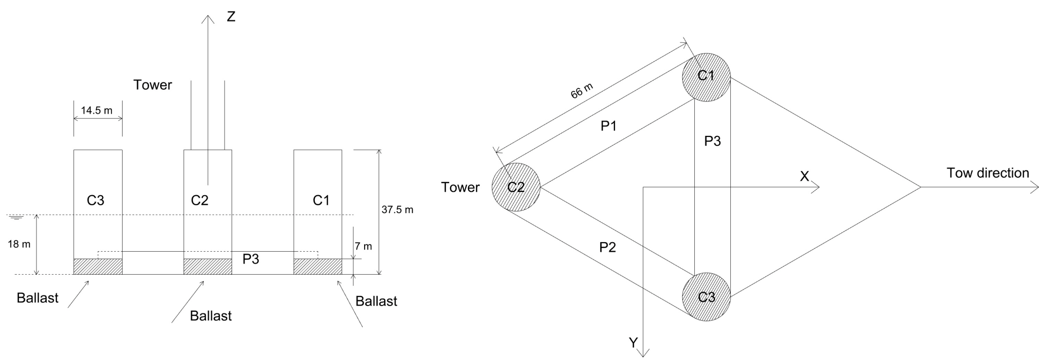

Figure 2. Main dimensions of the floater and towing arrangement

The experiments were performed in the ocean basin at the Lir NOTF (National Ocean Test Facility), University College Cork, Ireland [9]. The operational draught of 18 m is applied in the tests since the primary focus of the original test campaign was on operational conditions at zero speed. This draught is not the minimum towing draught but was adopted in the simulations because of available model test results for validation. The model was first towed at various speeds in calm water to ascertain the drag and thereby the required bollard pull. Then the system was towed in an irregular sea state. The towing line was attached to columns C1 and C3 (see Figure 2) of the model and was towed using a PI-controlled winch-motor system [10]. The tension on the winch cable was dynamically controlled to give constant speed to the model. A

Table 1. Main particulars of the model in the towing configuration

Main Particulars	Model Scale	Full Scale
Total mass	167.3 kg	20,912.5 ton
KG	0.17 m	8.5 m
GM	0.295 m	14.75 m
Draught	0.36 m	18 m
Roll moment of inertia	72.481 kg m^2	2.26E07 ton m^2
Pitch moment of inertia	73.413 kg m^2	2.29E07 ton m^2
Yaw moment of inertia	88.849 kg m^2	2.78E07 ton m^2
T_n Heave	2.8 s	19.8 s
T_n Roll	2.9 s	20.5 s
T_n Pitch	2.9 s	20.5 s

spring (to absorb snap loads) and a loadcell were mounted on the winch wire and a wave probe mounted off the instruments bridge was used to record wave elevations. A rope was tied to the stern of the model to pull it back to its start position after each test. Any potential extra drag caused by the retrieving wire was mitigated using the PI controller. The response of the FOWT system was recorded using a Qualisys motion tracking system. The tow-out operation is usually carried out at low speeds (1.5 – 3 kn) [4], but since the ambitions are to tow at higher speeds a towing speed of 5 knots is used in the experiment as well as in the numerical calculations. Table 2 shows the details of the tests performed. The model scale and prototype values (in brackets) are shown.

Table 2. Test matrix

Description	Towing speed (m/s)	Wave height (m)	Remarks
Calm water	0.07(0.5), 0.22(1.56), 0.36(2.54)	-	Head-sea
Irregular waves	0.36(2.54)	Hs =0.06(3) m, Tp=1.13(8) s	Head-sea

4. Hydrodynamics of the FOWT system

4.1. Limiting motion criteria and conditions

According to the default motion criteria set by DNV, the maximum permissible roll and pitch amplitude must be 5 degrees and heave acceleration must be 0.1g [5]. The limits vary according to the duration of towing, but as a starting point, the towing is assumed to be a weather-restricted operation in benign conditions. A total acceleration (vector sum) limit of 1 m/s^2 for the NREL 5 MW wind turbine is chosen based on previous studies [11]. The identified limits are mentioned in Table 3. This list is not exhaustive, and it is possible that other limiting factors which are not yet identified may exist and require dedicated research for identifying them. The limiting values can also be varied depending on the floater design and the wind turbine machinery.

Table 3. Limiting factors and values

Limiting factor	Limiting value (maximum)
Roll motion	5 degrees
Pitch motion	5 degrees
Heave acceleration	0.1 g
Total acceleration at the nacelle	1 m/s^2

4.2. Motions and accelerations

The motion response of the FOWT system recorded during the tank testing is presented in this section. The RAOs (Response Amplitude Operators) of the heave, roll and pitch motions were derived by analysing the data obtained from the Qualisys motion tracking system. All the results were converted into full-scale values. In parallel, a numerical model was set up using MARIN's (Maritime Research Institute, Netherlands) in-house hydrodynamic seakeeping code SEACAL. SEACAL can perform hydrodynamic analyses of bodies with forward speed. Viscous effects were neglected for the calculations. It is assumed that the wind turbine is in parked-feathered condition during towing. This would reduce the wind forces on the turbine during towing. The effect of wind and current would need a dedicated analysis but is neglected for this study. The commercial hydrodynamic software suite Ansys-Aqwa [12] was also used for the analysis as an additional tool and the option for analysing bodies with forward speed was utilised for analyses. The natural frequencies of the system in heave, roll and pitch have been determined experimentally in decay tests at the experimental facility. Figure 3 shows the validation of the numerical model using the test results. The towing speed was 5 knots, in head waves.

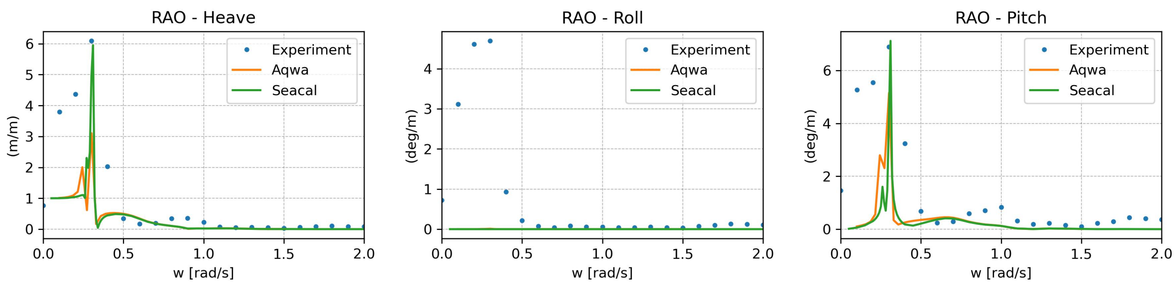

Figure 3. Comparison of motion RAOs

The resonance frequency has been correctly captured by the model and the motions at higher frequencies are in good agreement with the experimental results for pitch and heave. For frequencies lower than the resonance frequency the tests still show significant RAOs. Even though the roll motion is observed to be very low in head-sea conditions, some roll motion was observed during the experiments. This requires further investigation to check if this happened due to model asymmetry, wave reflections from the tank or unforeseen physical phenomena.

4.3. Motions of the system in various headings

In realistic sea conditions, the FOWT will encounter waves from different directions during towing. It is important to investigate the hydrodynamic performance of the system in various headings and to understand the effect of the direction of the incident waves on the motions of the system. In this section, the effect of the incident wave headings on the motions and accelerations of the FOWT system is presented using the validated SEACAL numerical model. Figure 4 shows the motion RAOs and acceleration transfer functions of the FOWT system under various wave encounter directions.

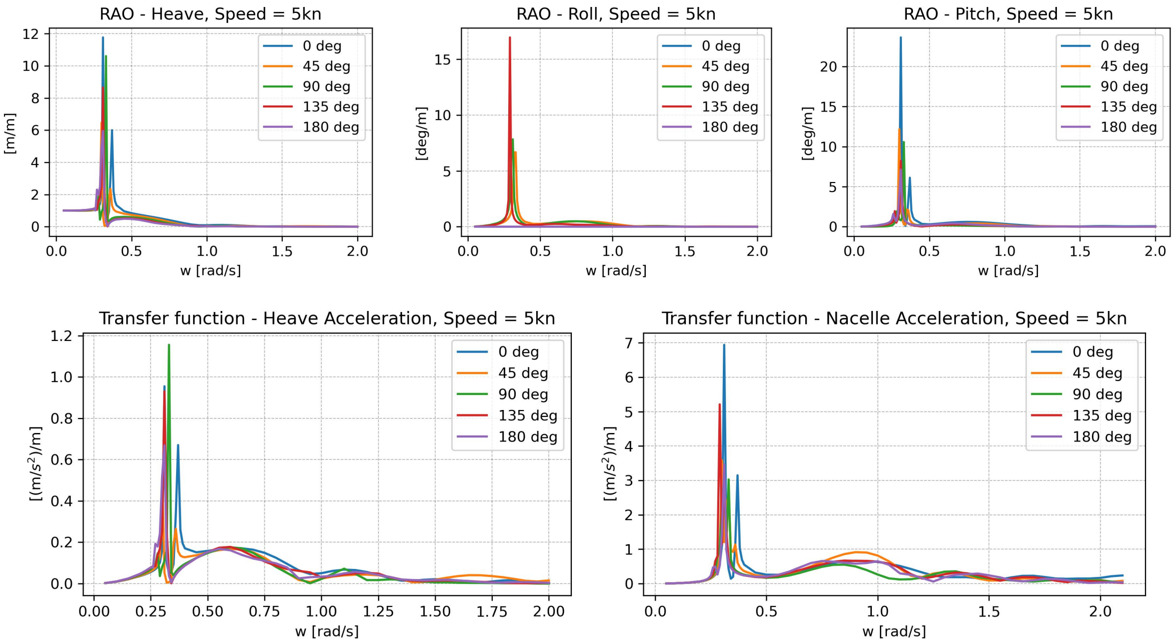

Figure 4. Motion and acceleration RAOs showing the influence of wave direction

The direction of the incident waves has a considerable impact on the motions and accelerations of the FOWT system. In beam and quartering seas, the pitch and roll motions are severe. The chances of exceeding the permissible motion limits are high in such sea-states.

4.4. Motions of the floater system in irregular waves

It is important to analyse the motion of the FOWT system during towing in irregular seaways as significant wave height (Hs) and peak period (Tp) impact the motions of the towed system. Moving out into deeper waters will be required in the near future to meet the energy supply demands [1]. Eventually, towing operations have to be performed in rougher seas and analysing the hydrodynamic behaviour of the floaters in rough seas is of paramount importance. Using SEACAL, the FOWT system is analysed and the results are plotted. JONSWAP (Joint North Sea Wave Project) spectrum is used for the analyses and the expected maximum values are calculated for roll motion, pitch motion, heave acceleration and nacelle acceleration. These values are plotted for various Tp conditions. From the previous numerical analyses, it was evident that the wave headings have a significant impact on the motions of the floater. So, the maximum values are plotted for various headings assuming a towing speed of 5 kn. The range of peak periods to be analysed for towing operations is given by [4]:

$$\sqrt{13Hs} \leq Tp \leq \sqrt{30Hs}$$

The range of Tp values (3.6s – 15.5s) is calculated assuming a maximum Hs of 8 m given by the above equation. Figure 5 shows the maximum values calculated for roll and pitch motions

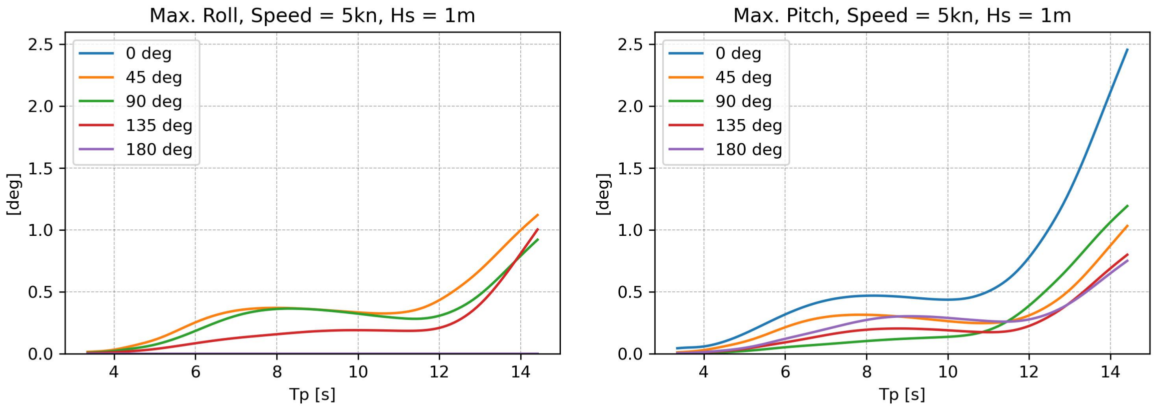

Figure 5. Maximum values of roll and pitch motions in various wave headings

and Figure 6 shows the maximum values calculated for heave acceleration and acceleration at the nacelle for the system at a Hs of 1 m.

In Figure 5, it can be observed that the FOWT system experiences maximum roll motions in stern-quartering waves. As the Tp value increases, the roll motion amplitude comes closer to 1 degree at a Tp value of 14 s. For Tp values between 7 s and 11 s, the roll amplitude remains slightly below 0.4 degrees. Pitch motion is severe in following sea conditions. At a Tp value of 15.5 s the maximum pitch amplitude is 2.5 degrees. For Tp values between 7 s and 11 s, the pitch amplitude remains slightly below 0.5 degrees.

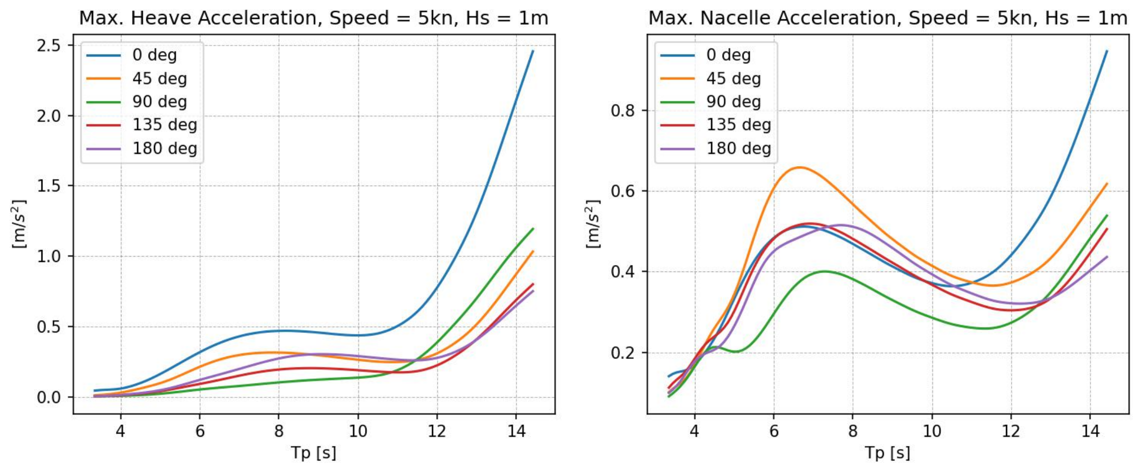

Figure 6. Maximum values of heave acceleration and acceleration at nacelle in various wave headings

In Figure 6, the heave acceleration exceeds the limiting value of 0.1g close to a Tp value of 12.5 s in the following-sea condition. For Tp values ranging from 7 s to 11 s, the heave acceleration remains below 0.5 m/s^2. Acceleration at the nacelle gets closer to the limiting value of 1 m/s^2 around a Tp value of 15.5 s. Assuming the motions and accelerations vary linearly with respect to Hs, the limiting Hs values can be calculated. The Hs and Tp at which the motions and accelerations remain under the permissible limits for the chosen limiting factors are shown in Figure 7. It can be observed that the acceleration at the nacelle is the strictest limiting factor and determines the towing characteristics. The wave conditions (Hs, Tp) at which the towing operation is feasible fall into the green area in Figure 7.

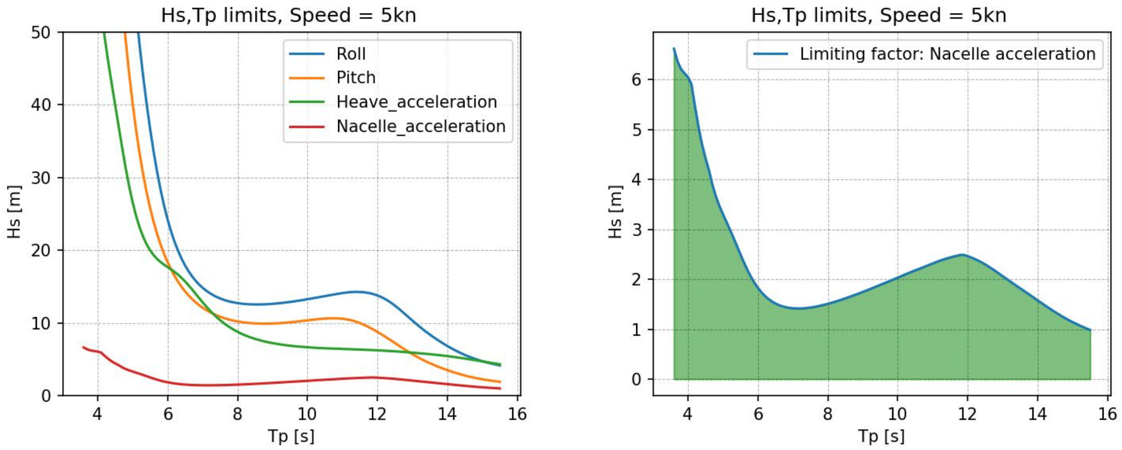

Figure 7. Hs,Tp limits for various limiting factors (left) Hs,Tp limits for the strictest limiting factor (right)

4.5. Bollard pull

The tension on the cable while towing was recorded and these values indicate the bollard pull for towing the FOWT system. The bollard pull for various speeds was derived from the experiment results for calm water and calculated using the numerical model for irregular waves. Figure 8 shows the variation of the required bollard pulls with respect to towing speed in calm waters and irregular waves under head-sea tow.

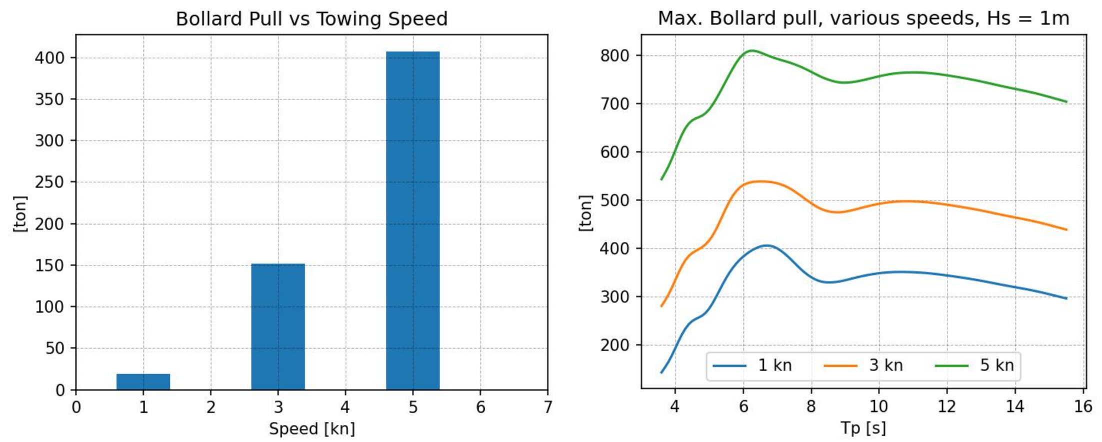

Figure 8. Required bollard pull vs towing speed (left) Bollard pull requirement in various sea-states (right)

Figure 8 only shows the calm water bollard pull at even keel of the FOWT. The bollard pull will increase due to wave added resistance, wind loads, trim etc. The bollard pull requirement increases quadratically as the towing speed increases. Figure 8 shows that a maximum bollard pull of around 800 tons is required for towing the FOWT with the mentioned draught and speed in irregular waves. A tug efficiency factor of 1 is assumed for the calculation, but in reality, the value is 0.75 for ocean towing [2], which raises the bollard pull requirement even higher.

5. Conclusions and further research

This paper has provided a general framework for the assessment of the hydrodynamic performance of a fully assembled FOWT system in different draught, wave and towing speed conditions. For the semi-submersible platform considered, the motions of the system remain under acceptable limits for many wave conditions, but the acceleration at the nacelle is the strictest limiting factor here and hence determines the limiting environmental conditions and hence the towing characteristics. A Hs of around 1.5 m is a realistic significant wave height at the mentioned draught and speed for safe towing in all the sea-states analysed in the study. Identifying the strictest limiting factors and raising the limiting value by improving the design of the component in the FOWT system will help raise this Hs limit.

The towing speed and draught analysed in this study are not optimised and a systematic iterative study using various towing draughts and speeds can improve the towing characteristics. A basic analysis revealed that the bollard pull increases quadratically when the towing speed increases. If the required bollard pull is more than that can be handled by a single tug, multiple tugs can be used, but this increases costs.

To date, FOWTs have generally been towed by AHTSs (Anchor Handling Tug Supply) during installation. Some AHTSs have up to 300 ton bollard pull but higher bollard pulls are rare [4]. Detailed dedicated analyses are required for checking the effect of wind and current also before commencing towing operations for large floating offshore wind turbines. Further research is required for the development of the method using a voyage-analysis approach. In this approach the environmental conditions along the route are derived from a hindcast time series. Checking the towability at every time step reveals the towability of the complete voyage. Additionally, involuntary or voluntary speed or course changes can be applied for long towing operations. The effect of wind, trim of the floater and VIM should also be included in the studies. For long tows, the directional stability of the FOWT system should also be checked for course-keeping. As the FOWTs get larger, large ocean-worthy tugs with high bollard pulls might be required in the near future for the installation, major repairs and decommissioning of such FOWTs.

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